Michigan State University
Pavement Research Center of Excellence

Evaluation of MDOT's Methodologies for both Quantifying Pavement Distress and Modeling Pavement Performance for Life-Cycle Cost and Remaining Service Life Estimation Purposes

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FINAL REPORT

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16. Abstract
MDOT has been using the Distress Index (DI) since the inception of its pavement management system (PMS) in the early 1990s. DI was developed to help MDOT engineers decide, allocate budgets, and prioritize future maintenance or reconstruction activities. However, the raw data requirements for the DI are complicated (and somewhat unique compared to the rest of the nation). Over the last three decades, the pavement industry has seen many advances in data collection, distress identification, performance modeling, and other processes fundamental to PMSs. Consequently, there was a need to revisit the DI used by MDOT and revise it according to modern pavement data collection standards and calculation methodology. This study aimed to develop an enhanced pavement condition score and associated PMS data collection methodology for use by MDOT. To meet this objective, 2081 flexible and 741 rigid pavement sections were selected from MDOT's performance database. Then, five different condition indices used by other state agencies were computed using the MDOT's PMS data and compared against MDOT's Distress Index (DI). Maintenance records were used to compare the magnitudes of different indices right before maintenance activities were performed. The new pavement condition parameter was selected to follow the current state of the practice in its rating scale and consider major distresses. Furthermore, various performance models were used to predict the new condition index and International Roughness Index (IRI) data, and pavement fix lives were estimated for both asphalt and rigid pavements. Building on these advancements, network-level modeling methods were developed to project the future condition of MDOT's pavement network in terms of IRI, cracking, rutting, and faulting. Using Markovian Transition Probability Matrices (TPMs) and multinomial logistic regression, the study established a robust analytical framework to forecast pavement performance under various maintenance and rehabilitation scenarios. These models enable MDOT to evaluate the long-term effects of different funding strategies, set realistic performance targets in alignment with federal requirements, and support data-driven decision-making for statewide pavement management.

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1 INTRODUCTION

State Department of Transportations (DOTs) in the US typically use a pavement management system (PMS) to manage their pavement network efficiently. PMSs work as data-driven and informed decision-making tools that helps state DOTs maintain their future budget allocation, repair needs, and prioritization of maintenance activities (Bektas et al. 2015; Ragnoli et al. 2018). Therefore, a functional PMS is very crucial for the overall decision-making process. An element of a PMS database is the vast collection of historical pavement condition data. Various types of observed distress are surveyed annually and stored in a PMS database. Pavement distresses are quantifiable defects in the pavement's surface that can be attributed to construction defects, functional or structural deterioration, and general aging of the layer materials. A study of the severity and extent of specific distress types can inform engineers and decision-makers about the cause of the distress, which can then point to the particular maintenance actions available for consideration (Pierce and Weitzel 2019). Essentially, the costs to manage pavements to a specified level of performance are directly affected by the condition metrics being collected on that pavement segment.

In asset management, performance measures are vital in determining the progress toward a goal (Systematics 2006). Performance measures usually include pavement surface distresses and roughness in evaluating the pavement condition. Performance measures often represent the deciding factor in assessing the current health conditions of the roadway network. However, this terminology should not be limited to assessing current health conditions; rather, performance measure indices should be able to guide state offices to know each year which pavement needs maintenance and rehabilitation (M&R) treatment. Moreover, it should further assess the effectiveness of the applied M&R to that pavement over the years (Simpson et al. 2013). Collectively, pavement performance measures should help to make strategic decisions on allocating budgets, monitoring, and sustaining road networks by applying the right M&R on the right road at the right time. Pavement performance modeling linked to the pavement condition index helps to reflect past performance and predict future pavement conditions.

It has long been known that fixing the worst pavement first is not the best option in M&R planning. Research has shown that early minor treatment activities delay the deterioration of pavements and can be economical in the long run (K.H. 2002). For example, MDOT roughly estimates the cost per mile for rehabilitation at $121,000 to $423,000 and the cost per mile for reconstruction at $328,000 to over $1 million for some freeways (Belzowski and Ekstrom 2015). These figures reflect 2015 estimates; since then, pavement construction costs have increased substantially—driven by inflation, materials, and labor—so current unit costs are expected to be higher. An agency can reduce costs by avoiding major rehabilitation or reconstruction at early/late pavement lives. Therefore, proper assessment of current pavement health conditions with a robust performance modeling approach is necessary for every state agency to follow.

MDOT maintains approximately 10,000 route miles of trunkline road, and the parameter used by the MDOT to assess the condition of those pavements has historically been the Distress Index (DI) (Abu-Lebdeh et al. 2003). MDOT has been using DI since the inception of its PMS in the early 1990s. The DI is calculated by assigning increasing-value numeric 'points' to the quantity and severity of various surface distresses such as cracks, potholes, etc.

To record DI values for the MDOT pavement network, distress surveys were conducted approximately every two years for each pavement. These surveys rely on pavement video footage, where vendors visually classify distresses into numerous categories known as Principal Distresses (PDs). The MDOT PMS database stores these individual distresses using PD codes, and Associated Distress (AD) matrices are used to define the severity of each distress. The level of detail in the AD matrices is inconsistent with the practice followed nationwide and causes issues such as the limited availability of vendors to perform this task. As a result, in 2020 MDOT decided to suspend the collection of distresses at the current level of detail required. Therefore, DI can no longer be computed for the network. To be consistent with the national data reporting requirements of the FHWA, MDOT decided only to acquire data on percent cracking, rutting, faulting, and the international roughness index (IRI) until such time that the DI can be revised or replaced.

Consequently, there is an urgent need for a new pavement condition parameter consistent with the state of the practice in data acquisition. This research study produced a new pavement condition parameter, called Pavement Distress Score (PDS), that MDOT can readily implement with very little need to change existing systems. The new parameter was chosen such that it would be backward compatible, and the required observed distresses can be collected by the pavement data collection industry in an accurate and timely manner. Therefore, this study has assisted MDOT in identifying important distresses that must be collected. Each distress definition with severity levels is defined so that vendors can easily capture those using their automated technology.

Moreover, performance models were developed for the PDS so that fix lives of the road network can be estimated. Deterministic models—including logistic growth and asymmetric sigmoid functions—were calibrated for multiple pavement families to estimate fix lives and predict condition progression for both asphalt and concrete surfaces. MDOT's LCCA practice was reviewed and established a method for estimating service lives compatible with the PDS. MDOT's DI-based "sawtooth" approach was revised to a PDS-based framework by (i) quantifying treatment-specific improvements (ΔPDS) at each maintenance cycle from historical records, (ii) fitting Logistic and Asymmetric Sigmoid deterioration models to pavement families, and (iii) constructing composite, length-weighted curves to compute both fix life (to a selected PDS threshold) and service life (with scheduled preventive maintenance drops). This provides LCCA with model-based, treatment-specific lives for major surface types (flexible and rigid), ensuring backward compatibility with MDOT practice while aligning with data the industry can reliably collect. Also, fix life curves were also developed based on IRI, faulting and rutting, however these produced much longer lives than PDS.

The research also developed a comprehensive network-level modeling framework. This framework uses Markovian Transition Probability Matrices (TPMs) and multinomial logistic regression to simulate how pavement conditions evolve over time across MDOT's statewide network. These models integrate deterioration and improvement matrices derived from historical performance and maintenance data, allowing projections of IRI, cracking, rutting, and faulting under different maintenance strategies. The TPM-based approach enables MDOT to conduct scenario analyses, assess funding impacts, and forecast long-term network performance in compliance with federal performance management requirements.

2 OBJECTIVES

The specific objectives of this study are summarized in Table 2-1, The first eight objectives were completed as part of this project. Although service lives were developed separately for both PDS and IRI, a unified methodology for jointly using these two measures was not pursued, as the IRI-based service lives were consistently higher than the PDS-based estimates.

Table 2-1. The research objectives

No.	Description of the objective
1	Conduct an evaluation of methods used nationwide for measuring pavement condition, including MDOT's DI system. Provide benefits and drawbacks to each one, effort levels for MDOT to implement, an assessment of compatibility with MDOT systems, processes, and procedures, and an assessment of backward compatibility with MDOT's DI system.
2	Recommend implementation steps for the new pavement condition parameter chosen by MDOT to begin to be used.
3	Find alternative methodologies for estimating/modeling pavement performance and establishing fix lives and/or service lives.
4	Evaluate the different methodologies for accuracy of predicting the performance of Michigan's different fix types and the overall network, including a comparison to the logistic growth model used by MDOT. The evaluation will be based on the new pavement condition parameter chosen by MDOT.
5	Recommend a pavement performance modeling methodology. The method should have an acceptable level of accuracy for predicting the performance of MDOT's pavements and not be difficult to implement.
6	Recommend implementation steps for the new pavement performance modeling method chosen by MDOT to begin to be used.
7	Provide a software program or other application that can utilize the pavement performance modeling method chosen by MDOT on individual projects or groups of projects. It must be on a software platform that is compatible with State of Michigan IT policies.
8	Find and recommend methodologies to enable MDOT to model network-level IRI, cracking, faulting, and rutting. The methodologies should allow for MDOT to set target network pavement conditions goals to meet the federal pavement performance rule. If existing ones do not exist or are found to be lacking, new methodologies may need to be developed.
9	Recommend a methodology for using both the new pavement condition parameter and IRI on individual projects or groups of projects so that they can be utilized to establish service lives for use in MDOT's life-cycle cost analysis process.

3 TASK 1: LITERATURE REVIEW AND REVIEW OF PAVEMENT CONDITION INDICES

This chapter includes the literature review on current pavement data collection methodology, condition measures, and performance modeling of individual pavement condition indices used by different state agencies.

3.1 PAVEMENT DISTRESS COLLECTION METHODS

To any state agency, appropriate and consistent pavement distress identification is crucial in maintaining its PMS (Ragnoli et al. 2018). However, in reality, pavement behavior and performance are highly variable due to many influential factors, e.g., structural design, traffic, climate, material, construction practices, etc. (Pierce et al. 2013). Having these unavoidable issues, state agencies try their best to capture network-level distress measures for as small as segments of 0.1-mile intervals.

Before 1990, the pavement data collection method was based on manual windshield survey and walking along the shoulders of pavement surface(McQueen and Timm 2005). The raters conducted condition surveys using pen and paper. Different state highway agencies in the United States at that period faced issues related to data measurement, processing, and reporting inconsistencies. Therefore, in the early 1990s, FHWA and SHRP developed the famous Long-Term Pavement Performance (LTPP) distress Identification Manual (Miller and Bellinger 2014). The purpose of this reference guide was to help state officials identify all possible distress present on a pavement surface with proper standards and definitions. The LTPP distress identification manual covers flexible pavement, jointed plain concrete pavement (JPCP), and continuously reinforced concrete pavement (CRCP). However, as the LTPP distress manual was still based on manual data collection, it created other issues, for example, safety and data monitoring efficiency. After 2000, the practice of semi-automated and automated data collection came into focus. Over the last decade, extensive research has been conducted in this regard especially in improving operational survey, safety and the cost-benefit ratio. In that effort, the National Highway Research Program (NCHRP) and the American Association of State Highway and Transportation Officials (AASHTO) have created documents so that data consistency among state highway agencies (SHAs) can be attained. Apart from that, some SHAs have also developed their data collection manuals.

The semi-automated method needs some human intervention to classify and quantify pavement distress. A trained staff typically analyzes raw distress data within an office by reviewing images and video logs (Pierce and Weitzel 2019). One type of semi-automated method, probably the most human involvement, asks raters to classify distress, visually measure the extent of each distress from the computer screen, and then enter distress data directly into the PMS. The other type of semi-automated method is less involved, where the rater is required only to locate the distress and classify the distress type and severity (i.e., low, medium, and high) by visually observing from a computer screen. Then, the computer software will automatically calculate the extent of each distress in required units and save them in a database system.

With technological advancement, most state agencies are moving towards fully automated distress data collection (Chang et al. 2020). This process requires zero to minimal human involvement during pavement data collection, analysis, and compiling them into a pavement database. Computer software reads downward images to classify each distress with severity level and quantify the actual measurements of each distress.

3.2 PAVEMENT CONDITION INDICES USED IN THE USA

In this section, various pavement condition indices used nationwide are reviewed. Based on the literature review, it was found that each condition measure can represent pavement health conditions from different aspects. Two or more state agencies may share the same performance measure terminology but may include different distress types and calculation processes in estimating their pavement condition indices. Therefore, condition indices are not universal and may not be expected to match well. In general, most State agencies measure pavement conditions based on distresses such as cracking and rutting and then combine these measured values into a small subset of composite metrics. The first condition rating was developed at the AASHO Road Test in the 1960s. It was called the present serviceability index (PSI). Subsequently, a more objective and comprehensive metric known as the Pavement Condition Index (PCI) was developed by the U.S. Army Corps of Engineers. PCI was valued on a scale of 0 to 100, where 100 represents the perfect condition. The original form of PCI was further standardized in ASTM D6433 (ASTM 6433-16 2016). The state agencies' condition indices described in subsections below are based on the original PCI method.

3.2.1 Colorado DOT

The Colorado Department of Transportation (CDOT) has used Drivability Life (DL) as its performance measure index since 2013. Prior to that, CDOT used to use remaining service life (RSL) (4). The concept of DL is similar to the RSL. DL in years defines how long a pavement will have drivable conditions in terms of safety and smoothness (Colorado Department of Transportation 2019)

CDOT maintains an enriched PMS database for its road networks. CDOT converts collected distresses (rutting, transverse, fatigue, and longitudinal cracking) and roughness for asphalt pavements into five different indices. These indices are scaled from 0 to 100 range. A pavement with a 100 rating means it does not have any distress, and 0 means the pavement is in the worst condition. These distress indices can be calculated using the following equations,

$$Cracking\ Index = 100 \times \left(1 - \frac{Cracking_{LOW}}{Max_{LOW}} - \frac{Cracking_{MED}}{Max_{MED}} - \frac{Cracking_{HIGH}}{Max_{HIGH}}\right) \quad 3.1$$

$$Ride\ Index = 100 \times \left(1 - \frac{IRI_{avg} - A_{min}}{B_{max}}\right) \quad 3.2$$

$$Rut\ Index = 100 \times \left(1 - \frac{Rut_{avg} - B_{min}}{B_{max} - B_{min}}\right) \quad 3.3$$

Where, $Cracking_{LOW}$, $Cracking_{MED}$, $Cracking_{HIGH}$: are the cracking quantities at low, medium, and high severity levels, respectively. Max_{LOW}, Max_{MED}, Max_{HIGH}: Maximum possible cracking quantities at low, medium, and high severity levels, respectively. IRI_{avg}, Rut_{avg}: Average measured IRI and rut depth, respectively. In these equations, A_{min} represents the minimum IRI value, corresponding to the smoothest pavement condition. When the average IRI (IRI_{avg}) approaches A_{min}, the term ($IRI_{avg} - A_{min}$) becomes negligible, resulting in a Ride Index approaching the maximum value of 100. Similarly, B_{min} denotes the minimum or ideal average rut depth. When the measured rut depth (Rut_{avg}) is near B_{min}, the numerator ($Rut_{avg} - B_{min}$) approaches zero, producing a Rut Index also approaching 100. The parameter B_{max} defines the upper threshold or maximum acceptable value of the respective distress measure. More details on these calculations can be found in reference: (Saha and Ksaibati 2019).

3.2.2 Florida DOT

The Florida Department of Transportation (FDOT) translates its distress and smoothness data into a composite index called Pavement Condition Rating (PCR) (Florida Department of Transportation 2019). Flexible pavement distresses include cracking rating (different severity of cracking, raveling, and patching) and rut rating. Rigid pavement distresses include surface deterioration, spalling, patching, transverse cracking, longitudinal cracking, corner cracking, shattered slab, faulting, pumping, and joint condition. Depending upon the severity level of each distress type, deductions are considered against the PCR for both flexible and rigid pavements. PCR is reported on a scale of 0 to 10, where 10 is the best score.

3.2.3 Idaho Transportation Department

The Idaho Transportation Department (ITD) developed a pavement rating guide in 2011 that defined the distress severity and extent information (Idaho Transportation Department 2011). The severity and extent definitions used by the ITD were found to be similar to those used by other agencies in this review. ITD uses the Cracking Index (CI) and Roughness Index (RI) as their pavement condition indices. The rating scale ranges from 0 to 5, with 5 being the best score.

3.2.4 Illinois DOT

The Illinois Department of Transportation (IDOT) converts it's measured distresses into a condition measure index called Condition Rating Survey (CRS). CRS has been used by IDOT since 1974. In 1994, IDOT started using mathematical models to calculate CRS and to predict future pavement performance (Vavrik et al. 2013). CRS is reported on a scale of 1 to 9. A road with nine represents newly constructed or resurfaced pavement, whereas the CRS value of 1 represents a total failed roadway. CRS is a composite index that takes account of the type, amount, and severity of different captured distress, roughness of the pavement surface, level of wheel path rutting, and magnitude of transverse joint faulting (Premkumar and Vavrik 2016).

3.2.5 Indiana DOT

The Indiana Department of Transportation (INDOT) collects pavement distress data automatically on an annual basis. Apart from the FHWA requirements, INDOT collects a wide variety of distresses on its state roadway network to assess the condition of pavements. Trained raters review the field-collected video-logs and identify severity and extent manually. Table 3-1 and Table 3-2 list the pavement surface distresses and their associated severity and extent definitions INDOT collects for asphalt and concrete pavements, respectively (Indiana

Department of Transportation 2010). These two tables should be used as examples of how DOTs generally define their surveyed distresses.

INDOT uses Pavement Condition Rating (PCR) as the condition metric. PCR ranges from 0 to 100, where 100 is the best condition possible and 0 is the worst condition. PCR helps to rank the different road projects, identify the probable reason for the serviceability losses, and help with proper budget allocation.

INDOT defines distress weight for each distress type, then based on associated severity and extent, deduct points are calculated as Deduct points = Distress weight × Severity × Extent. Then PCR is calculated by subtracting the total deduct points from the perfect score of 100, as shown in Equation 3.4.

$$\text{PCR} = 100 - \sum deduct\ points \qquad 3.4$$

3.2.6 Louisiana Department of Transportation and Development (DOTD)

The two documents titled “Louisiana Cracking and Patching Protocol for Asphalt Surface Pavements” and “Louisiana Cracking and Patching Protocol for Concrete Pavements” outline the distress data collection practices and distress severity definitions for each parent fix type. Along with patching, rutting, potholes, and roughness (IRI), the guidelines define two cracking types for asphalt pavements: fatigue and random cracking. In addition to patching and faulting for concrete pavements, the protocols list longitudinal and transverse cracking types.
Louisiana Department of Transportation and Development (DOTD) uses the Pavement Condition Index (PCI) to assess its pavement condition. It is a composite index that considers several indices into a single “pavement condition” index for each parent fix type. For asphalt pavement, alligator cracking index, random cracking index (longitudinal and transverse cracking), patching index, rutting index, and roughness index are the inputs to calculate PCI (LDOTD 2018a) Whereas, for rigid pavement, longitudinal cracking index, transverse cracking index, patching index, and roughness index are the inputs (LDOTD 2018b). PCI ranges from 1 to 100, where 100 is the perfect score.

Table 3-1 Indiana DOT surveyed flexible pavement distresses with associated severity and extent.

Distress	Severity	Extent
1. Raveling	1) Light Aggregate Loss	1) <20% of Area
	2) Moderate Aggregate Loss	2) 20% - 50% of Area
	3) Severe Aggregate Loss	3) > 50% of Area
2. Patching	1) Minor Distress, Rides Well	1) 1 - 2 Patches/1 mile
	2) Fair Condition	2) 3 - 4 Patches/1 mile
	3) Deteriorated or Temp Patch	3) > 4 Patches/1 mile
3. Potholes	1) < 1" deep and < 1 syd	1) 1/1 mile
	2) < 1" deep and > 1 syd; OR > 1" deep and < 1 syd	2) 2 - 3/1 mile
	3) > 1" deep and > 1 syd	3) > 4/1 mile
4. Wheel Path Cracks (alligator cracks)	1) Single, fine, intermittent longitudinal cracks, with no pattern, in the wheel path	1) Less than 50 Lineal Feet
	2) Tight, <¼ in primary crack with small secondary multiple cracks, patterned	2) < 20% Area (Part of One Track)
	3) Multiple cracks forming a complete pattern	3) > 20% Area
5. Transverse Cracks	1) Single crack, fine, no secondary cracks	1) < 10 Cracks In 500'
	2) <¼ in the primary crack, along with small tight secondary cracks	2) 10-25 Cracks/500'
	3) >¼ in; spalls; depressed; many secondary cracks	3) > 25 in 500’
6. Block Cracks	1) Single crack, fine, no secondary cracks	1) > 6’× 6’ in 100’
	2) <¼ in primary crack along with small tight secondary cracks	2) 6’×6’ - 3’×3' in 100’
	3) >¼ in; spalls; depressed; many secondary cracks	3) < 3’x 3’ in 100 feet
7. Edge Cracks	1) Single crack, fine, no secondary cracks	1) < 20% of Length
	2) <¼ in primary crack along with small tight secondary cracks	2) 20% - 50% of Length
	3) >¼ in; spalls; depressed; many secondary cracks	3) > 50% of Length
8. Longitudinal Cracks	1) Single crack, fine, no secondary cracks	1) < 20% of Length
	2) <¼ in primary crack along with small tight secondary cracks	2) 20% - 50% of the Length
	3) >¼ in; spalls; depressed; many secondary cracks	3) > 50% of Length

Table 3-2 Indiana DOT surveyed rigid pavement distresses with associated severity and extent

Distress	Severity	Extent
1. D-cracks/ASR	Yes - D-Cracking/ASR is a visible problem in the concrete	
	No - D-Cracking/ASR is not apparent	
2. Patching	1) Minor Distress, Rides Good	1) 1 - 2 Patches /1 mile
	2) Fair Condition	2) 3 – 4 Patches/1 mile
	3) Deteriorated or Temp Patch	3) > 4 Patches/1 mile
3. Faulting	1) < 1/4” height	1) 1 - 3 Joints or Cracks
	2) 1/4” to 1/2” height	2) 4 - 7 of Joints or Cracks
	3) >1/2” height	3) > 7 of Joints or Cracks
4. Joint or Crack Spalls	1) Small Chips, < Palm Size (4”)	1) < 20% of joints and cracks length
	2) Moderate, < Dinner Plate Size (9”)	2) 20% -75% of joints and cracks length
	3) Deep or Large, >Dinner Plate (9”)	3) > 75% of joints and cracks length
5. Transverse Cracks	1) Tight, Fine, hairline	1) 1-3 cracks
	2) < 1/4”	2) 4 -7 cracks
	3) >1/4”, Spalled, missing pieces	3) > 7 cracks
6. Longitudinal Cracks	1) Tight, Fine, hairline	1) 1 Panel
	2)< 1/4”	2) 2 to 3 Panels
	3) >1/4”, Spalled, missing pieces	3) Greater than 3 Panels
7. Corner Breaks	1) Tight, Fine hairline	1) 1 - 4 corner breaks
	2) <1/4”	2) 5 - 10 corner breaks
	3) >1/4”, Spalled, missing pieces	3) > 10 corner breaks
8. Pumping	Yes -- Pumping Is Evident, (Moving Blocks, Ghost Fines, Mud, Etc.)	
	No -- Pumping Is Not Evident	
Severity Rating: 0 = None; 1 = Low; 2 = Moderate; 3 = High; Extent Rating: 0 = None; 1 = Few; 2 = Several; 3 = Many.		

3.2.7 Minnesota DOT

The Minnesota DOT measures pavement condition in terms of the Ride Quality Index (RQI), Surface Rating (SR), and Pavement Quality Index (PQI) (Minnesota Department of Transportation 2011). The three indices are used to rank pavement sections and to predict future conditions and needs. The rating scale for RQI is 0 to 5.0, for SR is 0 to 4.0, and for PQI is 0 to 4.5. The higher the rating, the better the pavement is. In MnDOT data collection practice, extents are not directly calculated; the count or lineal feet of distresses present is recorded and then translated to a percentage of pavement area with the distress. Also, with the following exceptions, only the most severe distress in any lineal foot is counted: medium and high severity transverse cracks, raveling/weathering, patching, longitudinal joint cracking, and rutting shall be counted in combination with other deficiencies; Low severity transverse cracks shall not be counted in the same foot as multiple or alligator cracking.

3.2.8 New York State DOT

New York State DOT (NYSDOT) collects a wide variety of pavement surface distress data based on the extent, severity, and location of pavement cracking since 1981. Until 2015, these data were collected through the visual windshield survey/E-Score method, but after that NYSDOT has transitioned to automatic data collection (New York State Department of Transportation 2010). The 'Fugro Roadware' device captures 3-D surface images through the laser crack measurement system (LCMS). The reason behind this transition is that the E-Score Application was at the end of its useful life as the software would require updating or replacement through a contract; all the hardware needed replacement. Another motivation is that NYSDOT has already been collecting automatic crack data on a large portion of the NY highway network as part of federal requirements. The crack data is objective and can be more easily quantified and analyzed than the previous subjective visual windshield survey.

As part of surface distress data collection, NYSDOT also identifies the presence of dominant distresses. In general, a significant treatment is required for the pavement poses dominant distresses. Thereby, among different surface distresses NYSDOT classifies, alligator cracking for asphalt pavement, faulting and spalling for concrete pavement, and widening drop-off for asphalt overlaid pavement are identified as dominant distresses.

NYSDOT rates its pavement condition with a 1-10 rating system, called Surface Rating, based on the type of distresses. A pavement with no visual surface distress is rated as 10, whereas an impassible condition is rated as 1. In general, a Surface Rating of less than 5 is rare to be seen as rehabilitation or reconstruction is warranted for such pavements.

3.2.9 North Dakota DOT

The North Dakota Department of Transportation (NDDOT) uses a composite index known as Distress Score (DS) in assessing the pavement condition (North Dakota Department of Transportation 2009). Like PCR, NDDOT’s Distress score is also based on deduct point system. DS ranges from 0 to 99. A pavement with no visible distress is assigned a score of 99, from which points are deducted based on the severity and extent of observed distresses. As part of DS calculation or, in other words, assessing the current pavement health condition, NDDOT collects various surface distresses with the associated extent and severity for both flexible and rigid pavements. NDDOT’s pavement surface distress collection method is automatic, where the associated extent and severity for each distress type are also quantified by automated distress survey vehicles.

3.2.10 Ohio DOT

The Ohio Department of Transportation (ODOT) has been using Pavement Condition Rating (PCR) to characterize surface distress since 1985 (Vavrik et al. 2013). PCR is calculated using manually collected distress data by dedicated raters. As part of PCR calculation, ODOT collects several distresses for both asphalt and JPCP rigid pavement. The severity and extent definitions for this distress can be found in the PCR manual (Ohio Department of Transportation 2006). PCR helps ODOT to maintain its resources and identify proper maintenance activities accordingly. PCR ranges from 0 to 100, where 100 represents a perfect condition with no visual distress. Each distress type for both flexible and rigid pavement carries deduct points based on the severity and extent. For a given pavement section, summation of all these deduct values is subtracted from the perfect pavement condition, i.e., 100 to obtain PCR. PCR is calculated using Equation 3.5:

$$PCR = 100 - \sum_{I=1}^{n} Deduct_i \qquad 3.5$$

Where, n = number of observable distresses, and Deduct = (Weight for distress) (Wt. for severity) (Wt. for Extent)

It is worth noting that ODOT has explored, to some extent, the use of a 3-D downward imaging system to calculate PCR. Their findings suggest that while rutting can likely be measured with high repeatability, developing reliable algorithms to detect the various other distresses included in ODOT's PCR would require significant time and effort. The ODOT personnel are concerned that the current technology could never fully automate them all. Therefore, currently, ODOT is sticking to its sophisticated manual PCR process.

3.2.11 South Dakota DOT

The South Dakota Department of Transportation (SDDOT) uses the Surface Condition Index (SCI) to evaluate current overall pavement conditions (South Dakota Department of Transportation 2019). SCI is a composite index that is computed from the overall distress rating for each road segment. SCI is calculated using the following Equation 3.6:

$$SCI = \mu - 1.25\sigma \qquad 3.6$$

where, μ = mean of all contributing individual distress indexes (I), and σ = standard deviation for contributing individual distress index. Individual distress index (I) for distress I is computed as: $I_i = 5 - D_i$, where, D_i is the deduct value for distress i, which depends on its extent and severity. SCI is reported on a scale of 0 to 5.

3.2.12 Texas DOT

Texas DOT (TxDOT) uses a composite measure called Condition Score (CS). The CS is an aggregate of the measured pavement distresses, pavement roughness, daily traffic, and speed limit; pavement in the best condition receives a CS of 100 (Texas Department of Transportation 2014). Once the distresses are measured on a given pavement segment, they are translated into a utility value (between 0 and 1) using Equation 3.7.

$$U_i = 1 - \alpha e^{(\frac{\rho}{L_i})^{\beta}} \qquad 3.7$$

where *Ui* is the utility value for distress type *i*, *e* is the base of the natural logarithm, and the factors α, ρ, and β are variables that control the shape of the utility curve. L_i represents the density of the distress in the pavement section (i.e., quantity of distress per mile, quantity of distress per section area, quantity of distress per 100 ft, etc.). The CS and DS are calculated using the following formula:

$$CS = U_{Ride} \times DS \qquad 3.8$$

$$DS = 100 \times \Pi_{i=1}^{n} U_i \qquad 3.9$$

U_i (Equation 3.7) ranges between 0 and 1.0 and represents the quality of a pavement in terms of overall usefulness (e.g., a U_i of 1.0 indicates that distress type i is not present and thus is most useful).

3.2.13 Virginia DOT

Rada et al. (Rada et al. 2018) provided a detailed explanation of the Critical Condition Index (CCI), which the Virginia DOT uses as the condition indicator for asphalt pavements. The CCI is presented on a 100-point scale, with 100 being the best possible score and 0 being the worst possible score. To calculate the CCI, two different indices are calculated from the data collected during the distress survey, the load-related distress rating (LDR) and the non-load-related distress rating (NDR), and the lower value of the two is defined as the CCI. The LDR is calculated by estimating deduct values for each load-related distress that is deducted from 100. The distresses used in the LDR are alligator cracking, patching, potholes, delamination, and rutting. The NDR considers deduct values for non-load-related distresses: block cracking, patching, longitudinal cracking out of wheel path, transverse cracking, reflection cracking, and bleeding (K.H. 2002).

3.2.14 Wisconsin DOT

The Wisconsin Department of Transportation (WisDOT) uses the Pavement Condition Index (PCI) as its pavement condition measure (Wisconsin Department of Transportation 2020). PCI is a composite index that includes cracking, rutting, and potholes in its estimation. PCI is rated in the range of 0 to 100. A pavement with a PCI rating of 100 represents excellent condition, whereas 55 is the minimum PCI value to consider pavement in fair condition.

Table 3-3 and Table 3-4 summarize the various condition indices along with their associated rating scales and distress inputs. Notably, MDOT stands out for using an inverse rating scale—unlike other agencies, a pavement in perfect condition is assigned a score of zero (0), and the Distress Index (DI) increases as the pavement condition worsens.

Table 3-3 Summary of condition indices used nationwide for asphalt pavements.

Standard/State Agency	Condition Index	Rating Scale (Perfect→ Worst)	Distress Input
ASTM D6433-16	Pavement Condition Index (PCI)	100-0	All forms of distresses (approx. 19 types) are outlined in the ASTM standard.
Colorado	Cracking Index, Ride Index, Rut Index	100-0	Structural and Environmental Cracking, IRI, Rutting
Florida	Pavement Condition Rating (PCR)	10-0	Different severity of Cracking, Raveling, Patching, and Rut Depth
Idaho	Cracking Index (CI) and Roughness Index (RI)	5-0	Alligator Cracking, Longitudinal Cracking, Transverse Cracking, Block Cracking, Edge Cracking, Patching, IRI

Standard/State Agency	Condition Index	Rating Scale (Perfect→ Worst)	Distress Input
Illinois	Condition Rating Survey (CRS)	9-1	Surface cracking, IRI, rutting
Indiana	Pavement Condition Rating (PCR)	100-0	Alligator Cracks, Transverse Cracks, Longitudinal Cracks, Block Cracks, Edge Cracks, Longitudinal Joints, Pumping, Raveling, Patching, Potholes
Louisiana	Pavement Condition Index (PCI)	100-1	Alligator Cracking, Random Cracking (Longitudinal Cracking and Transverse Cracking), Patching, IRI, Rutting
Michigan	Distress Index (DI)	0-∞	Alligator Cracks, Transverse Cracks, Longitudinal Cracks, Block Cracks, Edge Cracks, Pumping, Raveling, Patching
Minnesota	Ride Quality Index (RQI); Surface Rating (SR); Pavement Quality Index (PQI)	RQI: 5-0; SR: 4-0; PQI: 4.5-0	RQI: IRI; SR: Surface Distresses; PQI = sqrt (RQI x SR)
New York	Surface Rating (SR)	10-1	All forms of cracking over the five zones of the pavement surface
North Dakota	Distress Score (DS)	99-0	Alligator Cracking, Longitudinal Cracking, Transverse Cracking, Block Cracking, Bleeding, Raveling and/or Weathering, Bituminous Patching, Rutting
Ohio	Pavement Condition Rating (PCR)	100-0	Wheel Track Cracking, Block and Transverse Cracking, Longitudinal Cracking, Edge Cracking, Thermal Cracking, Raveling, Bleeding, Patching, Debonding, Crack Sealing Deficiency, Rutting, Settlement, Potholes
Texas	Distress Score (DS), Ride Score (RS) and Condition Score (CS)	DS:100-0; RS: 5-0; CS: 100-0	Rutting, Longitudinal Cracking, Transverse Cracking, Alligator Cracking, Patching
South Dakota	Surface Condition Index (SCI)	5-0	Individual distress rating (cracking, roughness)
Virginia	Critical Condition Index (CCI)	100-0	Load related distresses (Alligator Cracking, Rutting, Patching, Potholes, Delamination) and Non-load related distress (Longitudinal and Transverse Cracking, Reflective Cracking, Patching outside wheel path, Bleeding, Block Cracking)
Wisconsin	Pavement Condition Index (PCI)	100-0	Flushing, Cracking, Rutting, Transverse and Longitudinal Distortion, Surface Raveling, Patching

Table 3-4 Summary of condition indices used nationwide for rigid pavements.

Standard/State Agency	Condition Index	Rating Scale (Perfect→ Worst)	Distress Input
ASTM D6433-16	Pavement Condition Index (PCI)	100-0	All forms of distresses (approx. 19 types) outlined in the ASTM standard.
Florida	Pavement Condition Rating (PCR)	10-0	Spalling, Patching, Transverse cracking, Longitudinal cracking, Corner cracking, Shattered slab, Faulting, Pumping, And Joint condition
Idaho	Cracking Index (CI) and Roughness Index (RI)	5-0	Transverse Cracks, Spalling, Meander, Scaling, Faulting, Corner Break
Indiana	Pavement Condition Rating (PCR)	100-0	D-cracking, Patching, Faulting, Joint or Crack Spalling, Transverse Cracks, Longitudinal Cracks, Corner Breaks, Pumping
Louisiana	Pavement Condition Index (PCI)	100-1	Longitudinal Cracking, Transverse Cracking, Roughness, Patching
Michigan	Distress Index (DI)	0-∞	Transverse Cracks, Longitudinal Cracks, Transverse Joint, Longitudinal Joint, Delaminated Area, Map Cracking, High Steel, Shattered Area, Putouts, Scaling, Patching
Minnesota	Ride Quality Index (RQI); Surface Rating (SR); Pavement Quality Index (PQI)	RQI: 5-0; SR: 4-0; PQI: 4.5-0	RQI: IRI; SR: Surface Distresses; PQI = sqrt (RQI x SR)
Standard/State Agency	Condition Index	Rating Scale (Perfect→ Worst)	Distress Input
New York	Surface Rating (SR)	10-1	All forms of cracking over the five zones of the pavement surface, Faulting
North Dakota	Distress Score (DS)	99-0	Longitudinal Cracking, Transverse Cracking, Longitudinal Joint Spalling, Transverse Joint Spalling, D-Cracking, Corner Breaks, Broken Slabs, Concrete Patch Deterioration, Bituminous Patching, Faulting
Ohio	Pavement Condition Rating (PCR)	100-0	Surface Deterioration, Longitudinal Joint Spalling, Patching, Pumping, Faulting (joints and cracks), Settlements, Transvers Joint Spalling, Transvers Cracking, Pressure

Standard/State Agency	Condition Index	Rating Scale (Perfect→ Worst)	Distress Input
			Damage, Longitudinal Cracking, and Corner Breaks
Texas	Distress Score (DS), Ride Score (RS) and Condition Score (CS)	DS:100-0; RS: 5-0; CS: 100-0	Shattered slab, Concrete patches, Longitudinal cracks
Virginia	Critical Condition Index (CCI)	100-0	Slab Distress Rating (Corner Breaks, Longitudinal Cracking, Transverse Cracking, Longitudinal Joint Spalling, Transverse Joint Spalling, Divided Slabs, Patching)
Wisconsin	Pavement Condition Index (PCI)	100-0	Cracking, Transverse Faulting, Longitudinal Joint Distress, Distressed Joints/Cracks, Patching

3.3 PERFORMANCE MODELS FOR PAVEMENT CONDITION INDICES

In this section, pavement performance models for different condition indices are presented. Pavement performance models are utilized to anticipate how pavements will behave and deteriorate over time by considering multiple factors such as traffic volume, climate, and pavement design. These models aid engineers and transportation agencies in making informed decisions about pavement maintenance, rehabilitation, and reconstruction. By using the models, engineers can estimate the expected decline of a pavement, detect potential issues, and devise cost-effective approaches for maintaining the pavement network.

3.3.1 New Jersey DOT's SDI performance model

Maher et al. developed a sigmoidal Surface Distress Index (SDI) model for the New Jersey Department of Transportation (NJDOT), as shown in Equation 3.10 (Maher Ali, Szary, Patricik Vitillo, Nicholas Bennert 2011):

$$SDI = SDI_0 - e^{\left(A - B \times C^{\ln\left(\frac{1}{Age}\right)}\right)} \qquad 3.10$$

where, SDI_0 = Index value at age zero (Recommended SDI = 5.0 at age zero), Age = Pavement age in years since last rehabilitation or construction activity, and A, B, C = Model coefficients.

Based on treatment activities on bituminous/concrete/composite pavements, NJDOT uses various model coefficients which can be found in the report by Maher et. al. (Maher Ali, Szary, Patricik Vitillo, Nicholas Bennert 2011).

3.3.2 North Carolina DOT's PCR performance model

In 1992, Chan et al. developed a PCR regression model for the NCDOT to predict the deterioration curve over the pavement age (Chan et al. 1997). The model is shown in Equation 3.11.

$$PCR = C_0 + C_1 \times Age^{C_2} \qquad 3.11$$

where, C_0, C_1, and C_2 are regression coefficients. C_0 determines the highest point on the flat portion of the curve. C_1 (ranges from 1.25 to 3.00) and C_2 (3.00) influence the rating deterioration.

3.3.3 Delaware DOT's OPC performance model

Mills et al. developed a multiple regression model for DelDOT to predict the Overall Pavement Condition (OPC) rating (Mills et al. 2012). The model is shown in Equation 3.12:

$$OPCx = a_o + a_1 AADT + a_2 AGE + a_3 EnvCr + a_4 FatCr + a_5 PAT + a_6 Sn + a_7 SurDe + a_8 EdCr + a_9 TraCr \qquad 3.12$$

where, AADT = Annual average daily traffic, AGE = Age since construction/major rehabilitation, EnvCr = Environmental cracking, FatCr = Fatigue cracking, PAT = Patching, Sn = Structural number for pavement, SurDe = Surface defects, EdCr = Edge cracking, TraCr = transverse cracks, and a_0, a_1, a_2, a_3, a_4, a_5, a_6, a_7, a_8, a_9 = regression coefficients.

3.3.4 MDOT's DI performance model

Kuo was the first to propose using both the logistic growth curve model and the Gompertz growth curve model to predict pavement performance for the Michigan Department of Transportation (MDOT) (Kuo 1995). The models are expressed by Equation 3.13 and Equation 3.14.

$$DI_{Logistic} = \alpha(\left[\frac{(\alpha + \beta)}{\alpha + \beta e^{-\gamma t}}\right] - 1) \qquad 3.13$$

$$DI_{Gompertz} = ((\alpha + \beta)\left(\frac{\alpha}{\alpha + \beta}\right)^{exp(-\gamma t)})) - \alpha) \qquad 3.14$$

where, DI = Distress index, α = Potential initial DI, β = Limiting DI, t = Age in years, γ = Deterioration pattern index = $\left(\frac{1}{DSL}\right) \ln\left\{\left(\frac{(\alpha + \beta)}{(\alpha + cDP)} - 1\right)\frac{\alpha}{\boldsymbol{\beta}}\right\}$, DSL = Design service life in years, and, cDP = Critical Distress Point.

3.3.5 Mississippi DOT's PCR performance model

In 2000, George developed a PCR performance model for the newly constructed pavement with support from the Mississippi Department of Transportation (MDOT) (George 2000). The model is shown in Equation 3.15.

$$PCR = (76.10 - Age^{0.6696}(1 + CESAL^{0.7100}))MSN^{0.0979} \qquad 3.15$$

where, Age = Pavement Age, CESAL = Cumulative 18-kip ESAL, MSN = Modified structural number. MSN can be calculated as follows:

$$MSN = SN + SN_{sg} \qquad 3.16$$

where, SN = Structural number and SN_{sg} = Pseudo structural number for the subgrade, which represents the contribution of subgrade to pavement load carrying capacity:

$$SN_{sg} = 3.51 \times log_{10}CBR - 85(log_{10}CBR)^2 - 1.43 \quad 3.17$$

where, a_i = i^{th} layer coefficient, m_i = i^{th} drainage coefficient, and D_i = Depth of the i^{th} layer, and CBR = California Bearing Ratio (%)

3.3.6 Washington DOT's PSC performance model

Washington Department of Transportation (WSDOT) used a generalized performance model to predict Pavement Structure Condition (PSC) (Uhlmeyer et al. 2016). The model is shown in Equation 3.18.

$$PSC = c - m \times A^p \quad 3.18$$

where, c = Model constant for maximum ratio (100), m = Slope coefficient, A = Age in years since last resurfacing or construction, and p = Selected constant which controls the degree of curvature of the performance curve.

3.3.7 Virginia DOT's CCI performance model

Amarh et al. developed pavement performance models for recycled pavements in Virginia (Amarh et al. 2020). The researchers tried different prediction models (such as linear regression, quadratic, logistic, etc.). Among those models, a negative binomial model was adopted with the highest second-order Akaike information criterion (AICc) weight. The closer the AICc weight of a model is to 1 or 100%, the better chance to claim a model as a true model. The model is shown in Equation 3.19.

$$CCI = a - Age^b \times Exp\ (c) \quad 3.19$$

where, Age = Age in years since last rehabilitation or construction, and a b, c = Model coefficients.

3.3.8 Iowa DOT's PCI performance model

The Iowa Department of Transportation uses a statistical regression equation to calculate its pavement performance measure, PCI. The exact model used by the Iowa DOT to predict PCI could not be found in the literature. Instead, a study by Bektas et al. (Bektas et al. 2015) was found relevant to the section heading. This study proposed alternative prediction equations to calculate PCI for three major types of pavements (full-depth asphalt concrete, Portland cement concrete, and AC over old concrete) used in Iowa. In their study, they showed that the new proposed prediction equation reflects the field condition better than the existing PCI prediction equation.

The overall PCI equation includes individual distress indices, i.e., cracking, rutting, and ride indices for asphalt pavements and cracking, faulting, and ride indices for PCC pavements. All of these individual indices were incorporated by different weighting factors. Equations 3.20 through 3.22 show different PCI models for full-depth asphalt concrete, Portland cement concrete, and AC over old concrete, respectively.

$$PCI_{AC\ full\ depth} = 92.34 - 36\ \times (pavement\ age) - 11.11\ \times IRI - 2.041\ \times (alligator\ cracking) + 55\ \times (patching) \quad 3.20$$

$$PCI_{PCC} = 92.56 - 108\ \times IRI - 52 \times (pavement\ age) - 118.40\ \times (durability\ cracking) + 3.24\ \times (structural\ rating\ at\ joints) \quad 3.21$$

$$PCI_{AC\ composite} = 95.00 - 7.18\ \times (IRI) - 92\ \times (pavement\ age) - 96\ \times (transverse\ cracking) - 22\ \times (wheelpath\ cracking) - 07 \times (percentage\ of\ life\ used\ based\ on\ ESALs) \quad 3.22$$

4 TASK 2: EVALUATION OF THE PAVEMENT CONDITION INDICES USED NATIONWIDE

Under this task, a few pavement condition indices were evaluated from the list mentioned in the previous section. Based on the literature search, Virginia DOT's Critical Condition Index (CCI), Minnesota DOT's Surface Rating (SR), North Dakota's Distress Score (DS), Louisiana DOTD's Pavement Condition Index (PCI), and Oregon DOT's Overall Condition Index (OCI) were evaluated for both flexible and rigid pavement sections. These condition indices were selected based on the available calculation steps, comparable type of distresses included in the condition index, and to cover different climatic regions nationwide to reflect how MDOT collected PMS data can be compatible with those condition indices. Figure 4-1 shows these selected five condition indices highlighted as blue-shaded colors on the US geographical map.

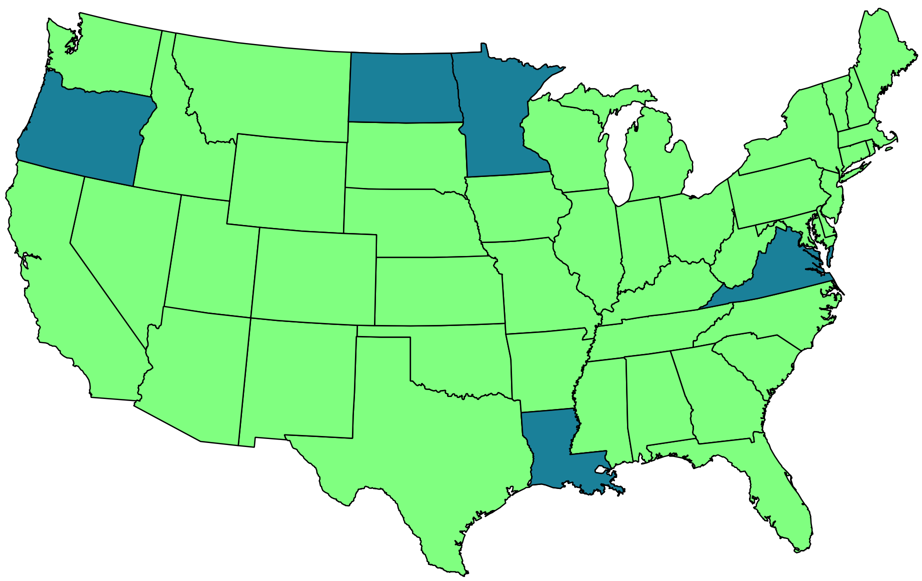


Figure 4-1. The geographical location of the selected pavement condition indices in the USA map

Also, Table 4-1 presents all five condition indices and MDOT's DI with corresponding rating scales. It can be observed that distress indices from each of these states have different scales, unlike MDOT's DI, which goes from zero to no upper bound. For comparison purposes only, to match with MDOT's DI scale, all distress indices were linearly scaled on a scale of 0 to 100, where 0 represents the perfect score. Moreover, for DI scores, only up to a value of 100 have been considered. This decision was made by observing MDOT's historical DI data as a very small portion of MDOT's data exceeded a DI value of 100. In this evaluation process, a total of 2081 flexible and 741 rigid pavement sections were selected, which were available in MDOT's pavement performance list. In this section, including MDOT's DI and all the attempted condition indices are described in terms of distress inputs and calculation processes for both flexible and rigid pavement.

Table 4-1 List of evaluated condition indices

Number	State Agency	Condition Index	Rating Scale (Perfect → Worst)
1	Louisiana	Pavement Condition Index (PCI)	100 - 1
2	Minnesota	Surface Rating (SR)	4 – 0
3	North Dakota	Distress Score (DS)	99-0
4	Oregon	Overall Condition Index (OCI)	100 – 1
5	Virginia	Critical Condition Index (CCI)	100 - 0
6	Michigan	Distress Index (DI)	0 - ∞

4.1 PAVEMENT CONDITION INDICES FOR FLEXIBLE PAVEMENTS

In the subsections below, calculation procedures for the MDOT's DI, Virginia DOT's CCI, Minnesota DOT's SR, North Dakota's DS, Louisiana DOTD's PCI and Oregon DOT's OCI for flexible pavement are described. It is important to note that MDOT's DI does not consider rutting and IRI, and thus these sensor data inputs were ignored even if the original calculation of a condition index requires them. Also, several assumptions were made based on MDOT's AD matrices to define principal distress with different severity levels as required for individual condition index calculations.

4.1.1 MDOT's Distress Index (DI)

MDOT's DI is calculated as the total accumulated distress points for a given road pavement section. In DI calculation, distress points do not act as deduction values, and therefore the DI does not have an upper bound. However, a threshold value of 50 represents a pavement in poor condition, and major rehabilitation or reconstruction is warranted for that section (Abu-Lebdeh et al. 2003). Similarly, DI ranges from 0 to 25 denotes good condition, and 26 to 49 denotes a fair condition pavement. As mentioned previously, the MDOT PMS database stores individual distresses that are represented by PD codes, and associated distress matrices are used to define the severity of each distress. Based on the associated distress combination, distress points were assigned for each cell of an associate distress table. Equations 4.1 through 4.3 are used to calculate MDOT's Distress Index.

$$DI = DI_1 + DI_2 \qquad 4.1$$

where, DI = Distress Index of entire pavement segment, DI_1 = Distress Index from transverse PDs, DI_2 = Distress Index from longitudinal PDs

$$DI_1 = [\sum_i N_i \times D_i] \times (\frac{B}{L}) \qquad 4.2$$

where, N_i = Number of transverse PD occurrences, D_i = Point per PD occurrence per basic segment length, B = Basic pavement segment length (0.1 miles), L = Total length of subject pavement section, mile

$$DI_2 = [\sum_i X_i \times P_i] \times (\frac{100\%}{L}) \qquad 4.3$$

where, X_i = Length of the subject of PD, mile, P_i = Point per % of L for subject PD, L = Total length of the subject pavement section.

4.1.2 VDOT's Critical Condition Index (CCI)

Virginia DOT's CCI is a composite index comprised of Load Related Distress (LDR) and Non-load Related Distress (NDR) (K.H. 2002). Table 4-2 shows the distress components for each of these three indices. It is important to note that in the MDOT PMS database, potholes, delamination, and reflection cracking data are not available for flexible pavements. It is also important to note that in the VDOT reference guide, longitudinal cracking under the wheel path is not mentioned separately, whereas this distress exists with a unique PD code in the MDOT PMS database. Thereby, in CCI calculation, longitudinal cracking was considered part of alligator cracking.

Table 4-2 Virginia DOT's condition indices with distress components.

Index	Components
LDR	Alligator cracking, patching, potholes, delamination, rutting
NDR	Block cracking, patching and longitudinal cracking out of wheel path, transverse cracking, reflection cracking, bleeding
CCI	The lowest of the LDR or NDR

Several distresses in the VDOT reference guide are classified into three severity levels (i.e., low, medium, and high). Whereas the MDOT PMS database does not explicitly mention similar severity levels, rather based on distress type, severities are expressed by either transverse length and/or maximum width of the associated distresses. For different transverse lengths and/or maximum width ranges, associated distresses of principal distress are grouped into a matrix. Therefore, to make the MDOT surveyed distresses compatible with the VDOT condition index calculation, a few assumptions related to severity levels were made from the associated distress matrix reported in the MDOT Distress Survey Manual (Michigan Department of Transportation, 2017a). Table 4-3 and Table 4-4 show the assumed severities from the MDOT PMS database for LDR and NDR distress components, respectively.

Several MATLAB codes were written to extract PMS data according to the VDOT required units and calculate LDR, NDR, and CCI for all asphalt pavement sections. Few other assumptions were made in the required unit conversion; for example, block cracking is not reported in the MDOT PMS database with associate distresses; rather, it is reported only in length. To satisfy the calculation unit of square feet, the transverse width of block cracking was assumed as 12 feet as per discussion with MDOT. Also, non-load-related transverse cracking is reported as the number of counts, not in length; therefore, this distress type was converted to length by multiplying the number of counts with the lane width (12ft), except for transverse tear, for which counts were multiplied by 3ft (Haider et al. 2014). Alligator cracking, longitudinal cracking in the wheel path, and patching were converted into square feet units by multiplying their length with the average maximum width, as shown in Table 4-3.

Table 4-3 PD and AD combinations used to compute LDR distress components.

Distresses [PD Codes]	Severity	Severity Definition from MDOT PMS
Patching [326,327]	Good	Condition: Good (<3' Distress)
	Fair	Condition: Fair (3-6' Distress)
	Poor	Condition: Poor (>6' Distress)
Alligator Cracking [110,220,221,234,235,730, 731]	Low	Maximum width :>0 - 2 ft.
	Medium	Maximum width :>2 - 4 ft.
	High	Maximum width :>4 - 6 ft.
Longitudinal Cracking in WP [204,205,724,725]	Low	Sealant Conditions (ADs 1-4) and Maximum width :>0 - 1 ft.
	Medium	Maximum width :>1 - 2 ft.
	High	Maximum width :>2 - 4 ft.
Note: PD = Principal Distress; AD = Associated Distress		

Table 4-4 PD and AD combinations used to compute NDR distress components.

Distresses [PD Codes]	Severity	Severity Definition from MDOT PMS
Transverse Cracking [101,103,104,110,114,701,703,704]	Low	AD Matrix: (1,1), (2,1), (3,1), (4,1), (5,2), (5,3), (5,4), (6,2), (6,3)
Transverse Cracking [101,103,104,110,703,704]	Medium	AD Matrix: (5,5), (6,4), (6,5), (7,2), (7,3), (7,4)
Transverse Cracking [101,103,110,703,704]	High	AD Matrix: (7,5), (8,2), (8,3), (8,4), (8,5)
Longitudinal Cracking in Non-WP [201,202,203,236,237,721,722]	Low	Maximum width :>0 - 1 ft.
	Medium	Maximum width :>1 - 2 ft.
	High	Maximum width :>2 - 4 ft.
Block Cracking [310,345,760]	-	N/A
Bleeding [406]	-	N/A
Note: PD = Principal Distress; AD = Associated Distress		

Total deduction points for all tabulated distress components were calculated through corresponding deduction equations outlined in the “Development and Implementation of Pavement Condition Indices for the Transportation Phase I” report (K.H. 2002). Equation 4.4 shows an example equation for calculating the low severity of alligator cracking. After calculating all deduction points, LDR and NDR were calculated by subtracting individual total deduct points from the perfect score of 100. At last, for a given year and pavement section, CCI was calculated as the minimum value of both LDR and NDR and similarly calculated for all other years and pavement sections. It is to be noted that CCI ranges from 0 to 100 (i.e., from worst to perfect condition). To align with the same scale of Distress Index (DI) (assumed DI’s higher range to be 100), CCI was inverted using Equation 4.5

$$A\_CR1\_DED = 000108{*}A\_CR1\_P^3 - 025576{*}\ A\_CR1\_P^2 + 2.056227{*}A\_CR1\_P \qquad 4.4$$

where, A_CR1_DED = low severity alligator cracking ; and A_CR1_P = low severity alligator cracking percentage.

$$CCI_{adjusted} = 100 - CCI \qquad 4.5$$

4.1.3 MnDOT's Surface Rating (SR)

Minnesota DOT's SR captures visible surface distress conditions. Table 4-5 lists the surface distresses considered in the SR calculation with associated deduct points at different severity levels (Minnesota Department of Transportation 2011). Assumptions related to the severity levels of surface distress are presented in Table 4-5. Several MATLAB codes were used to extract PMS data in the required unit, i.e., percentages. For flexible pavement, transverse cracking at three severities was converted to percentage using Equation 4.6.

$$\text{Percent Cracks (\%)} = \text{Number of crack occurrences} \times 1000/\text{section length in feet} \quad (4.6)$$

All other distresses were converted to a percentage by simply dividing the length of the distress by the section length being surveyed. Once all the distresses were in percentages, individual weighted distresses were calculated by multiplying the percent of each distress with the appropriate weighting factors shown in Table 4-5. Then, the sum of all individual weighting distress was calculated to get the total weighted distress (TWD). In the last step, using Equation 4.7, Surface Rating for a given year and road section was calculated.

$$SR = e^{(1.386-(0.045)(TWD))} \quad (4.7)$$

It is noted that the SR scale ranges from 0 to 4 (i.e., from worst to perfect condition). To make the SR scale similar to the MDOT's DI scale, the following conversion was made using Equation 4.8.

$$SR_{adjusted} = 100 - SR*25 \quad (4.8)$$

4.1.4 NDDOT's Distress Score (DS)

North Dakota's DS ranges from 0 to 99, where 99 refers to the best score possible, and 0 means the worst condition of a pavement section. Table 4-6 shows the distresses considered in the DS calculation. Based on the extent and severity of each distress, specific deduction points are assigned, as shown in Table 4-6.

However, except for patching, MDOT's survey manual classifies distress severities differently than those severity definitions shown in Table 4-6. As no further information is available, the same assumptions mentioned above for CCI severity levels (see Table 4-3 and Table 4-4) were considered for the sake of calculating the DS. It is to be noted that in the MDOT PMS database, no associated distress is involved with block cracking, bleeding, and raveling. Therefore, not all three severities could be assumed; rather, only the medium severity of these distresses was considered while choosing the deduction points from Table 4-6. Once total deduct points for all distresses were calculated, it was subtracted from the perfect score of 99 to get a DS. Then for comparing DS with DI, a simple conversion was followed using Equation 4.9.

$$DS_{adjusted} = 100 – DS*100/99 \quad (4.9)$$

Table 4-5 PD and AD combinations used to compute SR distress components.

Distresses [PD Codes]	Severity	Severity Definition from PMS	Weighting Factor
Transverse Cracking [101,103,104,110,114,701,703,704]	Low	AD Matrix: (1,1), (2,1), (3,1), (4,1), (5,2), (5,3), (5,4), (6,2), (6,3)	0.01
Transverse Cracking [101,103,104,110,703,704]	Medium	AD Matrix: (5,5), (6,4), (6,5), (7,2), (7,3), (7,4)	0.1
Transverse Cracking [101,103,110,703,704]	High	AD Matrix: (7,5), (8,2), (8,3), (8,4), (8,5)	0.2
Longitudinal Cracking [201,202,204,205,721,722,724,725]	Low	Sealant Conditions (ADs 1-4) and Maximum width :>0 - 1 ft.	0.02
	Medium	Maximum width :>1 - 2 ft.	0.03
	High	Maximum width :>2 - 4 ft.	0.04
Longitudinal Joint Deterioration [203,236,237,723]	Low	Maximum width :>0 - 1 ft.	0.02
	Medium	Maximum width :>1 - 2 ft.	0.03
	High	Maximum width :>2 - 4 ft.	0.04
Block Cracking [310,345,760]	-	N/A	0.15
Alligator Cracking [110,220,221,234,235,730, 731]	-	Maximum width :>0 - 2 ft.; Maximum width :>2 - 4 ft.; Maximum width :>4 - 6 ft.	0.35
Patching [326,327]	Good	Condition: Good (<3' Distress)	0.04
	Fair	Condition: Fair (3-6' Distress)	
	Poor	Condition: Poor (>6' Distress)	
Raveling [405]	-	N/A	0.02
Bleeding [406]	-	N/A	0.02

4.1.5 LADOTD's Pavement Condition Index (PCI)

Louisiana DOTD uses PCI to assess its pavement condition. It is a composite index that considers several indices into a single "pavement condition" index for each pavement type. For asphalt pavement, the alligator cracking index (ALCR), random cracking index (RNDM) (longitudinal and transverse cracking), patching index (PTCH), rutting index (RUT), and roughness index (RUFF) are the inputs to calculate PCI (LDOTD 2018a). PCI ranges from 1 to 100, where 100 is the perfect score.

It is also important to note that in the LADOTD reference guide, longitudinal cracking under the wheel path is not mentioned separately whereas it exists with unique PD codes in the MDOT PMS database. Thereby, in PCI calculation longitudinal cracking was considered as part of the alligator cracking. Also, in PCI calculation no sensor data (i.e., rutting, faulting, and IRI) was considered to make it comparable with the historical DI.

Table 4-6 List of distresses with deduct points used in DS calculation

CONDITION	EXTENT				SEVERITY
CODE	NONE	<10%	10-30%	>30%	LENGTH
ALLIGATOR CRACKING	0	3	6	9	HAIRLINE
		12	15	18	SPALLED & TIGHT
AC		21	24	27	SPALLED & LOOSE
	NONE	<10%	10-30%	>30%	LENGTH
BLEEDING	0	1	2	3	OCCASIONAL SMALL PATCHES
		4	5	6	WHEEL TRACKS SMOOTH
BLD		7	8	9	LITTLE VISIBLE AGGREGATE
	NONE	<1000'	1000'-2000'	>2000'	L.F. PER MILE
LONGITUDINAL CRACKING	0	1	2	3	<1/4" WIDTH
		4	5	6	1/4-1"
LC		7	8	9	>1" AND/OR SPALLED
	NONE	<1000'	1000'-2000'	>2000'	L.F. PER MILE
TRANSVERSE CRACKING	0	1	2	3	<1/4" WIDTH
		4	5	6	1/4-1"
TC		7	8	9	>1" OR SPALLED OR
	NONE	<10%	10-30%	>30%	LENGTH
BLOCK CRACKING	0	1	2	3	<1/4" WIDTH
		4	5	6	1/4-1"
BC		7	8	9	>1" AND/OR SPALLED
	NONE	<10%	10-30%	>30%	AREA OF SAMPLE
RAVELING AND/OR WEATHERING	0	1	2	3	MINOR LOSS
		4	5	6	SOME SMALL HOLES / PITS
RW		7	8	9	HIGHLY PITTED / ROUGH
	NONE	< 5%	5-15%	>15%	AREA OF SAMPLE
BITUMINOUS PATCHING	0	2	4	6	GOOD CONDITION
		8	10	12	FAIR CONDITION
BP		14	16	18	POOR CONDITION
	< 1/4 A	1/4-3/8"	3/8-1/2"	>1/2"	DEPTH SEVERITY CATEGORY
RUTTING **RT**	0	6	14	27	WITH 20% TRIGGER

Like VDOT's CCI, the same assumption related to the severity levels (see Table 4-3 and Table 4-4) of surface distresses were assumed. Several MATLAB codes were written to extract PMS data according to the LADOT required units and calculate the PCI. As mentioned above, PCI is calculated from individual distress indices. Those individual distress indices were calculated based on severity and extent. In the LADOTD reference document (LDOTD, 2018a) for different ranges of distress extent with different severity levels, deduction points are also provided in ranges rather than in single numbers. An example deduction points table for alligator cracking is shown in Table 4-7. To tackle this issue, for a calculated distress quantity or extent at a particular severity level, MATLAB linear interpolation was adopted to obtain a deduction point. Then, the sum of all deduction points at different severity levels was deducted from 100 to get the individual condition index. In the final step, PCI for flexible pavement was calculated using the Equation 4.10.

$$\text{PCI} = [\max(\min(\text{RNDM, ALCR, PTCH})), (\text{avg}(\text{RNDM, ALCR, PTCH}))] - 85 (\text{std}(\text{RNDM, ALCR, PTCH})) \quad 4.10$$

An example calculation of PCI using the equation above is as follows: Suppose for a pavement section:

$$RNDM = 82, ALCR = 70, PTCH = 90$$

Then:

$$\text{avg}(RNDM, ALCR, PTCH) = 80.7, \text{std}(RNDM, ALCR, PTCH) = 10.0$$
$$\min(RNDM, ALCR, PTCH) = 70, \ \max(\min, \text{avg}) = \max(70{,}80.7) = 80.7$$

Finally,

$$PCI = 80.7 - 85 \times 0.10 = 80.7 - 8.5 = 72.2$$

Thus, the PCI for this pavement section is approximately 72.

Later, to align with the same scale of Distress Index (DI) (assumed DI's higher range to be 100), PCI was flipped using the following Equation 4.11.

$$\text{PCI\_adjusted} = 100 - \text{PCI} \quad 4.11$$

Table 4-7 Deduct values for alligator cracking based on severity and extent for PCI calculations (LDOTD 2018a)

Severity	Extent (square Feet)					
	0-11	11-31	31-131	131-261	261-1000	> 1000
Low	0	1-13	13-23	23-31	31-35	35
Med	0	1-16	16-41	41-49	49-61	61
High	0	1-20	20-46	46-63	63-70	70

4.1.6 Oregon DOT's Overall Condition Index (OCI)

Oregon pavement distress data is used to calculate 0 to 100 index values that reflect specific pavement defects, with larger values indicating better pavement condition. Six condition index values are determined for each 0.1-mile segment along the highway: a rut index, a raveling index, a patching index, a fatigue index, a no load (environmental) index, and an overall index (Oregon Department of Transportation 2018). The overall index is used to categorize the condition of the pavement section as good, fair, poor, etc. It is to be noted that in the fatigue index calculation both longitudinal cracking in wheel path and alligator cracking were considered. Transverse cracking and longitudinal cracking in the non-wheel path were included as part of the no load (environmental) index. Like VDOT's CCI, the same assumption related to the severity levels (see Table 4-3 and Table 4-4) of surface distresses were assumed and MATLAB codes were used to extract PMS data according to the required units. Then, an index factor ranging from 0 to 1 for each distress type and each severity level (i.e., low, medium, and high) was calculated using Equation 4.12. The next step was to calculate the weighted average of the above calculated index factor for different severity levels using Equation 4.13.

$$\text{Factor(typeX)}_{\text{severityY}} = 1.00 - \text{A} \times \left(\frac{\text{Measured Distress}}{\text{Maximum Distress}}\right)^{\text{B}} \qquad 4.12$$

$$\text{Factor(typeX)}_{\text{severityY}} = \frac{[(\text{factor(typeX)} \times \text{qty})_{\text{sev1}} + (\text{factor(typeX)} \times \text{qty})_{\text{sev2}} + (\text{factor(typeX)} \times \text{qty})_{\text{sev3}}\ ]}{\text{qty}_{\text{sev1}} + \text{qty}_{\text{sev2}} + \text{qty}_{\text{sev3}}} \qquad 4.13$$

where qty = quantity. A and B = coefficients. Along with A and B coefficients, "Maximum Distress" in a 0.1-mile segment for each distress are tabulated in Oregon DOT's reference guide (Oregon Department of Transportation 2018).

Each of these weighted average/composite factors were then multiplied by 100 to obtain individual distress indices. In the last step, the overall condition index is determined as the minimum value of the rut index and the non-rut index (raveling index, patching index, fatigue index, and no load (environmental) index). To make the OCI scale similar to the MDOT's DI scale, the following conversion was made using Equation 4.14.

$$\text{OCI}_{\text{adjusted}} = 100 - \text{OCI} \qquad 4.14$$

4.2 PAVEMENT CONDITION INDICES FOR RIGID PAVEMENTS

The following subsections describe Virginia DOT's Critical Condition Index (CCI), Minnesota DOT's Surface Rating (SR), North Dakota's Distress Score (DS), Louisiana DOTD's Pavement Condition Index (PCI) and Oregon DOT's Overall Condition Index (OCI) for JPCP pavement.

4.2.1 Virginia DOT's Slab Distress Rating (SDR)

VDOT addresses the visible distress on slab surface using SDR. It is based on a score of 0 to 100 with 100 being the perfect score. Points are deducted from a perfect score of 100 based on the extent and severity of different distresses. Deduction points for each distress are calculated based on the deduct equation based on either extent or both extent and severity. For example, Equation 4.15 shows the deduct point equation for longitudinal joint spalling based on extent and Equation 4.16 shows the deduct point equation for longitudinal cracking based on both extent and severity (Mcghee et al. 2002). Equations 4.15 through 4.17 show the overall SDR calculation formula.

$$\text{Deduct} = 1.3*(\%\text{Slabs\_SJ})^{6} \qquad 4.15$$

$$\text{Deduct} = 1*(\text{SEV1\_\%Slabs})^{7} + 2.9*(\text{SEV2\_\%Slabs})^{5} \qquad 4.16$$

$$\text{SDR} = 100 - (\text{sum of all deduct points}) \qquad 4.17$$

where, %Slabs_SJ = Longitudinal joint spalling, %Slabs = Longitudinal cracking, and SEV1 = Low severity; SEV2 = High severity

The SDR is adjusted based on the number of distresses used for SDR calculations. The adjustment ensures that pavements with *multiple moderate distresses* are rated equivalently to pavements with a *single very severe distress* (such as divided slabs, which represent the worst possible condition). Without this adjustment, a section showing several smaller issues might appear to be in better condition than it truly is, simply because no single distress is extreme. For example, if a pavement has both longitudinal cracking and corner breaks, the cumulative effect on ride quality and performance would be similar to a pavement suffering from slab division. The SDR adjustment accounts for this by slightly reducing the overall SDR score when multiple distress types are present, ensuring that the index reflects the combined impact of multiple distresses rather than treating each in isolation.

Table 4-8 shows the different distresses and the assumptions made to categorize MDOT PMS data (based on PD codes) into the respective severity levels per the SDR calculations.

Table 4-8 Summary of assumptions to different severity and extent of distresses for SDR

Distresses [PD codes]	Severity	Severity definition from PMS
Corner breaks [401]	-	-
Transverse joint spalling [106]	-	AD matrix: All combinations
Longitudinal joint spalling [208,209]	-	AD matrix: All combinations
Transverse cracking [112,113]	Low	AD matrix: (1,1), (2,1), (3,1), (4,1), (5,2), (5,3), (5,4), (5,5), (6,2), (6,3), (6,4), (6,5), (7,2), (7,3), (8,2), (8,3)
	High	AD matrix: (7,4), (7,5), (8,4), (8,5)
Longitudinal cracking [227,228,229,230,231,232]	Low	No Associated Distress – No Seal No Associated Distress – Seal (full) No Associated Distress – Seal (part) No Associated Distress – Seal (open) Maximum width > 0-1 ft. Maximum width > 1-2 ft.
	High	Maximum width > 2-4 ft.
Divided slabs [344]	-	Shattered Area
PCC patches [326]	Good	Condition: Good (<3' Distress)
	Fair	Condition: Good (3-6' Distress)
	Poor	Condition: Good (>6' Distress)
AC patches [327]	-	All conditions (Good, Fair, Poor)

4.2.2 Minnesota MnDOT's Surface Rating (SR)

The Minnesota DOT (MnDOT) SR is an index representing surface distress. It uses a rating scale from zero to 4 with 4 being the perfect score for a brand-new pavement. The distresses used to calculate SR are determined by two trained raters from the Pavement Management Unit using the

MnDOT manual criteria. Each distress is calculated in terms of either percentage of slabs or percentage of joints, separately for each severity level.

Weighted distresses are calculated by multiplying the quantity of distress for each severity with their respective weighting factor. Total weighted distress (TWD) is calculated by summing up the individual weighted distresses:

$$TWD = \sum_{i=1}^{n} w_i D_i \quad 4.18$$

where, TWD = total weighted distress, n = number of distresses, D_i = quantity of distress for each distress-severity combination, w_i = weights for each distress. Then, the SR is calculated using the equation below:

$$PDS = e^{1.386294-(0.045*TWD)} \quad 4.19$$

Table 4-9 shows Minnesota's weighting factors for individual distresses. Table 4-10 presents the different distresses and the assumptions made to categorize MDOT PMS data (based on PD codes) into the respective severity levels as per the SR calculations

Table 4-9 Weighting factor for individual distresses to SR calculation.

Distress Type	Severity	Weighting Factor
Transverse Joint Spalling	Low	0.1
	High	0.2
Longitudinal Joint Spalling	Low	0.1
	High	0.2
Cracked Panels	-	0.07
Broken Panels	-	0.07
Faulted Joints	-	0.1
Faulted Panels	-	0.07
100% Overlaid Panels	-	0
Patched Panels	-	0.14
D-Cracking	-	0.1

Table 4-10 Summary of assumptions to different severity and extent of distresses for SR.

<table>
<tr><th>Distress</th><th>PD Codes and Severity</th></tr>
<tr><td>D Cracking</td><td>N/A</td></tr>
<tr><td>Transverse Joint Spalls</td><td>Severity : Slight
[106,501]

Severity: Severe
[106]

<table>
<tr><th colspan="6">ASSOCIATED DISTRESS MATRIX (AD1,AD2): AD_{12} 0001 x 0011</th></tr>
<tr><th>TRANSVERSE LENGTH</th><th colspan="5">MAX WIDTH (Perpendicular to Transvers Joint) (AD2)</th></tr>
<tr><th>Across Lane (AD1)</th><th>No Distress</th><th>>0 - 1 ft.</th><th>>1 - 3 ft.</th><th>>3 - 6 ft.</th><th>>6 - 8 ft.</th></tr>
<tr><td>No Distress</td><td>(1,1)</td><td>xxxxx</td><td>xxxxx</td><td>xxxxx</td><td>xxxxx</td></tr>
<tr><td>>0 - 1 ft.</td><td>xxxxx</td><td>xxxxx</td><td>xxxxx</td><td>xxxxx</td><td>xxxxx</td></tr>
<tr><td>>1 - 3 ft.</td><td>xxxxx</td><td>(3,2)</td><td>(3,3)</td><td>(3,4)</td><td>(3,5)</td></tr>
<tr><td>>3 - 6 ft.</td><td>xxxxx</td><td>(4,2)</td><td>(4,3)</td><td>(4,4)</td><td>(4,5)</td></tr>
<tr><td>>6 - 12 ft.</td><td>xxxxx</td><td>(5,2)</td><td>(5,3)</td><td>(5,4)</td><td>(5,5)</td></tr>
<tr><td colspan="6">Note that cells marked with xxxxx are not applicable.</td></tr>
</table></td></tr>
<tr><td>Long. Joint Spalls</td><td>Severity: Slight
[208,209,501]
MAXIMUM WIDTH :>0 - 1 ft.
MAXIMUM WIDTH :>1 - 2 ft.

Severity: Severe
[208,209]
MAXIMUM WIDTH :>2 - 4 ft.</td></tr>
<tr><td>Cracked Panels</td><td>[112,113, 227,228,229,230,231,232,501]
TRANSVERSE LENGTH :>0 - 1 ft.
TRANSVERSE LENGTH :>1 - 3 ft.
TRANSVERSE LENGTH :NO DIST-NO SEAL
TRANSVERSE LENGTH :NO DIST-SEAL(part)
TRANSVERSE LENGTH :NO DIST-SEAL(open)
TRANSVERSE LENGTH :NO DIST-SEAL(full)
MAXIMUM WIDTH :NO DISTRESS
MAXIMUM WIDTH :>0 - 1 ft.
MAXIMUM WIDTH :>1 - 3 ft.
MAXIMUM WIDTH :>0 - 1 ft.
MAXIMUM WIDTH :>1 - 2 ft.
MAXIMUM WIDTH :NO DIST-SEAL(open)
MAXIMUM WIDTH :NO DIST-SEAL(part)
MAXIMUM WIDTH :NO DIST-NO SEAL
MAXIMUM WIDTH :NO DIST-SEAL(full)</td></tr>
<tr><td>Broken Panels</td><td>[112,113, 227,228,229,230,231,232,344,501]
MAXIMUM WIDTH :>2 - 4 ft.
TRANSVERSE LENGTH :>3 - 6 ft.
TRANSVERSE LENGTH :>6 - 12 ft.
MAXIMUM WIDTH :>3 - 6 ft.
MAXIMUM WIDTH :>6 - 8 ft.</td></tr>
<tr><td>Patched Panels</td><td>[326, 327,501]</td></tr>
</table>

4.2.3 North Dakota NDDOT's Distress Score (DS)

North Dakota DOT (NDDOT) uses DS, with deduct points for each distress with specific severity and extent. It uses a rating scale from zero to 99, with 99 being the perfect score. The deduct point for each distress type, severity, and extent is calculated and added up to obtain the total deduct. This total deduct is subtracted from the perfect score of 99 to calculate the final DS value. As an example, Table 4-11 shows the deduct values for longitudinal cracking for different severities and extents. Similarly, the deduct values for all other distresses were obtained from the NDDOT engineers provided documents. Table 4-12 presents the different distresses and the assumptions made to categorize MDOT PMS data (based on PD codes) into the respective severity levels per the DS calculations.

Table 4-11 Deduct values for longitudinal cracking based on severity and extent for DS calculations.

Distress Type	Extent				Severity
Longitudinal Cracking	None	<10%	10-30%	>30%	PER MILE
	0	1	2	3	<1/4" WIDTH
		4	5	6	1/4-1"
		7	8	9	>1"

Table 4-12 Summary of assumptions to different severity and extent of distresses for rigid DS.

Distresses [PD codes]	Severity	Severity definition from PMS
D- cracking	-	-
Transverse joint spalling [106]	Low	AD matrix: (1,1), (2,2), (2,3), (2,4), (2,5), (3,2), (3,3), (3,4), (4,2), (5,2)
	Medium	AD matrix: (3,5), (4,3), (4,4), (4,5), (5,3)

Distresses [PD codes]	Severity	Severity definition from PMS
	High	AD matrix: (5,4), (5,5)
Longitudinal joint spalling [208,209]	Low	Maximum width > 0-1 ft.
	Medium	Maximum width > 1-2 ft.
	High	Maximum width > 2-4 ft.
Transverse cracking [112,113]	Low	AD matrix: (1,1), (2,1), (3,1), (4,1), (5,2), (5,3), (5,4), (5,5), (6,2), (6,3), (6,4), (6,5), (7,2), (7,3), (8,2), (8,3)
	High	AD matrix: (7,4), (7,5), (8,4), (8,5)
Longitudinal cracking [227,228,229,230,231,232]	Low	No Associated Distress – No Seal; No Associated Distress – Seal (full); No Associated Distress – Seal (part); No Associated Distress – Seal (open); Maximum width > 0-1 ft.
	Medium	Maximum width > 1-2 ft.
	High	Maximum width > 2-4 ft.
PCC patches [326]	Good	Condition: Good (<3' Distress)
	Fair	Condition: Good (3-6' Distress)
	Poor	Condition: Good (>6' Distress)

4.2.4 Louisiana DOTD's Pavement Condition Index (PCI)

The Louisiana DOTD calculates rigid PCI from longitudinal cracking index, transverse cracking index, patching index, and roughness index (LDOTD 2018b). It uses a rating scale from zero to 100, with 100 being the perfect score for a brand-new pavement. Each distress is calculated in the required units separately for each severity level. Individual distress index is calculated based on measured distress and corresponding deduct points for each severity level. For example, Table 4-13 shows the deduct points for longitudinal cracking for different severities and extents. Equation 4.20 shows the calculation of the longitudinal cracking index. Similarly, indices are calculated for each distress type, combining all severity levels. Overall, PCI is calculated based on different distress indices as given in Equation 4.21.

$$\text{LONG} = \text{MIN}(100, \text{MAX}(0, 100 - \text{LNGCRK\_L DEDUCT} - \text{LNGCRK\_M DEDUCT} - \text{LNGCRK\_H DEDUCT})) \quad 4.20$$

$$\text{JPCP PCI} = [\text{MAX}(\text{MIN}(\text{LONG, TRAN, PTCH, RUFF})), \text{AVG}(\text{LONG, TRAN, PTCH, RUFF}))] - 85(\text{STD}(\text{LONG, TRAN, PTCH, RUFF})) \quad 4.21$$

where, LONG=Longitudinal cracking index, LNGCRK_L DEDUCT = Deduct points for low severity longitudinal cracking, LNGCRK_M DEDUCT = Deduct points for medium severity longitudinal cracking, LNGCRK_H DEDUCT = Deduct points for high severity longitudinal cracking, TRAN= Transverse cracking index, PTCH= Patching index, RUFF = Roughness index. An example calculation of PCI using the Louisiana method is provided in section 4.1.5.

Table 4-14 shows the different distresses and the assumptions made to categorize MDOT PMS data (based on PD codes) into the respective severity levels as per the PCI calculations.

Table 4-13 Deduct values for longitudinal cracking based on severity and extent for PCI calculations (LDOTD 2018b)

Severity	Extent (Linear Feet)					
	0-11	11-31	31-131	131-261	261-1000	> 1000
Low	0	1-13	13-23	23-31	31-35	35
Med	0	1-16	16-41	41-49	49-61	61
High	0	1-20	20-46	46-63	63-70	70

Table 4-14 Summary of assumptions to different severity and extent of distresses for PCI

Distresses [PD codes]	Severity	Severity definition from PMS
Transverse cracking [112,113, 106]	Low	AD matrix: (1,1), (2,1), (3,1), (4,1), (5,2), (5,3), (5,4), (5,5), (6,2), (7,2), (8,2)
	Medium	AD matrix: (6,3), (6,4), (6,5), (7,3), (8,3)
	High	AD matrix: (7,4), (7,5), (8,4), (8,5) + Spalling all levels
Longitudinal cracking [227,228,229,230,231,232]	Low	No Associated Distress – No Seal No Associated Distress – Seal (full) No Associated Distress – Seal (part) No Associated Distress – Seal (open) Maximum width > 0-1 ft.
	Medium	Maximum width > 1-2 ft.
	High	Maximum width > 2-4 ft.
Patching AC+PCC [326, 327]	Good	Condition: Good (<3' Distress)
	Fair	Condition: Good (3-6' Distress)
	Poor	Condition: Good (>6' Distress)

4.2.5 Oregon DOT's Overall Condition Index (OCI)

The OCI by the Oregon DOT (ODOT) is calculated by combining condition indices for pavement management section of 1 mile. It uses a rating scale from 0 to 100 with 100 being the perfect score for a brand-new pavement. Each distress is calculated in the required units separately for each severity level. Individual distress index is calculated for each distress and each severity level as shown in Equation 4.22. The recommended values of A, B and "Maximum Distress" given in the ODOT manual (Oregon Department of Transportation 2018) are used for all OCI calculations. An average distress index is calculated for each distress by combining different severity levels as shown in Equation 4.23 . Finally, the maximum of the individual indices multiplied by 100 is the OCI.

$$\text{Factor(typeX)}_{\text{severityY}} = 1.00 - \text{A} \times \left(\frac{\text{Measured Distress}}{\text{Maximum Distress}}\right)^{\text{B}} \qquad 4.22$$

$$\text{Factor(typeX)}_{\text{severityY}} = \frac{[(\text{factor(typeX)} \times \text{qty})_{\text{sev1}} + (\text{factor(typeX)} \times \text{qty})_{\text{sev2}} + (\text{factor(typeX)} \times \text{qty})_{\text{sev3}}\ ]}{\text{qty}_{\text{sev1}} + \text{qty}_{\text{sev2}} + \text{qty}_{\text{sev3}}} \qquad 4.23$$

where qty = quantity.

Table 4-15 shows the different distresses and the assumptions made to categorize MDOT PMS data (based on PD codes) into the respective severity levels as per the PCI calculations.

Table 4-15 Summary of assumptions to different severity and extent of distresses for OCI

Distresses [PD codes]	Severity	Severity definition from PMS
D- cracking	-	-
Transverse joint spalling [106]	Low	AD matrix: (1,1), (2,2), (2,3), (2,4), (2,5), (3,2), (3,3), (3,4), (4,2), (5,2)
	High	AD matrix: (3,5), (4,3), (4,4), (4,5), (5,3), (5,4), (5,5)
Longitudinal joint spalling [208,209]	Low	Maximum width > 0-1 ft.
	Medium	Maximum width > 1-2 ft.
	High	Maximum width > 2-4 ft.
Transverse cracking [112,113]	Low	AD matrix: (1,1), (2,1), (3,1), (4,1), (5,2), (5,3), (5,4), (5,5), (6,2), (7,2), (8,2)
	Medium	AD matrix: (6,3), (6,4), (6,5), (7,3), (8,3)
	High	AD matrix: (7,4), (7,5), (8,4), (8,5)
Longitudinal cracking [227,228,229,230,231,232]	Low	No Associated Distress – No Seal No Associated Distress – Seal (full) No Associated Distress – Seal (part) No Associated Distress – Seal (open) Maximum width > 0-1 ft.
	Medium	Maximum width > 1-2 ft.
	High	Maximum width > 2-4 ft.
Patching AC+PCC [326, 327]	Good	Condition: Good (<3' Distress)
	Fair	Condition: Good (3-6' Distress)
	Poor	Condition: Good (>6' Distress)
Divided slabs [344]	-	Shattered Area

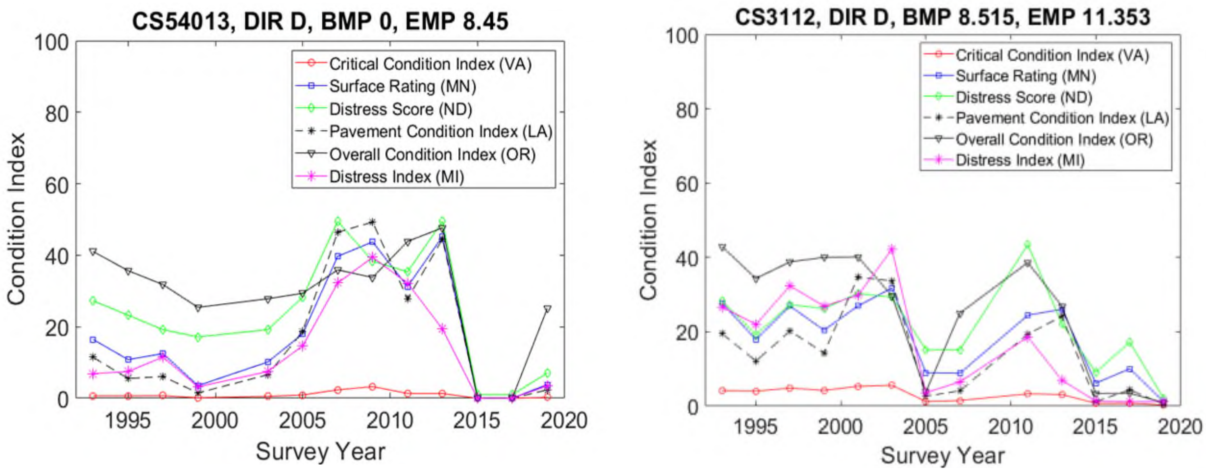
4.3 COMPUTING DIFFERENT CONDITION INDICES WITH MDOT PMS DATA

In this section, the evaluation results of five different condition indices are described. Both quantitative and qualitative approaches were followed to determine which condition index is more compatible with the MDOT PMS database. The findings of this section demonstrate the importance of careful evaluation of condition indices in pavement management systems. This, in turn, can lead to providing a better base to develop an enhanced and effective pavement condition score for Michigan roads.

4.3.1 Relationship between the condition indices and historical DI

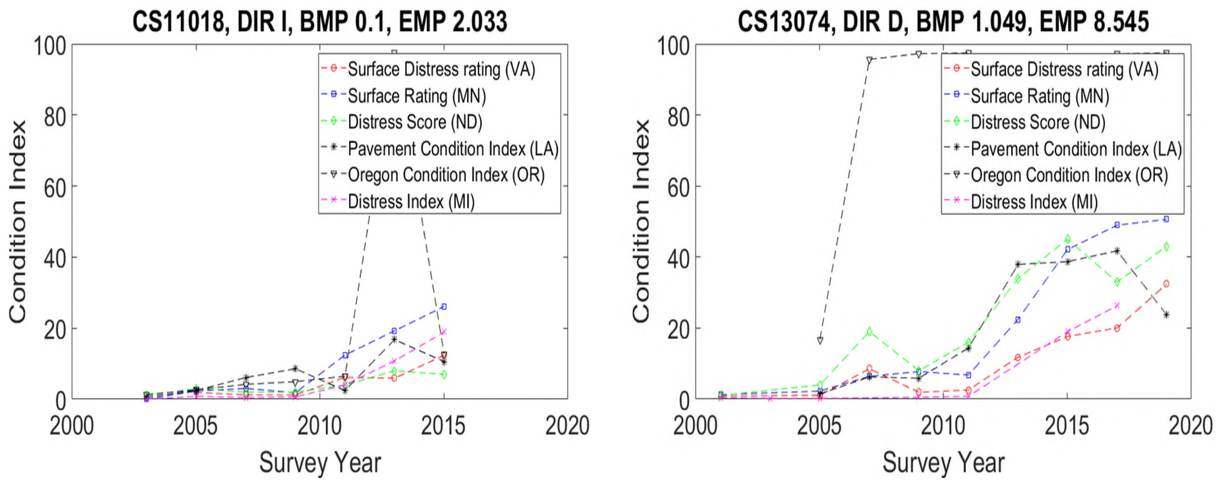
In this subsection, comparisons between individual condition indices and historical DI are presented to assess the compatibility of Michigan pavement distress data. Since the DI is from zero (best possible condition) to infinity (worst) scale, in order to compare with DI, the indices under consideration were “flipped” to a 0 (best) to 100 (worst) scale. To observe how individual condition indices relate to historical DI values, time series plots for 2,081 flexible and 741 rigid pavement sections were plotted individually. For brevity, only a couple of example time series plots of five distress indices and Michigan’s DI for both flexible and rigid pavement sections are shown in Figure 4-2 and Figure 4-3, respectively. In these figures, the abbreviations in the titles are defined as follows: CS stands for 'Control Section', DIR for 'Direction', BMP for 'Beginning Mile Post', and EMP for 'Ending Mile Post'. As shown in Figure 4-2 and Figure 4-3, Minnesota’s SR and Louisiana’s PCI showed good agreement with the DI trend. In general, Virginia’s CCI showed the lowest magnitude in flexible pavement time series plots. It should be noted that when calculating the CCI, the LDR, and NDR are determined using deduction equations that are specifically tailored to the pavement distresses and severity definitions of Virginia DOT. These equations may not be appropriate for other states with different local conditions, so adjustments would need to be made. Additionally, rather than adding the LDR and NDR indices together, the CCI is calculated as the minimum of either index. This approach could potentially result in a lower magnitude of CCI when using the MDOT’s flexible pavement database. However, Virginia’s SDR was found to be a reasonably good match with rigid DI. On the other hand, Oregon’s OCI provided the worst fit among other condition indices for both flexible and rigid pavement. This trend in OCI is also apparent in a study conducted by Gharaibeh et al. (Gharaibeh et al. 2010), wherein the authors compared OCI with Texas DOT's DS and Ohio DOT's PCR.

To better understand what the overall comparison between DI and individual condition indices looks like, separate plots of historical DI against individual condition indices (called “comparison sets”) were also plotted for all considered flexible and rigid pavement sections. Figure 4-4 through Figure 4-13 present overall comparisons between DI and individual condition indices for asphalt and rigid pavements. It can be observed that compared to the other four indices, Minnesota’s SR matches well with DI, as most of the data points are clustered around the line of equality. The next promising one is the PCI from Louisiana, and the least convincing is Oregon’s OCI. These overall comparison results also support the above-mentioned comments on time series plots of different condition indices.



(a) (b)

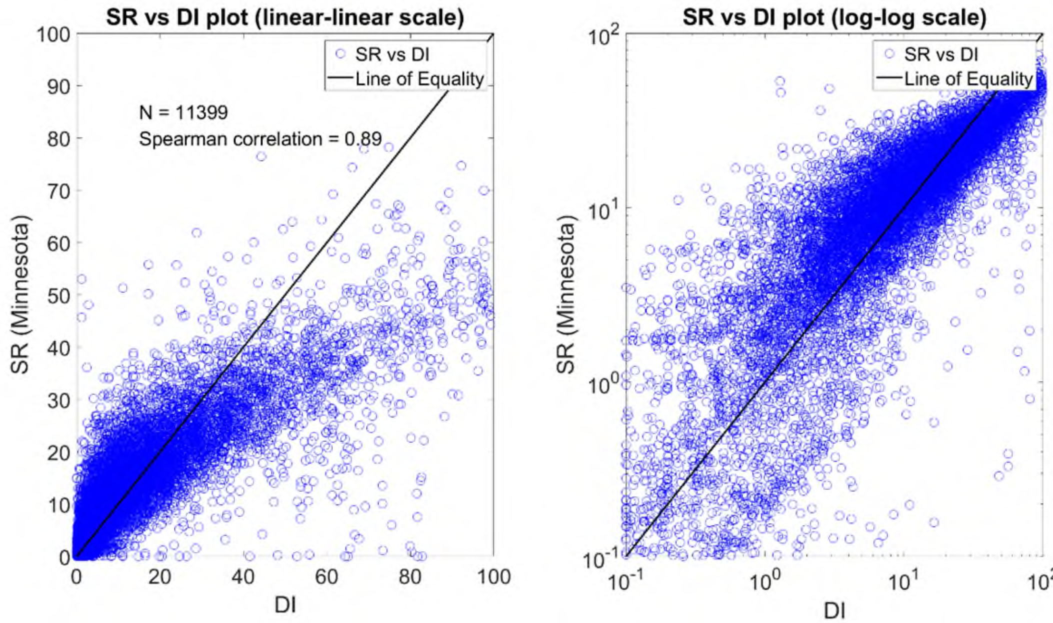
Figure 4-2 Time series plots of all condition indices including DI for flexible sections: (a) CS54103 and (b) CS3112



(a) (b)

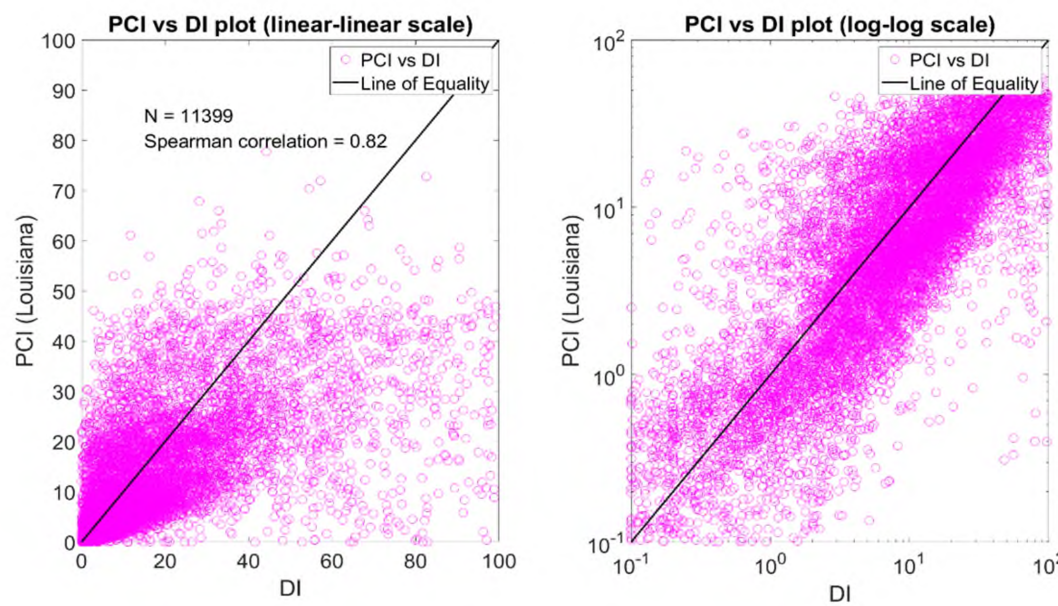
Figure 4-3 Time series plots of all condition indices, including DI for rigid sections: (a) CS11018 and (b) CS13074

To quantify the comparison results better, the Spearman correlation analysis was run for each of the comparison sets. The final results supported the above observation that among the attempted condition indices, Minnesota's SR correlated reasonably well with the historical DI values with a spearman correlation value of 89 and 75 for flexible and rigid sections, respectively. Spearman Correlation for the other indices are as follows: Louisiana's PCI - 82 (flexible) and 63 (rigid), North Dakota's DS - 76 (flexible) and 52 (rigid), Virginia's CCI - 71 (flexible) and SDR - is 73 (rigid), and Oregon's OCI - 65 (flexible) and 42 (rigid). Based on the foregoing, it can be concluded that Minnesota's SR seems the most compatible with the MDOT's distress data.



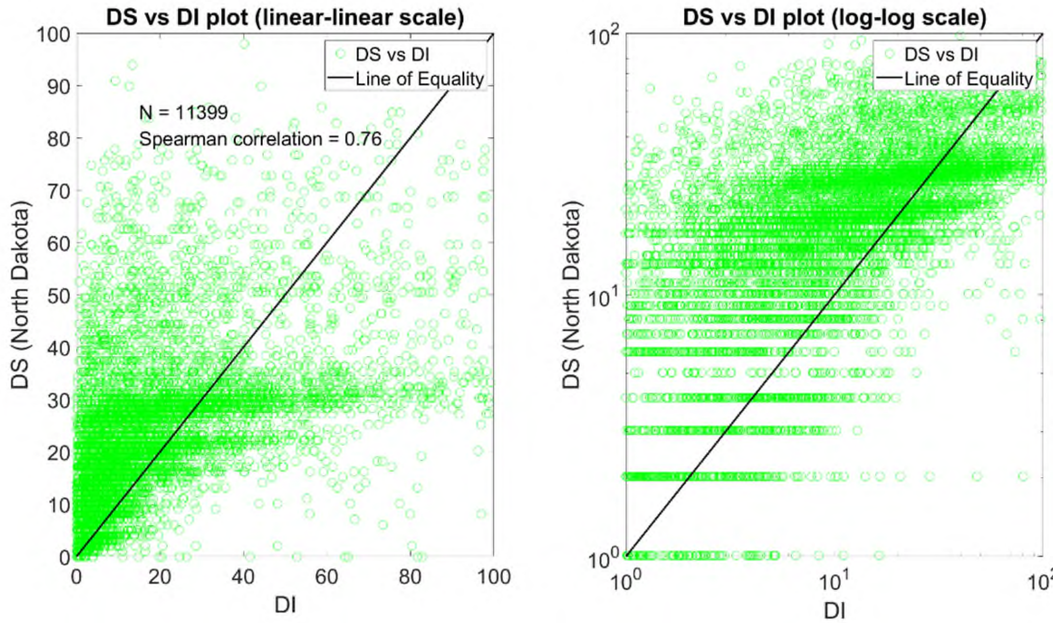
(a) (b)

Figure 4-4 Overall comparison between Surface Rating (SR) vs. Distress Index (DI) for flexible sections: (a) linear-linear scale (b) log-log scale



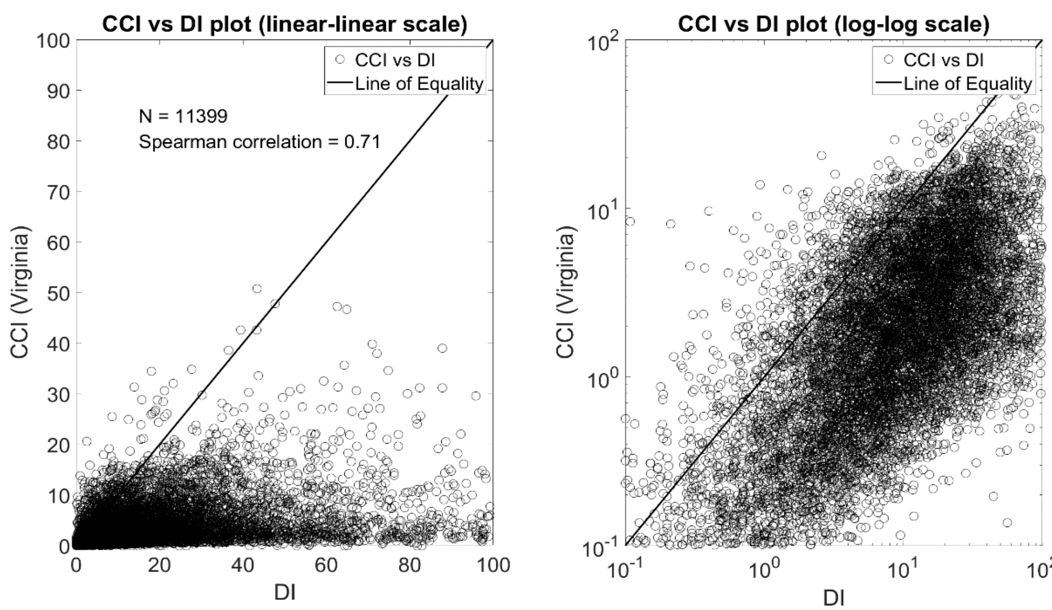
(a) (b)

Figure 4-5 Overall comparison between Pavement Condition Index (PCI) vs. Distress Index (DI) for flexible sections: (a) linear-linear scale (b) log-log scale



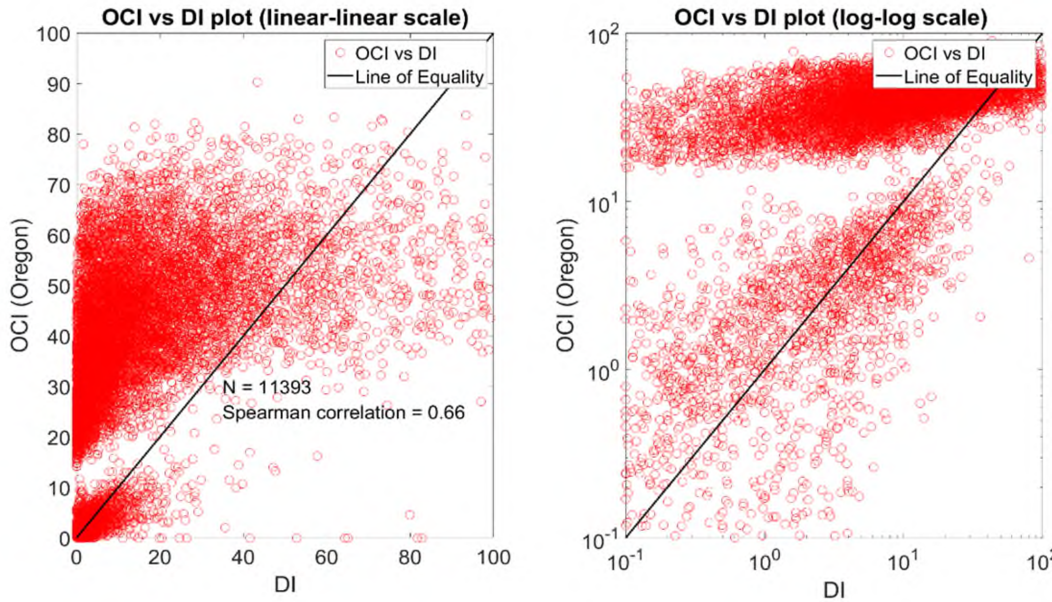
(a) (b)

Figure 4-6 Overall comparison between Distress Index (DI) vs. Distress Score (DS) for flexible sections: (a) linear-linear scale (b) log-log scale



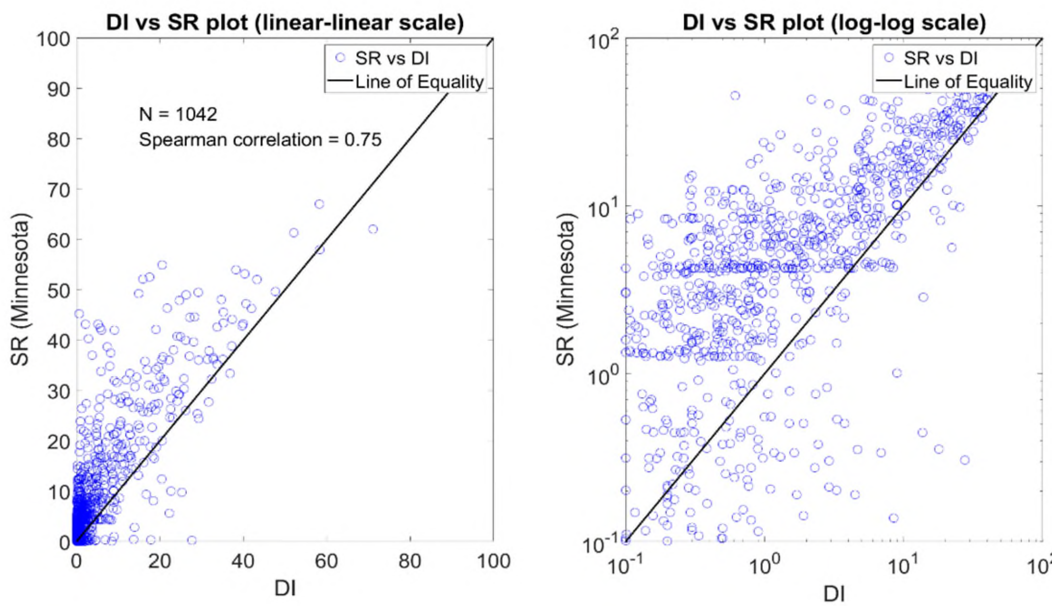
(a) (b)

Figure 4-7 Overall comparison between Critical Condition Index (CCI) vs. Distress Index (DI) for flexible sections: (a) linear-linear scale (b) log-log scale



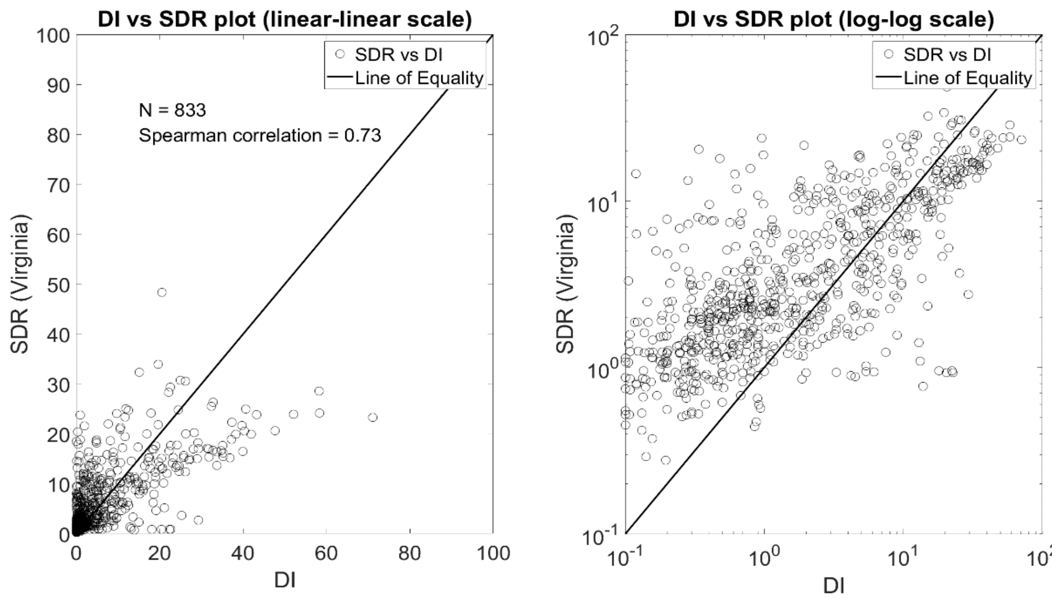
(a) (b)

Figure 4-8 Overall comparison between Overall Condition Index (OCI) vs. Distress Index (DI) for flexible sections: (a) linear-linear scale (b) log-log scale



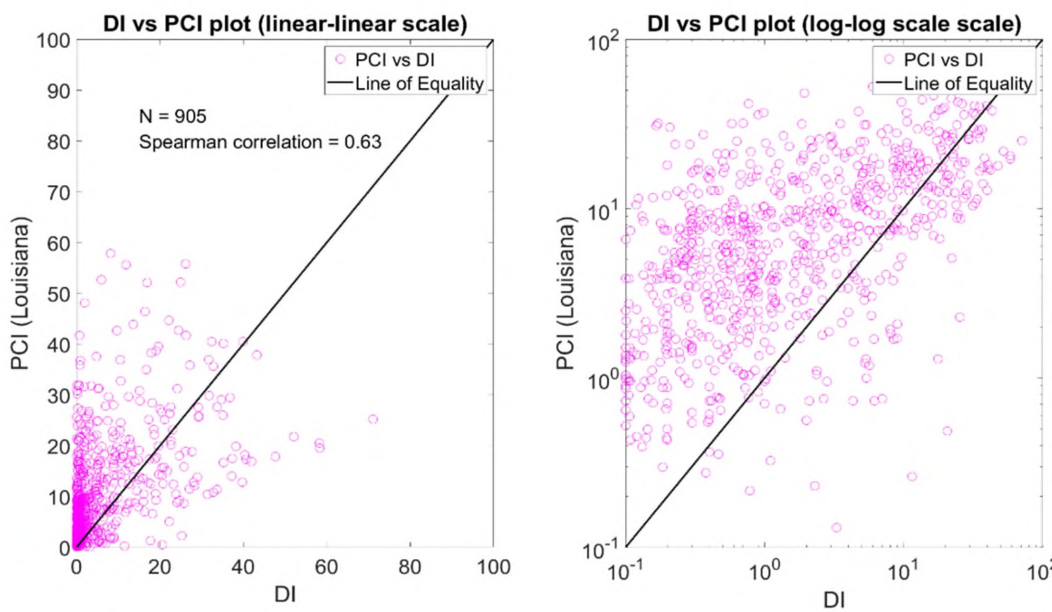
(a) (b)

Figure 4-9 Overall comparison between Surface Rating (SR) vs. Distress Index (DI) for rigid sections: (a) linear-linear scale (b) log-log scale



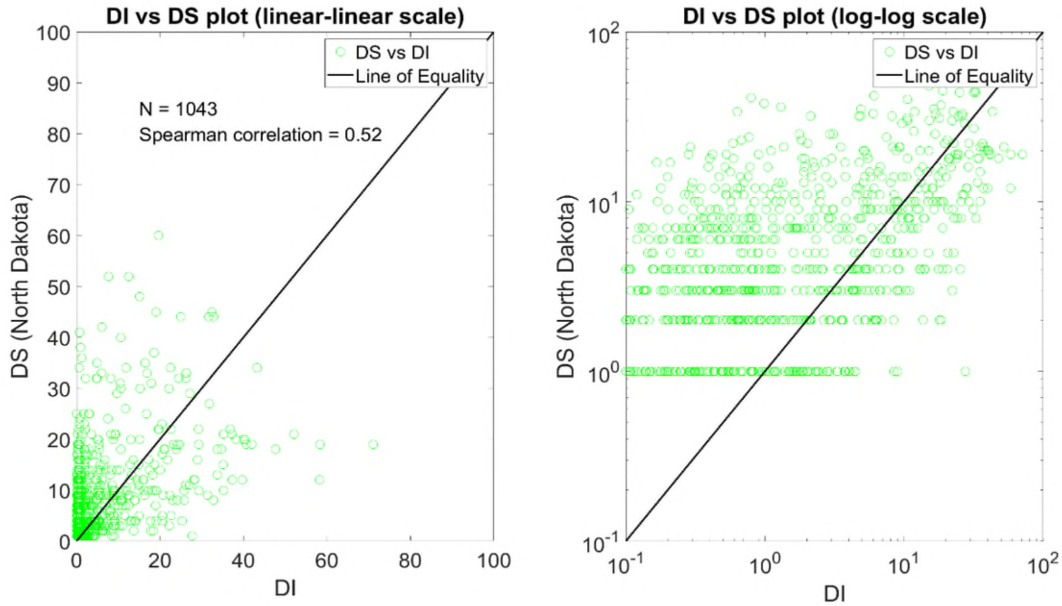
(a) (b)

Figure 4-10 Overall comparison between Slab Distress Rating (SDR) vs. Distress Index (DI) for rigid sections: (a) linear-linear scale (b) log-log scale



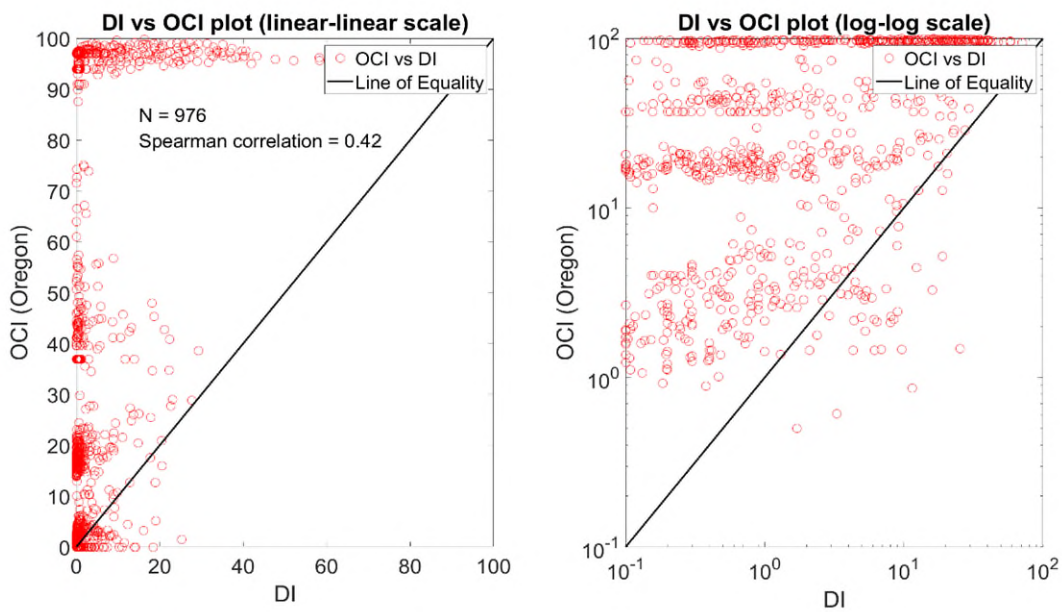
(a) (b)

Figure 4-11 Overall comparison between Pavement Condition Index (PCI) vs Distress Index (DI) for rigid sections: (a) linear-linear scale (b) log-log scale



(a) (b)

Figure 4-12 Overall comparison between Distress Score (DS) vs. Distress Index (DI) for rigid sections: (a) linear-linear scale (b) log-log scale



(a) (b)

Figure 4-13 Overall comparison between Overall Condition Index (OCI) vs. Distress Index (DI) for rigid sections: (a) linear-linear scale (b) log-log scale

4.3.2 Magnitudes of condition indices before different types of maintenances were applied to flexible pavements

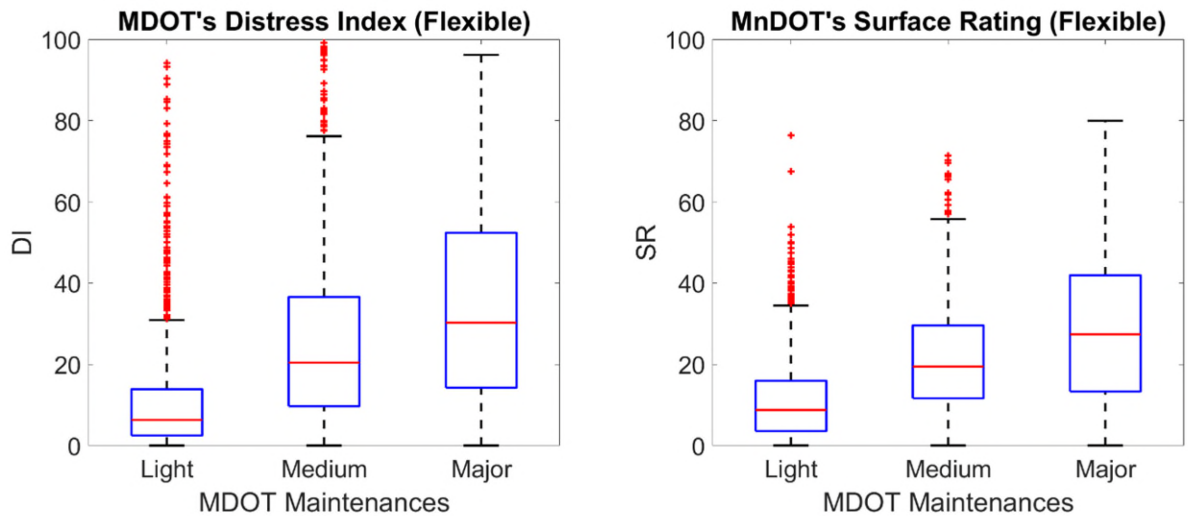
The MDOT Project Scoping Manual, chapter 5 (Michigan Department of Transportation 2017), provides guidelines for fixing flexible pavements based on DI values. Table 4-16 outlines these guidelines. It is noted that MDOT Project Scoping Manual was a previous version and it has currently been replaced by another version. In order to assess the alignment of MDOT's actual maintenance records with the suggested DI numbers, boxplots of actual DI values were generated for different maintenance and rehabilitation activities. The DI values of pavements at a year (or two years) before a particular maintenance application were recorded and box plots were generated. A total of 11 different fix types for flexible pavements were identified from the MDOT maintenance records, and Table 4-16 shows the number of records available for each of these fix types for flexible pavements. However, to facilitate the boxplot representation better, all individual MDOT maintenances were grouped into light, medium, and major categories, as shown in Table 4-16.

Figure 4-14 shows the MDOT's maintenance record boxplots with DI values, where the left side of the figure represents light fix types (such as crack treatment (CT), single micro surface, and overband crack fill (OCF), etc.), while the right side represents heavy fix types (including cold mill and resurface (CM&R), crush and shape, and reconstruction). A boxplot is a graphical representation of a dataset that shows the distribution of values along with some key descriptive statistics. The box in the plot represents the middle 50% of the data, with the median (the middle value) marked by a red line within the box. The lower and upper edges of the box represent the 25th and 75th percentiles of the data, respectively. The "whiskers" that extend from the box show the range of the data, typically up to 1.5 times the interquartile range (IQR), which is the distance between the 25th and 75th percentiles. Any points that fall outside of the whiskers are marked as individual points or "outliers." An ideal index should exhibit narrow boxes with minimum outliers such that each box shows a distinct magnitude range. The DI box plots display a general trend where the median value increases from left to right, although it is important to note that other factors, such as AADT, site location, budget constraints, etc., may have influenced the MDOT's decision-making process beyond DI values. Nonetheless, from Figure 4-14(a), it can be observed that measured DI could reflect on the recommended fix types.

In Figure 4-14(b) through Figure 4-16, similar box plots were created with the other five condition indices evaluated in the previous section. The idea was to see which condition index could capture MDOT's past maintenance records in an effective manner so that a clear distinction could be observed between light to medium and medium to major maintenance with less variability. Among these figures, Minnesota's SR index appeared to be the most effective, as the variability within a single boxplot was reduced, yet it showed a similar increasing trend as the DI box plot. Conversely, the OCI displayed a higher magnitude, even for low categories of fix types. Whereas Virginia's CCI represented very low magnitude, rendering it incapable of differentiating different fix types. NDDOT's DS also presented a similar trend as SR, but its median value was slightly high for the light maintenance group. Based on these analyses conducted, the Minnesota DOT's SR seems to be promising for flexible pavements.

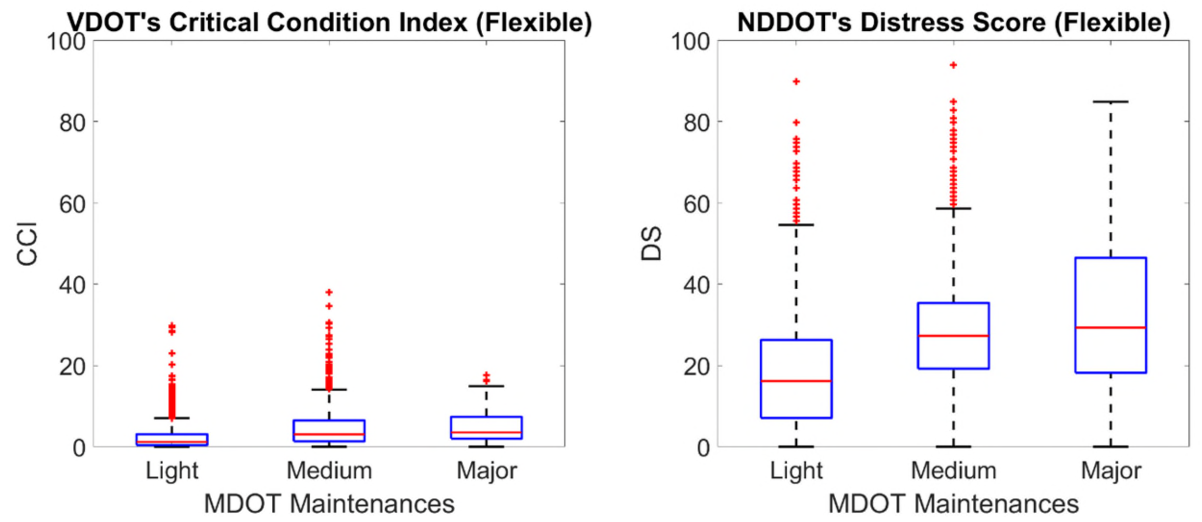
Table 4-16 MDOT fix types for the flexible pavement with the available number of records in the MDOT pavement performance lists

Maintenance Group	MDOT Fix Options	DI Rating	No. of Records
Light	Crack Treatment (CT)	< 15	759
	Single Micro-Surface	< 15	13
	Overband Crack Filling (OCF)	< 20	305
	Ultra-Thin Overlay	< 20	18
	Single Chip Seal	< 25	17
Medium	Double Micro Surface	< 30	18
	Double Chip Seal	< 30	27
	Added HMA	< 40	165
	Cold Mill & Resurface (CM&R)	> 50	591
Major	Crush and Shape	> 50	41
	Reconstruction	> 50	58



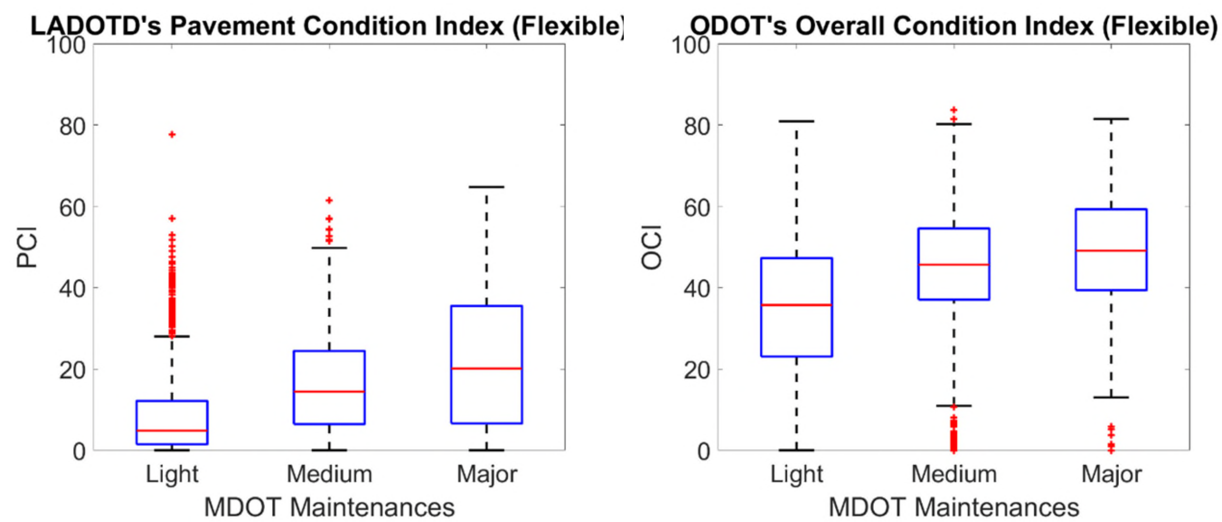
(a) (b)

Figure 4-14 Box plots showing MDOT maintenance records and corresponding (a) Distress Index (Michigan) and (b) Surface Rating (Minnesota) for flexible sections



(a) (b)

Figure 4-15 Box plots showing MDOT maintenance records and corresponding (a) Critical Condition Index (Virginia) and (b) Distress Score (North Dakota) for flexible sections



(a) (b)

Figure 4-16 Box plots showing MDOT maintenance records and corresponding (a) Pavement Condition Index (Louisiana) and (b) Overall Condition Index (Oregon) for flexible sections

4.3.3 Magnitudes of condition indices before different types of maintenances were applied to rigid pavements

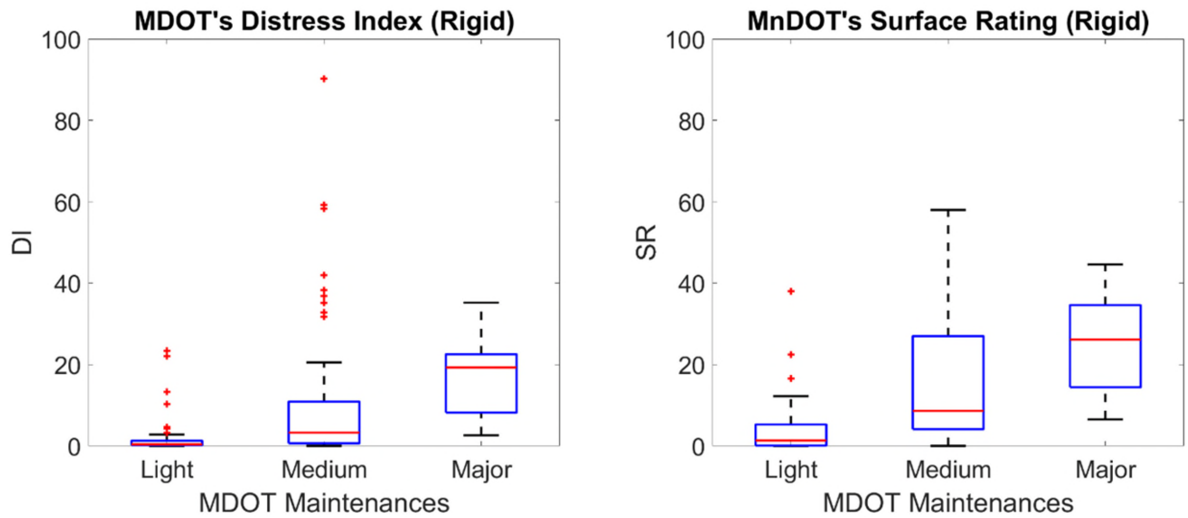
MDOT performs various maintenance and reconstruction activities on rigid pavements depending on the distress level, type, and overall DI value. All maintenance activities were considered for the overall database of 741 rigid sections, and the DI value for up to 2 years prior to the maintenance activity and the corresponding DI year was recorded. All five condition indices were also calculated for the same year for which the DI was recorded. Following the MDOT's fix-type guidelines reported in the MDOT's Project Scoping Manual, chapter 5 (Michigan Department of Transportation 2017), the maintenance activities for rigid pavement were also divided into three categories, as shown in Table 4-17. It is noted again that the MDOT's Project Scoping Manual mentioned herein is a previous version and it has been replaced with another version.

Figure 4-17 through Figure 4-19 show the box plots of each maintenance activity for different rigid pavement condition indices. For the MDOT Distress Index Figure 4-17 (a), there are distinct differences between light and major maintenance. The median value for the light maintenance DI is close to zero, with few outliers observed in the light and medium categories. On the other hand, the median value for the major maintenance group is close to 20, suggesting that the DI alone may not have been the sole determining factor for major rehabilitation or reconstruction efforts.

MnDOT's SR in Figure 4-17 (b) shows clear and distinct differences, with the medium category having more variability, and the SR median value for the major category is close to 25. In Figure 4-18(a), VDOT's SDR, unlike CCI for HMA, shows bigger differences among the three groups, with fewer outliers and less variability. The median value for major maintenance is around 18. In contrast, the NDDOT's DS in Figure 4-18(b) displays poor distinct differences, with more variability in the medium and major categories. Interestingly, the DS median value for the major is lower than the median value for the medium category. In Figure 4-19(a), LADOTD's PCI demonstrated good distinct differences, with reasonable variability in the medium and major categories. Finally, in Figure 4-19(b), ODOT's OCI displayed poor distinct differences, with significant variability in the medium and major categories. The median values for both the major and medium categories are close to 100, indicating unrealistic poor performance.

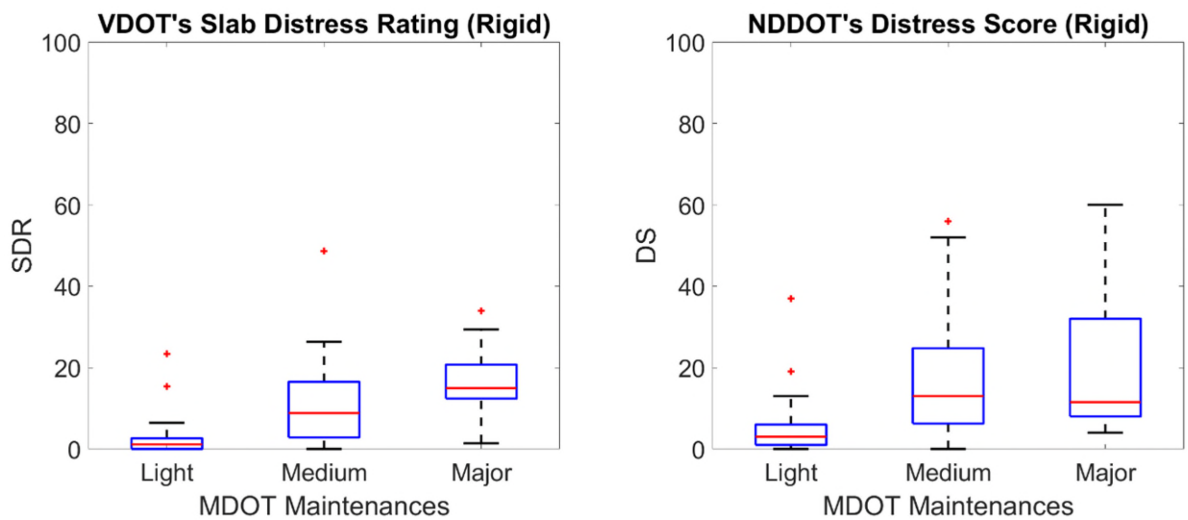
Table 4-17 MDOT fix types for rigid pavement with available number of records in the MDOT pavement performance lists

Maintenance Group	MDOT Fix Options	DI Rating	No. of Records
Light	Diamond Grinding (DG)	<15	118
	Joint Sealing (JS)		
	Longitudinal JS		
	Centerline Repairs		
Medium	Concrete Pavement Repair	<40	476
	AMZ		
Major	Added HMA	>40	91
	JPCP Inlay		
	JPCP Reconstruction		
	Concrete Pavement Inlay		
	Inlay Inside Lane		
	Recon Outside Shoulder w/5" HMA		



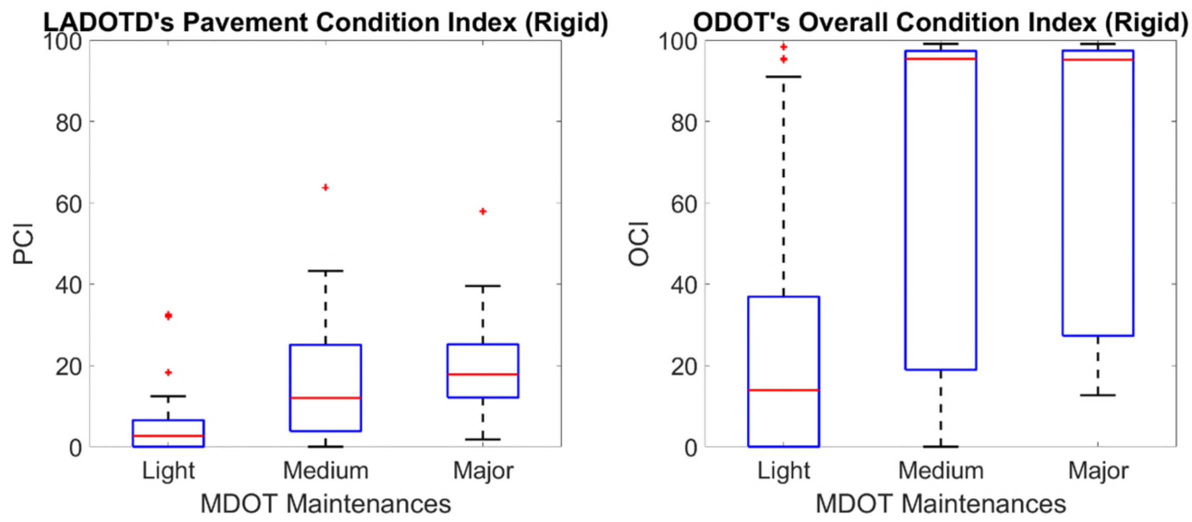
(a) (b)

Figure 4-17 Box plots showing MDOT maintenance records and corresponding (a) Distress Index (Michigan) and (b) Surface Rating (Minnesota) for rigid sections



(a) (b)

Figure 4-18 Box plots showing MDOT maintenance records and corresponding (a) Slab Distress Rating (Virginia) and (b) Distress Score (North Dakota) for rigid sections



(a) (b)

Figure 4-19 Box plots showing MDOT maintenance records and corresponding (a) Pavement Condition Index (Louisiana) and (b) Overall Condition Index (Oregon) for rigid sections

4.3.4 Qualitative evaluation of condition indices

When developing a pavement condition performance measure, it's essential to consider its overall purpose. Performance measures are used in asset management to describe the state of the pavement network (Bryce et al. 2017). However, there are several different approaches to developing pavement condition measures, and the approach used should reflect the intended use or application of the measures. For instance, McGhee et al. (Mcghee et al. 2002) aimed to communicate the current pavement condition as concisely and accurately as possible in their development of performance measures for VDOT. In contrast, Christiansen et al. (Christiansen, A. S. et al. 2010) first adopted a set of performance models for Nordic countries and then selected performance measures based on these models and other factors. Their objective was to develop measures that can be used to predict future pavement conditions.

It is important to acknowledge that the goals of McGhee et al. and Christiansen et al. are not conflicting, but they do impact how the chosen metric should be assessed. McGhee et al. aimed to convey the existing pavement condition, while Christiansen et al. aimed to create indicators that can forecast future conditions. As a result, the assessment of the selected metric should be conducted based on the specific application or purpose intended.

Bryce et al. (Bryce et al. 2016) conducted an evaluation of criteria for condition indices by compiling a comprehensive list of these criteria from the literature and merging similar ones. The following criteria were identified:

- Feasibility (i.e., is it possible to collect the necessary data?)
- Policy sensitivity (i.e., does it capture information that is important to MDOT?)
- Ease of understanding (i.e., can engineers and decision-makers interpret its meaning easily?)

- Usefulness in decision-making (e.g., does it differentiate between pavements in need of different types of repair?)
- Ease of implementation and backward compatibility with historical condition data
- Objectivity

These criteria were used to evaluate the performance measure under consideration, and the study employed several activities to assess the metrics within the umbrella of the six criteria. These activities included a literature review to identify standard distress, frequent discussion with MDOT engineers, analysis of the historical PMS database, etc.

4.3.4.1 Feasibility

The feasibility of the performance measure is determined by its data requirements, which essentially answers the questions:

- Can the data be reliably collected with the current technology and at the stated level of accuracy?
- Is the data standardized in a way that it can be collected by different vendors without requiring a single specialized vendor?

To address these concerns, a comprehensive review of the current state of technologies, standards, state quality management plans, and similar documents was conducted to ensure that the distress severity and extent of data collected are feasible. The study found that adhering closely to national standards, such as defining transverse cracking severity by crack width, ensures high feasibility in collecting the required distress data.

4.3.4.2 Policy sensitivity

The criterion of policy sensitivity aims to ensure that the new condition index captures important trends in the pavement network condition and can be used to make resource allocation decisions. To address this, the study ensured that all functions listed for the DI in the 2019 Transportation Asset Management Plan (TAMP) (Michigan Department of Transportation 2019) were met, including evaluating and monitoring surface condition as a screening tool for project selection, performing a time series analysis to develop fix-life estimates and support the Life Cycle Cost Analysis (LCCA) process for pavement-type selection, and calculating remaining service life for health reporting of the network.

To evaluate this criterion, past fix-type decisions were compared to the values of the condition measures preceding those fix types, with the goal of maximizing the differences among light, medium, and major maintenance categories. This analysis has been detailed in the chapter previously.

4.3.4.3 Ease of understanding

Developing a new condition index that is unambiguous is a fundamental aspect of this evaluation. MDOT's decision to move away from the current DI is driven by the need for greater clarity. This is evaluated in three ways:

- Like the ‘Feasibility’ criteria, this relates to the interpretation of the collected data. This is addressed in the same way as the ‘Feasibility’ criteria.
- Is the range (and specific values within the range) of the new condition index easily understood? In other words, is it clear whether a pavement with a given new condition index value is in good, fair, or poor condition?
- Is the interpretation of individual distresses (both severity and extent) clear to engineers in a way that enables them to identify specific fix types?

This is addressed through a thorough review of existing performance measures, recommendations for future distress, consistent communication with MDOT stakeholders, and analyses performed to meet other objectives on this list.

4.3.4.4 Decision making

The 2019 MDOT Transportation Asset Management Plan (TAMP) states that the DI is used for screening and retrospective analysis of past decisions at the network level. Therefore, the new condition index must also fulfill these roles and be sensitive to distresses most likely to affect a change in fix type. For example, if a specific distress is more likely to change the fix type recommendation from preservation to light rehabilitation, the new condition index must be sensitive to changes in that distress. To evaluate this criterion, two approaches were used:

- MDOT pavement personnel were consulted regarding their experience with assessing pavement distresses and recommending fix types.
- Box plots were analyzed to compare the range of individual condition index values to historical decisions made on the pavement segments.

4.3.4.5 Ease of implementation and backward compatibility

The objective of ease of implementation is to ensure that the existing MDOT systems can support the storage of data and calculation of the condition index with minimal modification. This is achieved by maintaining clear communication with MDOT throughout the evaluation process and ensuring that the project team understands the data requirements.

Furthermore, backward compatibility is a crucial aspect of the project, closely linked to ease of implementation. Backward compatibility refers to the ability to calculate the proposed condition index using historical data from the MDOT PMS and establish a connection between the DI and the new index. This is accomplished by using historical data from the MDOT PMS to calculate each proposed condition measure and analyze factors such as assumptions, data gaps, trends with the DI, and other considerations.

4.3.4.6 Objectivity

The objectivity of the condition index relates to the consistency and repeatability of the gathered distress and roughness data. Objective metrics, such as the International Roughness Index (IRI), rely on standardized processes and leave little room for subjective interpretation. In contrast, subjective measurements like the present serviceability index (PSI) may be influenced by personal biases and driver comfort levels. To ensure objectivity, the recommended condition index and data items must be measured in a repeatable manner with minimal discrepancy.

To evaluate each of the indices against the criteria explained above, both quantitative and qualitative assessments were conducted using a four-point rating scale. Based on the results shown in Table 4-18, the **SR appears to be the most promising condition index for selection**. Therefore, Minnesota's Surface Rating (SR) can serve as the basis for developing Michigan's enhanced pavement condition score.

Table 4-18 Overall assessment of each condition index

Index	Feasibility	Policy Sensitivity	Ease of Understanding	Decision Making	Ease of Implementation and Backward Compatibility	Objectivity	Average
CCI	4	2.9	4	2	2.2	4	3.29
OCI	4	3	4	2.8	2.2	4	3.31
SR	4	3.8	4	3.4	3.6	4	3.79
PCI	4	3.2	4	3	3.5	4	3.61
DS	4	2.8	4	3.3	2.4	4	3.44
Note: The following rating scale was assumed: 1 = poorly meets criterion, 2 = partially meets criterion, 3 = mostly meets criterion, 4 = meets criterion very well							

5 TASK 3: DEVELOPMENT OF PAVEMENT DISTRESS SCORE (PDS)

This chapter is organized into two sections, corresponding to the two distinct phases of the project:

- **Phase I:** This phase focused on the initial development of the Pavement Distress Score (PDS) and the proposed distress definitions. The project team defined a recommended set of distresses to be collected by MDOT in the future and developed the corresponding formulation for calculating the PDS.
- **Phase II:** Following the completion of most of the tasks of Phase I, MDOT's data collection team modified some of the distress definitions and began collecting new data. However, the data collected during this phase did not fully align with the original Phase I recommendations, as adjustments were made to accommodate internal MDOT business needs. This revised data collection approach was named the **Surface Defect Survey (SDS)**. Consequently, PDS coefficients had to be updated to reflect the SDS format, and PDS values were recalculated accordingly. A key component of Phase II also involved converting historical PD/AD data into SDS-equivalent format to maintain consistency over time.

The following sections detail the work completed in each phase: **Phase I** and **Phase II**.

5.1 PHASE I EFFORT

5.1.1 Pavement Distress Score (PDS) formula and distress definitions

The analysis presented in the previous chapter identified Minnesota's Surface Rating (SR) formula as the most promising foundation for developing the Pavement Distress Score (PDS). The original SR formulation assigns a maximum value of 4 to a brand-new pavement and a minimum of 0 to a pavement considered non-drivable. However, most state transportation agencies across the U.S. use a scoring system where pavements start at 100, and points are deducted as the condition worsens. MDOT determined that this nationally adopted approach would offer better alignment with industry standards. As a result, the SR formula was modified accordingly, leading to the revised PDS formula presented below:

$$TWD = \sum_{i=1}^{n} w_i D_i \qquad 5.1$$

$$PDS = 25 * (e^{1.386294-(0.045*TWD)}) \qquad 5.2$$

where, TWD = total weighted distress, n = number of distresses, D_i = quantity at each distress-severity combinations, w_i = weights for each distress, PDS = Pavement Distress Score.

Extensive discussions were held between the research team and MDOT engineers to determine which distress types (D_i) should be collected and incorporated into the PDS formula. The next subsection provides a detailed description of the proposed distress definitions recommended for future data collection. Once the target distress types and severity levels (D_i) were identified, it became necessary to convert historical Principal Distress/Associated Distress (PD/AD) data into equivalent formats compatible with the new PDS framework. The methodology for this conversion is described in detail in the following chapters of this report. Furthermore, the weight factors (w_i) for each distress needed to be 'calibrated' to the MDOT practice, based on the pavement treatment type selections historically done by MDOT. This calibration is done via an optimization scheme that is described in a later part of this chapter.

5.1.2 Recommendations on future distress collection methodology

Historically, MDOT has collected many surface distresses with the help of vendors. Since 1992 MDOT has maintained its PMS database, where all the raw distress data are stored. MDOT assigned Principal Distress (PD) codes along with Associate Distress (AD) codes to reflect the severity and extent of individual distress. MDOT collected around 30 different PDs for both asphalt and rigid pavements. Table 5-1 and Table 5-2 present pavement distresses that MDOT collected on their road network for asphalt and rigid pavements, respectively. An example associated distress matrix table of flexible pavement transverse crack (TC) (PD 103) is shown in Table 5-3 ("MDOT Pavement Condition Data System: Distress Survey Manual" 2017). According to the MDOT's survey manual ("MDOT Pavement Condition Data System: Distress Survey Manual" 2017), the severity of a TC is estimated by transverse length (total accumulated length along crack alignment where associated distress is observed), and maximum width (at any single location along crack alignment) of the ADs that occur within 2 feet of the TC. The complex, and at times contradictory, nature of the PD/AD definition method had periodically led MDOT to experience challenges in contracting the service with vendors, including quality issues and delivery delays. Additionally (as mentioned previously), this complex definition of crack severity had become overtime inconsistent with the developing nationwide practice. . That challenging aspect of the PD/AD methodology, coupled with other important related factors regarding the data's management and use, led MDOT to discontinue the practice after the 2019 season and pursue development of a replacement methodology.

A survey in 2018 conducted by Pierce et al. (Pierce and Weitzel 2019) showed that most of the state agencies capture a similar type of distress on their pavement surface except a few distresses which are not commonly observed or captured in some states. Fifty-seven agencies participated in that survey, including 46 U.S. highway agencies and 11 Canadian provincial and territorial governments. Figure 5-1 and Figure 5-2 show all the distresses often collected for asphalt and rigid pavements, respectively. Referring to Figure 5-1 and Figure 5-2 it can be observed that the MDOT distress lists align with the nationwide commonly observed distresses. However, there are few redundancies in the MDOT distress list compared to other states. After discussing with MDOT engineers on several occasions and based on the nationwide common distress types and related information collected in this study, it was suggested to combine and eliminate several Principal Distresses (PDs). For example, flexible pavement Transverse Crack - TC (straight), Transverse Crack - TC (irregular), and Transverse Tear can be combined under a single distress type known as Transverse Crack (TC). It is recommended to assign a new PD code of 901 to this consolidated distress type. Likewise, Longitudinal Crack - LC (Right Wheelpath - WP), Longitudinal Crack - LC (Left Wheelpath - WP), Alligator Crack (Right WP), and Alligator Crack (Left WP) can be combined. Also, Longitudinal Crack - LC (Left edge) and Longitudinal Crack - LC (Right edge) can be merged under a single distress type called Edge Crack.

Furthermore, Raveling and Potholes with high severity can be identified as a new PD code of 906. Lastly, Partial Width Patch (white) and Partial Width Patch (black) are replaced with the new SDS codes called "Patch_Area_Conc" and "Patch_Area_Asphalt".

Table 5-1 Flexible pavement distress list collected by MDOT

PD Code	MDOT PD Title	PD Code	MDOT PD Title
103	Transverse Crack - TC (Straight)	236	Longitudinal Crack- LC - (Left edge)
104	Transverse Crack - TC (irregular)	237	Longitudinal Crack- LC - (Right edge)
114	Transverse Tear	326	Partial Width Patch (W)
202	Longitudinal Crack- LC- (Center of lane)	327	Partial Width Patch (b)
204	Longitudinal Crack- LC- (Right Wheelpath - WP)	345	Block Crack
205	Longitudinal Crack- LC- (Left Wheelpath - WP)	405	Raveling
234	Alligator Crack -Right WP	406	Flushing
235	Alligator Crack -Left WP	-	-

Table 5-2 Rigid pavement distress list collected by MDOT

PD Code	MDOT PD Title	PD Code	MDOT PD Title
106	Transverse Joint -TJ	327	Partial Width Patch (b)
113	Transverse Crack - TC	341	Delaminated Area
208	Longitudinal Joint - Left	342	Map Crack
209	Longitudinal Joint - Right	343	High Steel
230	Longitudinal Crack - LC (Right Wheelpath - WP)	344	Shattered Area
231	Longitudinal Crack - LC - (Center of Lane)	402	Popouts
232	Longitudinal Crack - LC (Left Wheelpath - WP)	403	Scaling
326	Partial Width Patch (W)	-	-

Table 5-3 Associated Distress (AD) matrix for transverse cracks on flexible pavements

Transverse Length Across Lane (along crack) (AD1)	Maximum Width (Perpendicular to Transverse Crack) (AD2)			
	No Assoc. Distress	>0 – 1 ft.	>1 – 2 ft.	> 2 – 4 ft.
No. Assoc. Distress – No Seal	(1,1)	NA	NA	NA
No. Assoc. Distress –Seal (full)	(2,1)	NA	NA	NA
No. Assoc. Distress –Seal (part)	(3,1)	NA	NA	NA
No. Assoc. Distress –Seal (full)	(4,1)	NA	NA	NA
>0 –1 ft.	NA	(5,2)	(5,3)	(5,4)
>1 – 3 ft.	NA	(6,2)	(6,3)	(6,4)
>3 – 6 ft.	NA	(7,2)	(7,3)	(7,4)
>6 – 12 ft.	NA	(8,2)	(8,3)	(8,4)
Note: 'NA' = Not Applicable.				

For rigid pavements, PDs that were suggested to be eliminated are Map Crack, High Steel, Popouts, Scaling, and Shattered Area. Additionally, based on the practices of other state agencies, it is recommended that MDOT consider including two distress types, namely (i) Corner Crack and (ii) Punchout, in their list of rigid pavement surveys for future reference.

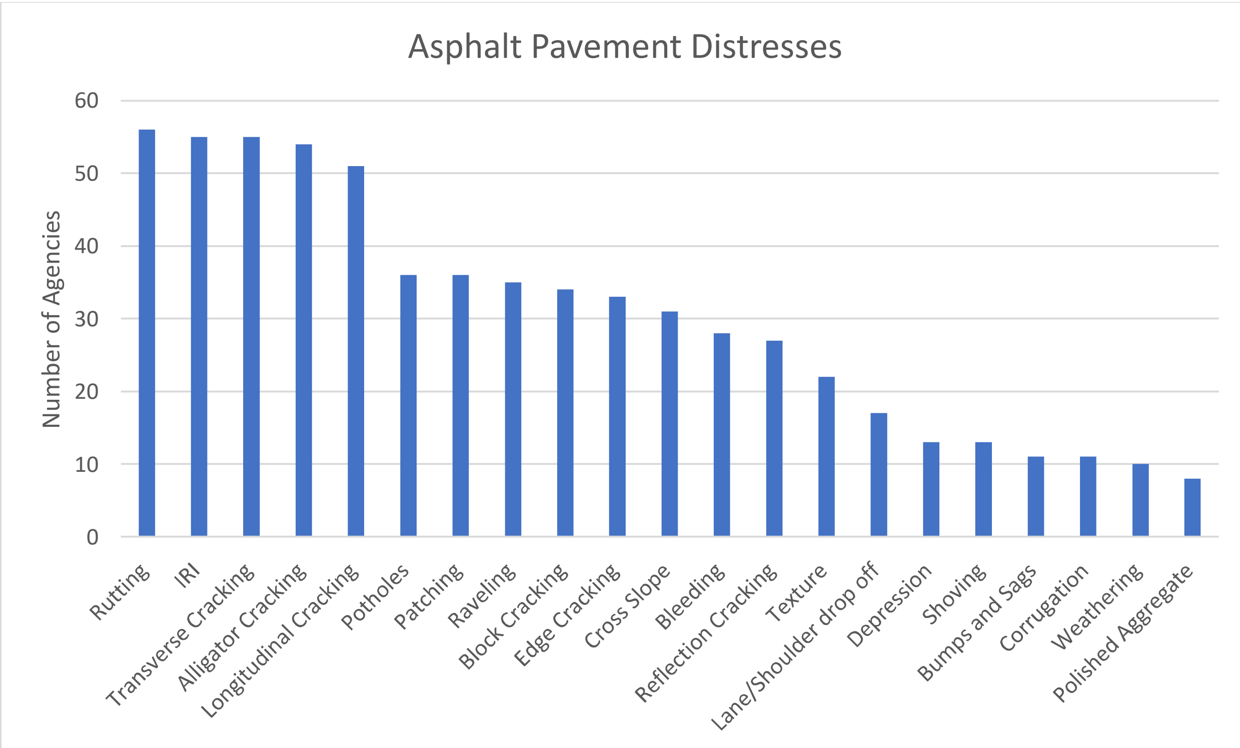


Figure 5-1 List of flexible pavement distresses collected nationwide as of 2019.

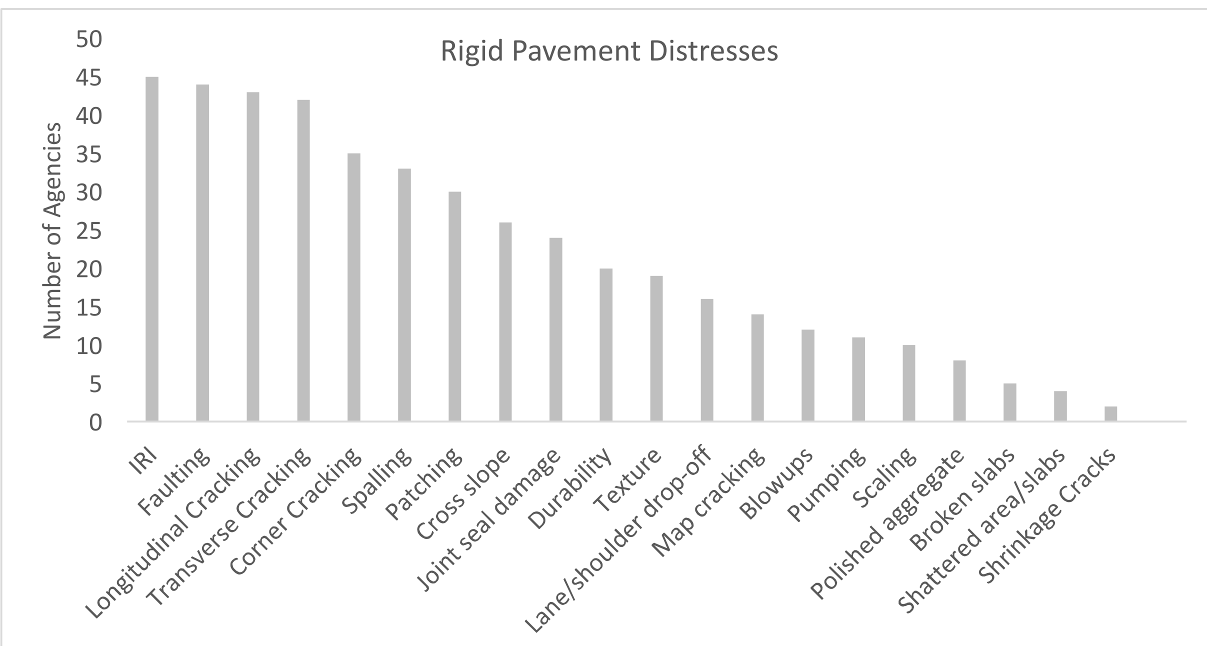


Figure 5-2 List of rigid pavement distresses collected nationwide as of 2019.

Table 5-4 and Table 5-5 show the proposed distress list for flexible and rigid pavements, respectively. General definitions of the flexible pavement distresses are provided in the next subsections. For definitions of the Zones listed in these tables, refer to AASHTO R 85-18.

Table 5-4 New distress list for flexible pavements.

New PD Code	Old PD Codes (i)	New PD Title	Definition (ii)	Severity (iii)		
				Low	Medium	High
901	101, 103, 104, 110, 114, 701, 703, 704	Transverse Crack	TC	Total length (feet) of unsealed transverse crack, width < 0.25"	Total length (feet) of unsealed transverse crack, width 0.25" – 0.50"	Total length (feet) of unsealed transverse crack, width > 0.50".
902	204, 205, 210, 220, 221, 222, 224, 234, 235, 724, 725, 730, 731	Longitudinal Wheelpath Crack	LWC	Total length (feet) of unsealed longitudinal crack in Zones 2 and 4, width < 0.25".	Total length (feet) of unsealed longitudinal crack in Zones 2 and 4, width 0.25" - 0.50".	Total length (feet) of unsealed longitudinal crack in Zones 2 and 4, width > 0.50". Include alligator crack.
903	202, 218, 722	Longitudinal Center (center of the lane) Crack (non-Wheelpath)	LCC	Total length (feet) of unsealed longitudinal crack in Zone 3, width < 0.25".	Total length (feet) of unsealed longitudinal crack in Zone 3, width 0.25" - 0.50".	Total length (feet) of unsealed longitudinal crack in Zone 3, width > 0.50".
904	201, 203, 236, 237, 721, 723	Longitudinal Edge Crack (non-Wheelpath)	LEC	Total length (feet) of unsealed longitudinal crack in Zones 1 and 5, width < 0.25".	Total length (feet) of unsealed longitudinal crack in Zones 1 and 5, width 0.25" - 0.50".	Total length (feet) of unsealed longitudinal crack in Zones 1 and 5, width > 0.50".
905	310, 345, 760	Block Crack	BC	No severity definitions. Percentage of total lane area where block crack exists.		
906	405	Raveling + Potholes	RP	No severity definitions. Reported as total area (square feet) of raveling		
907	406	Flushing/Bleeding	FB	No severity definitions. Reported as total area (square feet) of bleeding		
908	326, 327	Patching	PAT	No severity definitions. Reported as total area (square feet) of patching.		

Note: (i) Based on latest MDOT distress manual, (ii) definitions are provided within the text, (iii) sealed cracks will be reported as medium severity cracks

Table 5-5 New distress list for rigid pavements.

New PD Code	Old PD Codes (i)	New PD Title	Definition (ii)	Severity (iii)		
				Low	Medium	High
801	102, 105, 107, 112, 113, 712, 713	Transverse Crack	TC	Total length (feet) of unsealed transverse crack, width < 0.25"	Total length (feet) of unsealed transverse crack, width 0.25" - 0.50"	Total length (feet) of unsealed transverse crack, width > 0.50".
802	206, 207, 212, 213, 214, 215, 227, 229, 230, 232, 737, 740, 742	Longitudinal Wheelpath Crack	LWC	Total length (feet) of unsealed longitudinal crack in Zones 2 and 4, width < 0.25".	Total length (feet) of unsealed longitudinal crack in Zones 2 and 4, width 0.25" - 0.50".	Total length (feet) of unsealed longitudinal crack in Zones 2 and 4, width > 0.50".
803	219, 228, 231, 738, 741	Longitudinal Center (center of the lane) Crack (non-Wheelpath)	LCC	Total length (feet) of unsealed longitudinal crack in Zone 3, width < 0.25".	Total length (feet) of unsealed longitudinal crack in Zone 3, width 0.25" - 0.50".	Total length (feet) of unsealed longitudinal crack in Zone 3, width > 0.50".
804	208, 209	Longitudinal Joint Spalling	LJS	Total length (feet) of longitudinal joint in Zones 1 and 5 with no spalling or spall width < 3".	Total length (feet) of longitudinal joint in Zones 1 and 5 with spall width 3" - 6".	Total length (feet) of longitudinal joint in Zones 1 and 5 with spall width > 3".
805	106, 706	Transverse Joint Spalling	TJ	Number of transverse joints with maximum spall width < 3".	Number of transverse joints with maximum spall width 3" - 6".	Number of transverse joints with maximum spall width > 6".
806	301, 341, 751	Delaminated Area	DA	No severity definitions. Reported as total area (square feet) of delaminated area		
807	326, 327	Patching	PA	No severity definitions. Reported as total area (square feet) of patching		
808	NA	Corner Crack	CC	Number of corner breaks with LTPP-defined severity = Low	Number of corner breaks with LTPP-defined severity = Moderate	Number of corner breaks with LTPP-defined severity = High

New PD Code	Old PD Codes (i)	New PD Title	Definition (ii)	Severity (iii)		
				Low	Medium	High
809	NA	Punchout	PO	No severity definitions. Total combined area (square feet) of all punchouts.		

5.1.2.1 Flexible Pavement Distress Definitions

TC **-** *Transverse Crack:* The cracks that extend more in the transverse direction than the longitudinal direction where the angle between the overall crack line and the edge line is more than 45 degrees. It must be visible for at least ½ of the lane width. Reported as length in feet.

LCC **-** *Longitudinal Center Crack (non-Wheelpath):* (i) The cracks that extend more longitudinally than transversely where the angle between the overall crack line and the paved lane's edge line is less than 45 degrees. (ii) Any 0.01-mile segment along the lane has at least 50% of its length covered by the distress type occurrence. Reported as length in feet. Applies to crack in Zone 3 (see Figure 5-3).

LWC **-** *Longitudinal Wheelpath Crack:* (i) The cracks that extend more longitudinally than transversely where the angle between the overall crack line and the paved lane's edge line is less than 45 degrees. (ii) Any 0.01-mile segment along the lane has at least 50% of its length covered by the distress type occurrence. Alligator Crack is included in LWC and applies to high severity only. Alligator Crack is defined as two or more parallel longitudinal cracks (originating in a wheel path – WP) with transverse tears running between them, displaying a pattern similar to an alligator hide. The center of each wheelpath shall be assumed to be located approximately 3 ft from the center of the lane. Reported as LWC length in feet. Also, the distance between the center of LWC from the centerline of the pavement is reported in feet. Applies to crack in Zones 2 and 4 (see Figure 5-3).

LEC **-** *Longitudinal Edge Crack (non-Wheelpath):* (i) The cracks that extend more longitudinally than transversely where the angle between the overall crack line and the paved lane's edge line is less than 45 degrees. (ii) Any 0.01-mile segment along the lane has at least 50% of its length covered by the distress type occurrence. Reported as LEC length in feet. Applies to crack in Zones 1 and 5 (see Figure 5-3).

BC **-** *Block Crack*: A Block Crack area is where transverse and longitudinal crack have progressed to a point where at least 6 individual blocks (each less than 12' by 12' in size) are visible. The shape of each block may be irregular because of the form of the initial transverse crack and later-induced longitudinal crack. Reported as *BC* area in ft^2.

RP **-** *Raveling/Potholes*: A Raveling area is where the original smooth surface has partially or entirely eroded away in more areas than just the Wheelpaths, leaving the inner aggregate of the bituminous mixture exposed and creating a rough surface texture. Pothole is a deep surficial cavity formed by the erosion of aggregates, especially by the action of water and traffic. Reported as total area (square feet) of raveling.

FB **-** *Flushing/Bleeding:* A Flushing or Bleeding area is where the pavement is noticeably darker due to asphalt cement being squeezed to the top of the pavement mixture and deposited on the surface. It usually occurs in the wheel paths and may appear shiny in the perspective view. Reported as total area (square feet) of bleeding.

PAT - *Patching:* Patching is a repaired section where the original pavement has been partially removed and replaced. Patching can have any width (transversely measured - across the survey lane) up to, but not equal to, the full lane width, and can have any length up to or equal to 0.01 miles in longitudinal direction. Full-lane-width patches and bridge approach slabs shall not be identified/recorded. Utility access holes with patching around them and pavement coring holes shall be considered as patching. Traffic signal detection loop (sealed) cuts shall not be considered patching (but as other crack PDs based upon observed deterioration if present). Reported as total area (square feet) of patching.

5.1.2.2 Rigid Pavement Distress Definitions

TJS - *Transverse Joint Spalling:* A Transverse Joint (TJ) is a regularly spaced saw cut across the slab width. Transverse Joint Spalling (TJS) is breaking of the sides of Transverse Joint into smaller pieces/fragments within 2 ft (6 m) of the side of the joint. Reported as TJ counts (i.e., number of transverse joints).

TC - *Transverse Crack:* The cracks that extend more in the transverse direction than the longitudinal direction where the angle between the overall crack line and the edge line is more than 45 degrees. It must be visible for at least ½ of the lane width. Reported as TC length in feet.

LJS - *Longitudinal Joint Spalling:* Longitudinal Joint Spalling (LJS) is breaking of the sides of Longitudinal Joint into smaller pieces/fragments within 2 ft (6 m) of the side of the joint. Reported as LJS length in feet. Applies to joints in Zones 1 and 5 (see Figure 5-3).

LWC - *Longitudinal Wheelpath Crack:* (i) The cracks that extend more longitudinally than transversely where the angle between the overall crack line and the paved lane's edge line is less than 45 degrees. (ii) Any 0.01-mile segment along the lane has at least 50% of its length covered by the distress type occurrence. Applies to crack in Zones 2 and 4. Reported as *LWC* length in feet.

LCC - *Longitudinal Center (center of the lane) Crack:* (i) The cracks that extend more longitudinally than transversely where the angle between the overall crack line and the paved lane's edge line is less than 45 degrees. (ii) Any 0.01-mile segment along the lane has at least 50% of its length covered by the distress type occurrence. Applies to crack in Zone 3. Reported as *LCC* length in feet.

DA - *Delaminated Area*: A Delaminated Area has partial-depth pieces of concrete broken out from the surface (usually beginning with circular-shaped edges) and may reach down to the reinforcing steel. Reported as *DA* area in feet^2

CC - *Corner Crack*: A crack that intersects the concrete slab joints near the corner. "Near the corner" is typically defined as within about 6 ft (2 m). Reported as *CC* counts (i.e., number of corner breaks).

PO - Punchouts: Localized slab portions broken into several pieces. Typically, a concern only with Continuously Reinforced Concrete Pavement (CRCP). Reported as PO area in ft^2.

PAT - Patching: Patching is a repaired section where the original pavement has been partially removed and replaced. Patching can have any width (transversely measured - across the survey lane) up to, but not equal to, the full lane width, and can have any length greater than or equal to 0.01 miles in longitudinal direction. Full-lane-width patches and bridge approach slabs shall not be identified/recorded. Utility access holes with patching around them and pavement coring holes shall be considered as patching. Traffic signal detection loop (sealed) cuts shall not be considered patching (but as other crack PDs based upon observed deterioration if present). Reported as total area (square feet) of patching.

5.1.2.3 Normalization of proposed distress units into percentage

The *future* distresses that are proposed to be collected as length (in feet), count or area (in square feet). These units need to be converted to percentages, as needed in PDS formula. Table 5-6 shows the equations to convert new distress units to percentage.

Equation [T.1] calculates the percentage of thermal cracking (TC) relative to its theoretical maximum. The denominator, *(Section Length ÷ TC Spacing),* represents the expected number of transverse thermal cracks in the section based on a standard spacing assumption. Multiplying this value by the lane width yields the maximum possible total length of thermal cracks—assuming that every expected crack occurs and spans the full lane width. The numerator reflects the actual measured total length of thermal cracks. Thus, the resulting TC percentage indicates the extent to which observed cracking approaches the theoretical maximum. A TC value of 100% means the measured crack length equals the full-width cracks occurring at the expected minimum spacing. Lower percentages indicate that the cracks are less frequent, or shorter than assumed. For example, if the lane width is 12 feet, the section length is 1 mile (5280 feet), and the assumed TC spacing is 10 feet, then the maximum possible crack length is: (5280 / 10) × 12 = 6336 ft. So, if 6336 feet of thermal cracking is measured in that 0.1-mile section, the TC percentage would be 100%.

Equation [T.2] yields a value of **100%** when both **Zone 2** and **Zone 4** exhibit longitudinal cracking (or longitudinal spalling) that spans the entire length of the pavement section (see Figure 5-3). This reflects a worst-case scenario where longitudinal distress is present along the full length in both designated wheelpath zones.

Equation [T.3] functions similarly, producing **100%** when **Zone 3**, which typically corresponds to the centerline or interior of the lane, contains a continuous longitudinal crack or spall over the full section length (see Figure 5-4).

Equation [T.5] calculates the extent of distress in **Zone 1** and **Zone 5**, representing the edges of the lane. A value of **100%** indicates that both edges are fully cracked or spalled along the entire section (see Figure 5-5 and Figure 5-6). This measurement helps assess edge-related longitudinal failures, which can significantly impact pavement performance.

For corner cracking (Equation [T.7]), the formula considers the theoretical maximum of **four cracks per slab or joint**. To normalize this count, the number of observed corner cracks is divided by four in the equation's numerator, ensuring that a fully cracked slab (with cracks in all four corners) equates to a value of **100%**.

Table 5-6 Equations to convert new distress units to percentage.

New PD Title (New PD Code)	Equation	No.
Transverse Crack (801, 901)	$TC\ (\%) = \frac{TC\ (ft)}{Lane\ width\ (ft)\ *\ \frac{Length\ of\ section\ (ft)}{TC\ spacing\ (ft)}} \times 100$	[T.1]
Longitudinal Wheelpath Crack (802, 902)	$LWC\ (\%) = \frac{LWC(ft)}{2 * Length\ of\ section\ (ft)} \times 100$	[T.2]
Longitudinal Center Crack (803, 903)	$LCC\ (\%) = \frac{Distress\ length\ (ft)}{Length\ of\ section\ (ft)} \times 100$	[T.3]
Transverse Joint Spalling (805)	$TJ(\%\ ) = \frac{TJ(count)}{\frac{Length\ of\ section\ (miles) \times 5280}{joint\ spacing\ (ft)}} \times 100$	[T.4]
Longitudinal Edge Crack (904) and Longitudinal Joint Spalling (804)	$Distress\ (\%) = \frac{Distress\ length\ (ft)}{2 * Length\ of\ section\ (ft)} \times 100$	[T.5]
Raveling + Potholes (906), Flushing/Bleeding (907), Patching (908, 807), Delaminated Area (806), Punchout (809)	$Distress\ (\%) = \frac{Distress\ area\ (ft^2)}{Lane\ width\ (ft)\ *\ Length\ of\ section\ (ft)} \times 100$	[T.6]
Corner Crack (808)	$CC(\%\ ) = \frac{CC(count)/4}{\frac{Length\ of\ section\ (miles) \times 5280}{joint\ spacing\ (ft)}} \times 100$	[T.7]

5.1.3 Conversion of historical PD/AD data to distress units required for PDS calculation

MDOTs PMS includes comprehensive data collected since 1992. Different distresses are denoted with different PD codes, and their severity is defined by associated distress in the surrounding area. Generally, transverse cracks and transverse spalling are reported as the number of occurrences in the MDOT PMS database, whereas all other distress reported in length and the units are in miles. However, for the calculation of the new PDS, the DI-based distresses and severity levels are required to be converted to percentages. To facilitate the raw data extraction and convert them to the required unit, an algorithm was written in MATLAB. MDOT provided the raw distress data in comma delimited Excel files. The MATLAB code processes each excel file corresponding to a given survey year (e.g., 1992 through 2019). Data extraction is conducted by this code for each pavement section and all distress available in that particular year.

The main MATLAB code involves several functions named by the individual distress type. Each function generally begins with defining a list of current and historical PD codes related to that particular distress type. Then from the project location lists provided by MDOT (2081 sections for flexible and 741 sections for rigid) considered in this study, each unique pavement section is filtered based on the project-specific control section (CS), traffic direction (DIR), beginning mile post (BMP), ending mile post (EMP) and PD codes. Next, the filtered PMS records related to the previously assigned PD codes are further filtered based on their severity levels or Associated Distress (AD) matrix outlined in the MDOT distress survey manual. In the MDOT PMS database, Associated Distress (AD1) and Associated Distress (AD2) are reported as two separate columns 'ROW' and 'COL.

In the next step, for each severity level, the considered distress type is extracted for each 0.1-mile interval from the 'LENGTHORCOUNT' column of the raw distress spreadsheet as a length in miles or the number of counts. If the PD code is 501 (the code for no distress), distress measurement is set as 0 for those filtered rows. Then to calculate the percentage of considered distress for each 0.1-mile interval, specific equations (see next subsections) are utilized based on the distress type. In case multiple zones or wheel paths, such as left and right wheel path crack, are involved in collecting a distress type within a unique 0.1-mile segment, the calculated percent distress is combined and divided by two. However, if distresses (PD codes) exist in only one zone for a unique 0.1-mile interval, all the calculated percent distresses are summed.

Then, calculated distress (%) for all unique 0.1-mile intervals are summed for the entire section length for sections listed in the project location lists. Before calculating the average distress (%) for the whole given section, some adjustments are made. MDOT measured distresses for 2012 through 2017 data were performed on a sample basis (about 29.41% of any 0.1-mile segment of each control section). Therefore, a 0.2941 division factor was used to expand distress quantities to any total mileage of interest for those years of measured PMS data. Next, for the considered section length, the average value of the distress at each severity level is calculated. The computed average distress at the specified severity level is subsequently used in the Pavement Distress Score (PDS) calculation for the given section.

Similarly, the process mentioned above is repeated for other applicable severity levels to calculate the corresponding average and standard deviation. Then the algorithm continues with the next distress type and calculates average and standard deviation values. After processing all pavement sections listed for the first survey year or PMS excel file, the code moves on to the next survey year. It does the process for all those pavement sections and continues until it finishes the latest available survey year.

The data extraction for other distress types follows the same process utilizing the specific MATLAB function for that distress type. The next subsections describe the PD codes considered for each distress type and the related AD matrix to define severity levels when applicable. Also, mathematical formulas for calculating each distress type are provided, along with any necessary assumptions.

5.1.4 Flexible Pavement Distress PD Codes and Assumed Severity Levels

5.1.4.1 Transverse Crack

In MDOT's PMS database, a transverse crack is reported as a count. For a typical 0.1-mile segment, transverse crack is converted to percent using Equation 5.3.

$$Transverse\ crack(\%) = \frac{Transverse\ crack\ (count)}{\frac{Length\ of\ section\ (miles) \times 5280\ (\text{ft/mile})}{TC\ spacing\ (ft)}} \times 100 \qquad 5.3$$

Typical thermal crack spacing in asphalt pavements ranges from 10 to 12 feet, based on an FHWA report (Baladi et al 2017)(Baladi et al. 2017). In the formula used, the measured count of transverse cracks (TC) is divided by the maximum possible number of cracks that could occur over the section length, given an assumed spacing. The denominator of the equation: *Length of section (miles) × 5280 (ft/mile) ÷ TC spacing (ft)* represents the maximum number of cracks that could theoretically occur if the cracks were spaced uniformly at the assumed distance (in this case, 10 feet). We selected a 10-foot spacing because it yields the highest possible number of cracks per mile—essentially representing a maximum crack condition. This approach provides a conservative estimate and standardizes the conversion of count data to percentage values.

PDs considered in transverse crack data extraction are 101, 103, 104, 110, 114, 701, 703, 704, and 501. However, PD codes 101, 114, and 701 (i.e., transverse tear) are considered only for low severity levels, as shown in Table 5-7. It was assumed that four transverse tears are equivalent to one regular transverse crack. In the MDOT Distress Survey Manual (dated 06/20/2018 and shared with the team), a transverse tear is defined as: "*A Transverse Tear is a transverse-oriented short crack (4 inches to ½ of lane width) that appears in any location across the survey lane.*" Assuming a standard lane width of 12 feet, half the lane would be 6 feet (or 72 inches). Therefore, the length range for a transverse tear is approximately 4 inches to 72 inches, with an average length of (4+72)/2 = 38 inches = 3.17 ft. A full transverse crack is typically assumed to span the entire 12-foot lane width. Dividing the full width by the average tear length: 12 / 3.17 = ~ 4. Thus, four transverse tears are considered roughly equivalent to one full-width transverse crack, based on the average size of the tears.

Table 5-7 Assumed severity definitions of HMA transverse crack.

Distress [PD Codes]	Severity	Severity Definition from PMS
Transverse Crack [101,103,104,110,114,701,703,704]	Low	AD Matrix: (0,0), (1,1), (2,1), (3,1), (4,1), (5,2), (5,3), (5,4), (6,2), (6,3)
Transverse Crack [103,104,110,703,704]	Medium	AD Matrix: (0,0), (6,4), (7,2), (7,3), (7,4)
Transverse Crack [103,104,110,703,704]	High	AD Matrix: (0,0), (8,2), (8,3), (8,4)

5.1.4.2 Longitudinal Wheelpath Crack (Zones 2 and 4)

Longitudinal wheelpath crack that exists in the two-wheel paths (Zones 2 and 4) is called longitudinal wheelpath crack. It is measured as length in MDOT's database. For a typical 0.1-mile segment, longitudinal wheel path crack was converted to percent using Equation 5.4.

$$Longintudinal\ WP\ Crack\ (\%) = \frac{\sum Longitudinal\ WP\ cracking\ length\ (miles)}{2 \times Length\ of\ segment\ (miles)} \times 100 \quad 5.4$$

In Figure 5-3, two hypothetical LC crack scenarios are shown for better explanation of the longitudinal wheelpath crack calculation. Figure 5-3(a) shows only ‘zone 2’ is 100% cracked, that results in overall 50% longitudinal wheelpath crack for the specified 0.1-mile interval. If the two wheelpaths are 100% cracked, then the overall longitudinal wheelpath crack will be calculated as 100% as shown in Figure 5-3(b). Also, it is noted that if two parallel LC cracks exist within a same zone, then using Equation 5.4 may yield crack percentage more than 100%.

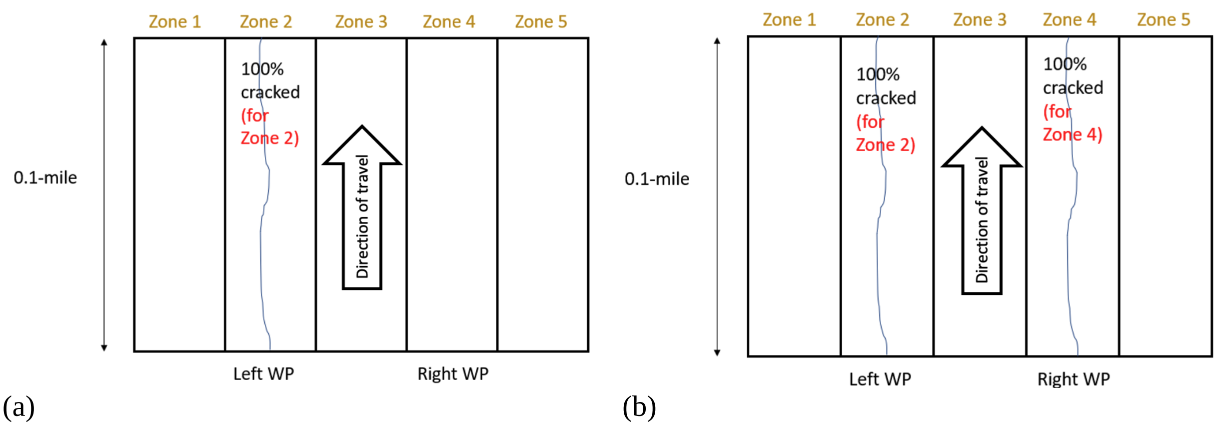


Figure 5-3 Longitudinal wheelpath crack scenarios (a) 50% cracked and (b) 100% cracked for a 0.1-mile interval segment.

PDs considered in longitudinal crack data extraction are 202, 204, 205, 218, 722, 724, 725, and 501. In addition, Alligator Crack is analyzed separately (same way as longitudinal crack) and added as a high severity longitudinal crack. Table 5-8 shows the severity assumptions based on the AD matrix.

Table 5-8 Assumed severity definitions of HMA longitudinal wheelpath crack.

Distress [PD Codes]	Severity	Severity Definition from PMS
Longitudinal Crack [204,205,724,725]	Low	AD Matrix: (0,0), (1,0), (2,0), (3,0), (4,0), (5,0)
Longitudinal Crack [204,205,724,725]	Medium	AD Matrix: (0,0), (6,0)
Longitudinal Crack [204,205,724,725] + Alligator Crack [210, 220, 221, 222, 224, 234, 235, 730, 731]	High	AD Matrix for Longitudinal Crack: (0,0), (7,0) + AD Matrix for Alligator Crack: (0,0), (1,0), (2,0), (3,0), (1,2), (1,3), (1,4), (1,5), (2,2), (2,3), (2,4), (2,5)

5.1.4.3 Longitudinal Center Lane Crack (Zone 3)

Longitudinal center lane crack that exists between the two-wheel paths (i.e., zone 3 as shown in Figure 5-3) is called longitudinal center lane (CL) crack. It is measured as length in MDOT's database. For a typical 0.1-mile segment, longitudinal center lane crack is converted to percent using Equation 5.4.

$$Longintudinal\ CL\ Crack\ (\%) = \frac{\sum Longitudinal\ CL\ crack\ length\ (miles)}{Length\ of\ segment\ (miles)} \times 100 \qquad 5.5$$

Two example crack scenarios for longitudinal center lane crack are shown in Figure 5-4; where Figure 5-4(b) depicts when longitudinal center lane crack may exceed 100% crack.

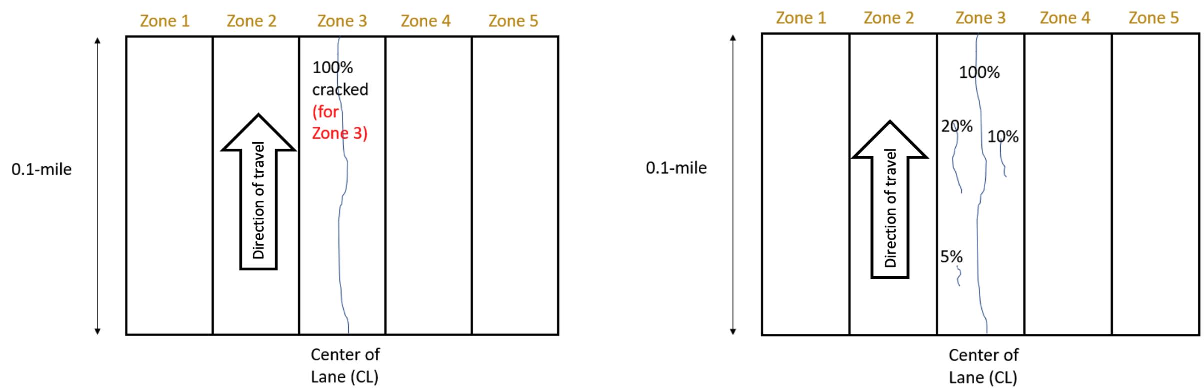


Figure 5-4 Longitudinal center lane crack scenarios (a) 100% cracked and (b) 135% cracked for a 0.1-mile interval segment.

PDs considered in longitudinal crack data extraction are 202, 204, 205, 218, 722, 724, 725, and 501. Table 5-8 shows the severity assumption based on the AD matrix.

Table 5-9 Assumed severity definitions of HMA longitudinal center lane crack

Distress [PD Codes]	Severity	Severity Definition from PMS
Longitudinal Center Lane Crack [202, 218,722]	Low	AD Matrix: (0,0), (1,0), (2,0), (3,0), (4,0), (5,0)
Longitudinal Center Lane Crack [202, 218,722]	Medium	AD Matrix: (0,0), (6,0)
Longitudinal Center Lane Crack [202, 218,722]	High	AD Matrix: (0,0), (7,0)

5.1.4.4 Longitudinal Edge Crack (Zones 1 and 5)

Left and right edge longitudinal crack are considered longitudinal edge crack, measured as length in MDOT's database. For a typical 0.1-mile segment, longitudinal edge crack is converted to percent using Equation 5.6.

$$Longintudinal\ Edge\ Crack\ (\%) = \frac{\sum Longitudinal\ edge\ crack\ length\ (miles)}{2 \times Length\ of\ segment\ (miles)} \times 100 \qquad 5.6$$

Two example crack scenarios for longitudinal edge crack are shown in Figure 5-5.

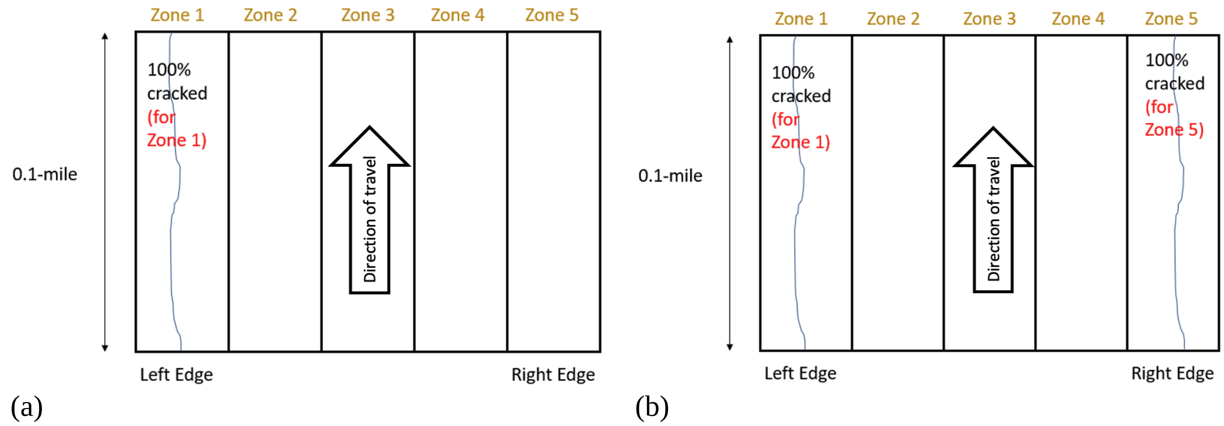


Figure 5-5 Longitudinal edge crack scenarios (a) 50% cracked and (b) 100% cracked for a 0.1-mile interval segment.

PDs considered in longitudinal edge crack data extraction are 201, 203, 236, 237, 721, and 723. Table 5-10 shows the severity assumption based on the AD matrix.

Table 5-10 Assumed severity definitions of HMA longitudinal edge crack

Distress [PD Codes]	Severity	Severity Definition from PMS
Edge Crack [201,203,236,237,721,723]	Low	For PD codes 201, 203, 721, and 723, AD matrix – (0,0), (1,0), (2,0), (3,0), (4,0), (5,0); For PD codes 236 and 237, AD matrix – (1,0)
	Medium	For PD codes 201, 203, 721, and 723, AD matrix – (6,0); For PD codes 236 and 237, AD matrix – (2,0)
	High	For PD codes 201, 203, 721, and 723, AD matrix – (7,0); For PD codes 236 and 237, AD matrix – (3,0)

5.1.4.5 Block Crack

In MDOT's PMS database, block crack is reported as length. For a typical 0.1-mile segment, block crack is converted to percent using Equation 5.7.

$$Block\ Crack\ (\%) = \frac{Block\ crack\ length\ (miles)}{Length\ of\ segment\ (miles)} \times 100 \qquad 5.7$$

The currently available MDOT survey manual represents block crack with PD code 345 only, and it does not have any other AD matrix. Before the 2000 survey period, PD codes 310 and 760 were used to represent block crack and those involved in the AD matrix shown in Table 5-11. Particularly, PD code 310 involves all ten different combinations.

Table 5-11 Assumed severity definitions of HMA block crack

Distress [PD Codes]	Severity	Severity Definition from PMS
Block Crack [310, 345, 760]	N/A	AD Matrix: (0,0), (1,0), (2,0), (3,0), (4,0), (5,0), (6,0), (7,0), (8,0), (9,0), (10,0)

5.1.4.6 Raveling

In MDOT's PMS database, raveling is reported as length. For a typical 0.1-mile segment, raveling is converted to percent using Equation 5.8.

$$Raveling\ (\%) = \frac{Raveling\ length\ (miles)}{Length\ of\ segment\ (miles)} \times 100 \qquad 5.8$$

In raveling data extraction, PD code 405 are used. As raveling has no severity level, the AD matrix (0,0) is only called.

5.1.4.7 Bleeding

In MDOT's PMS database, bleeding is reported as length. For a typical 0.1-mile segment, bleeding is converted to percent using Equation 5.9.

$$Bleeding\ (\%) = \frac{Bleeding\ length\ (miles)}{Length\ of\ segment\ (miles)} \times 100 \qquad 5.9$$

In bleeding data extraction, PD code 406 is used. As bleeding has no severity level, the AD matrix (0,0) is only called.

5.1.4.8 Patching

In MDOT's PMS database, patching is reported as length. For a typical 0.1-mile segment, patching is converted to percent using the following equation:

$$Patching\ (\%) = \frac{Patching\ length\ (miles)}{Length\ of\ segment\ (miles)} \times 100 \qquad 5.10$$

In patching data extraction, PD codes 326 and 327 were used. All severity levels in patching were aggregated into a single average.

5.1.5 Rigid Pavement Distress PD Codes and Assumed Severity Levels

5.1.5.1 Transverse crack

Transverse crack is measured in the PMS database as a count, and is converted to percent crack using Equation 5.11. It is noted that the denominator of this equation corresponds to the maximum *number of transverse cracks* in a given section length = *(Length of section (miles)×5280 (ft/mile))/(transverse crack spacing (ft))*. Since typically one transverse crack happens at the center of one slab (halfway between two joints). Therefore, the distance between two transverse cracks in two consecutive slabs is the same as joint spacing, transverse crack spacing is assumed to be 15 ft, which is a typical joint spacing for concrete. The PD codes and severity levels for transverse crack are summarized in Table 5-12

$$Transverse\ Crack(\%) = \frac{Transverse\ crack\ (count)}{\left(\frac{Length\ of\ section\ (miles) \times 5280\ (\text{ft/mile})}{transverse\ crack\ spacing\ (ft)}\right)} \times 100 \qquad 5.11$$

Table 5-12 PD Codes and Severity Levels for Transverse Crack

Distresses [PD codes]	Severity	Severity Definition from PMS
Transverse crack [102,105,107,712,713,112,113]	Low	AD matrix: (0,0), (1,1), (2,1), (3,1), (4,1), (5,2), (5,3), (5,4), (5,5), (6,2), (7,2), (8,2)
Transverse crack [102,105,107,712,713,112,113]	Medium	AD matrix: (0,0), (6,3), (6,4), (6,5), (7,3), (8,3)
Transverse crack [102,105,107,712,713,112,113]	High	AD matrix: (0,0), (7,4), (7,5), (8,4), (8,5)

5.1.5.2 Longitudinal Wheelpath Crack (Zones 2 and 4)

Longitudinal wheelpath crack that exists in the two-wheel paths is called longitudinal wheelpath (WP) crack. This is converted to percent using Equation 5.12. The PD codes and severity levels for longitudinal crack are summarized in Table 5-13.

$$Logitudinal\ Wheelpath\ Crack(\%) = \frac{\sum Logitudinal\ WP\ crack\ (length)}{2\ \times\ Length\ of\ section\ (miles)} \times 100 \qquad 5.12$$

5.1.5.3 Longitudinal Center Lane Crack (Zone 3)

Rigid longitudinal center lane (CL) crack is converted to percent using Equation 5.13. The PD codes and severity levels for longitudinal crack are summarized in Table 5-14.

$$Logitudinal\ CL\ Crack(\%) = \frac{\sum Logitudinal\ CL\ crack\ (length)}{Length\ of\ section\ (miles)} \times 100 \qquad 5.13$$

Table 5-13 PD codes and severity levels for rigid longitudinal wheel path crack

Distresses [PD codes]	Severity	Severity Definition from PMS
Longitudinal Wheel path Crack [206,207,212,213,214,215,227,229,230,232,737, 739, 740, 742]	Low	AD matrix: (0,0), (1,0), (2,0), (3,0), (4,0), and (5,0)
Longitudinal Wheel path Crack [206,207,212,213,214,215,227,229,230,232,737,	Medium	AD matrix: (0,0) and (6,0)

Distresses [PD codes]	Severity	Severity Definition from PMS
739, 740, 742]		
Longitudinal Wheel path Crack [206,207,212,213,214,215,227,229,230,232,737, 739, 740, 742]	High	AD matrix: (0,0) and (7,0)

Table 5-14 PD codes and severity levels for rigid longitudinal center lane crack

Distresses [PD codes]	Severity	Severity Definition from PMS
Longitudinal center lane crack [219,228,231,738,741]	Low	AD matrix: (0,0), (1,0), (2,0), (3,0), (4,0), and (5,0)
Longitudinal center lane crack [219,228,231,738,741]	Medium	AD matrix: (0,0) and (6,0)
Longitudinal center lane crack [219,228,231,738,741]	High	AD matrix: (0,0) and (7,0)

5.1.5.4 Longitudinal Joint Spalling (Zones 1 and 5)

Longitudinal joint spalling is measured in the PMS database as length. This is converted to percent using Equation 5.14.

$$Logitudinal\ Joint\ Spalling\ (\%) = \frac{Logitudinal\ joint\ spall\ length\ (miles)}{2 * Length\ of\ section\ (miles)} \times 100 \qquad 5.14$$

Two example scenarios for longitudinal joint spalling are shown in Figure 5-6.

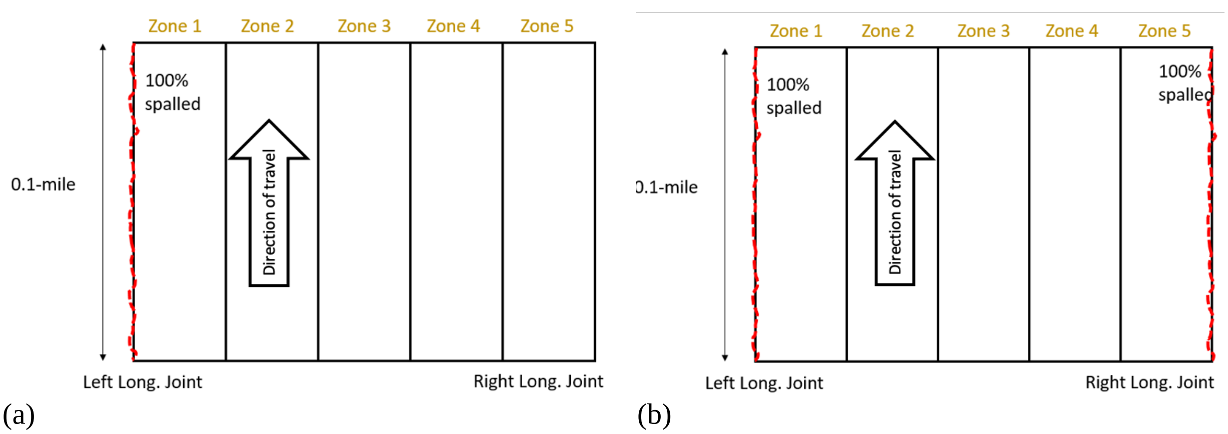


Figure 5-6 Longitudinal joint spalling scenarios (a) 50% spalled and (b) 100% spalled for a 0.1-mile interval segment

The PD codes and severity levels for longitudinal joint spalling are summarized in Table 5-15

Table 5-15 PD codes and severity levels for rigid longitudinal joints

Distresses [PD codes]	Severity	Severity Definition from PMS
Longitudinal joint spalling [208,209]	Low	AD matrix: (0,0) and (2,0)
Longitudinal joint spalling [208,209]	Medium	AD matrix: (0,0) and (3,0)
Longitudinal joint spalling [208,209]	High	AD matrix: (0,0) and (4,0)

5.1.5.5 Transverse Joint Spalling

Transverse joint spalling is measured in the PMS database as a count. This is converted to percent using Equation 5.15. It is noted that the denominator of this equation corresponds to the maximum *number of joints* in a given section length = *(Length of section (miles)×5280 (ft/mile))/(joint spacing (ft))*. The joint spacing has been assumed as 15 ft as no data is available. The PD codes and severity levels for transverse joint spalling are summarized in Table 5-16.

$$Transverse\ Joint\ Spalling(\%\ ) = \frac{Transverse\ joint\ spall(count)}{\left(\frac{Length\ of\ section\ (miles) \times 5280\ \text{(ft/mile)}}{joint\ spacing\ (ft)}\right)} \times 100 \qquad 5.15$$

Table 5-16 PD codes and severity levels for rigid transverse joints

Distresses [PD codes]	Severity	Severity Definition from PMS
Transverse joint spalling [106,706]	Low	AD matrix: (0,0), (2,2), (2,3), (2,4), (2,5)
Transverse joint spalling [106,706]	Medium	AD matrix: (0,0), (3,2), (3,3), (3,4), (4,2), (5,2)
Transverse joint spalling [106,706]	High	AD matrix: (0,0), (3,5), (4,3), (4,4), (4,5), (5,3), (5,4), (5,5)

5.1.5.6 Delamination

Delamination is measured in the PMS database as length. Delamination is converted to percent slabs using the equation below. The PD codes and severity levels for delamination are summarized in Table 5-17.

$$Delamination\ (\%) = \frac{Delamination\ (miles)}{Length\ of\ section\ (miles)} \times 100 \qquad 5.16$$

Table 5-17 PD Codes and severity levels for delamination

Distresses [PD codes]	Severity	Severity Definition from PMS
Delamination [301,751,341]	NA	AD matrix: All combinations

5.1.5.7 Patching

In MDOT’s PMS database, patching is reported as length. For a typical 0.1-mile segment, patching is converted to percent using the following equation:

$$Patching\ (\%) = \frac{Patching\ length\ (miles)}{Length\ of\ segment\ (miles)} \times 100 \qquad 5.17$$

In patching data extraction, PD codes 326 and 327 were used. All severity levels in patching were aggregated into a single average.

5.1.6 Methodology for optimization of distress weight factors used in PDS formula

This section includes description of the optimization of PDS weight factors. The optimization initially aimed to link the PDS values to past decisions of fix-types made by MDOT. However, this resulted in unrealistic PDS values for rigid pavements, and modifications were made to the coefficients so that resulting PDS values align with the engineering judgement of regional MDOT engineers who know the roads and their conditions well. More details are provided in the later parts of this section.

5.1.6.1 Optimization Based on Maintenance Records

The initial approach was to design a linear programming problem to investigate changes to the relative distress-severity weights. Once set as a linear programming problem, a gradient descent-based optimization algorithm was used in the objective function investigate the PDS's sensitivity to MDOT pavement conditions and fix types. MDOT fix-type selection guidelines note that the DI can be used as an initial screening tool for fix-type selection. Therefore, the analysis was setup to compare varying weights on the differences in the PDS among pavements that received different maintenance actions. The goal of this optimization effort is to maximize the difference among the maintenance, rehabilitation and reconstruction actions.

First, the weight factors (w_i) for each distress severity level were expressed in terms of cumulative coefficients called Z-factors ($\boldsymbol{Z}_i$), as shown in Table 5-18. This formulation ensures that medium severity weights are greater than low (e.g., w2>w1), and high severity weights are greater than medium (e.g., w3>w2). The algorithm varies Z-factors ($\boldsymbol{Z}_i$) during the optimization such that they are greater than zero and calculates the (w_i) values at the end of the optimization.

Table 5-18 Mapping of flexible pavement distress severity types to weight factors and z-factor construction.

Distress Name	Severity	Weight factor (w_i)	Z factor
Longitudinal Wheelpath Crack	Low	w1	w1 = Z1
	Medium	w2	w2 = Z1 + Z2
	High	w3	w3 = Z1 + Z2 + Z3
Longitudinal Center Crack	Low	w4	w4 = Z4
	Medium	w5	w5 = Z4 + Z5
	High	w6	w6 = Z4 + Z5 + Z6
Transverse Crack	Low	w7	w7 = Z7
	Medium	w8	w8 = Z7 + Z8
	High	w9	w9 = Z7 + Z8 + Z9
Longitudinal Edge Crack	Low	w10	w10 = Z10

Distress Name	Severity	Weight factor *(w_i)*	Z factor
	Medium	w11	w11 = Z10 + Z11
	High	w12	w12 = Z10 + Z11 + Z12
Block Crack	-	w13	w13 = Z13
Raveling	-	w14	w14 = Z14
Bleeding	-	w15	w15 = Z15

Table 5-19 Mapping of rigid pavement distress severity types to weight factors and z-factor construction.

Distress Type	Severity	Weight factor (w_i)	Z factor
Transverse Crack	Low	w1	w1 = Z1
	Medium	w2	w2 = Z1 + Z2
	High	w3	w3 = Z1 + Z2 + Z3
Longitudinal Wheelpath Crack	Low	w4	w4 = Z4
	Medium	w5	w5 = Z4 + Z5
	High	w6	w6 = Z4 + Z5 + Z6
Longitudinal Center Crack	Low	w7	w7 = Z7
	Medium	w8	w8 = Z7 + Z8
	High	w9	w9 = Z7 + Z8 + Z9
Longitudinal Joint Spalling	Low	w10	w10 = Z10
	Medium	w11	w11 = Z10 + Z11
	High	w12	w12 = Z10 + Z11 + Z12
Transverse Joint Spalling	Low	w13	w13 = Z13
	Medium	w14	w14 = Z13 + Z14
	High	w15	w15 = Z13 + Z14 + Z15
Delamination	-	w16	w16
Patching	-	w17	w17

Next, a three-dimensional matrix $\mathbf{X}_{ijk}$ was defined to organize the distress severity data used for PDS calculation (see Figure 5-7). Each element $\mathbf{X}_{ijk}$ stores the average distress-severity value of distress type *i*, measured on pavement section *j*, right before it received maintenance fix type *k*. This structure allows the optimization algorithm to evaluate how different combinations of weighted distress inputs correlate with MDOT's historical maintenance decisions.

In matrix $\mathbf{X}_{ijk}$ illustrated in Figure 5-7:

- *i* = 1 … 15 represents the **distress-severity types** (e.g., corresponding to the 15 weight factors for flexible pavements shown in **Table 5-18**).
- *j* = 1 … 2081 represents indexes for the **pavement sections** (there were 2081 flexible pavement sections)
- *k* = 1 … 11 represents the **fix type categories** (e.g., there are 11 fix types for flexible pavements as shown in Table 5-20)

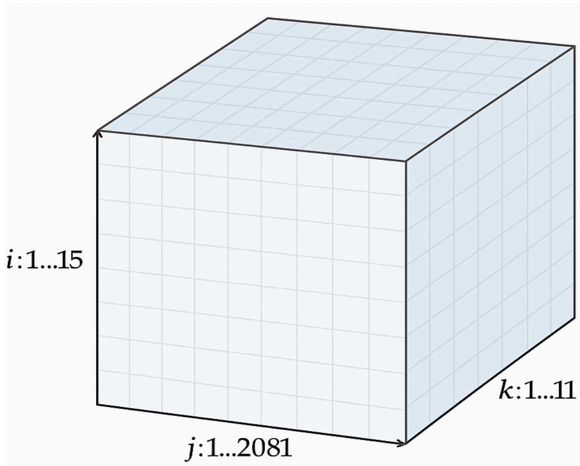


Figure 5-7 Structure of matrix X_{ijk} used in PDS optimization

Table 5-20 Fix type categories and their assigned index k

k	Flexible Pavement Fix Type Category	Rigid Pavement Fix Type Category
1	Crack treatment (e.g., crack filling)	Diamond grinding and joint sealant
2	Single microsurfacing	Concrete pavement repair (CPR)
3	Overband crack filling	AMZ
4	Ultrathin overlay	Added HMA
5	Single layer chip seal	Reconstruction
6	Double course microsurfacing	–
7	Double course chip seal	–
8	Added HMA	–
9	Cold mill and overlay (any depth)	–
10	Crush and shape	–
11	Reconstruction	–

Using each weight factor (w_i) and the corresponding distress values ($\mathbf{X}_{ijk}$), the PDS is calculated for each pavement section j and each fix type k, resulting in a table $\boldsymbol{PDS}_j^k$. A snapshot of the PDS table for k=1 (Crack Treatment) is shown in Figure 5-8. The PDS value in the 8th column of this figure represents the condition of each pavement section **prior** to the application of Crack Treatment by MDOT. Similar PDS tables were generated for all other fix types and used in the optimization process. It is important to note that the number of rows (i.e., pavement sections) in each of these PDS tables varies, as not every section received every type of fix. Therefore, each fix type category includes only the pavement segments that actually underwent that specific treatment.

	1 CS	2 BMP	3 EMP	4 Year_DI	5 DI	6 Year_Maint	7 Maintenance	8 PDS
1	69013	0	12.6160	1999	3.9790	2000	'CT'	84.1753
2	69013	0	12.6160	2009	7.5820	2012	'CT'	82.1100
3	69013	0	12.6500	1999	5.5210	2000	'CT'	79.3493
4	69013	0	12.6500	2011	13.2190	2012	'CT'	59.1412
5	18033	8.1970	12.8540	2009	64.5540	2010	'CT'	12.1303
6	18033	8.1970	12.8540	2011	35.6130	2012	'CT'	30.7868
7	18033	8.2250	12.8910	2009	22.8170	2010	'CT'	68.4521
8	18033	8.2250	12.8910	2011	6.8310	2012	'CT'	88.4388
9	18034	8.0500	12.1720	2007	4.4830	2008	'CT'	91.1864
10	18034	8.0500	12.1720	2011	20.5920	2012	'CT'	47.5154
11	18034	8.0500	12.1720	2015	4.8960	2016	'CT'	94.0550

Figure 5-8 A snapshot of the PDS table for k = 1 (Crack treatment)

Next, objective functions were defined for flexible and rigid pavements, as shown in Equation 5.18 and Equation 5.19, respectively.

$$\min \boldsymbol{z}_{\boldsymbol{flexible}} = \frac{\sum_{j=1}^{n}(k_j - \bar{k})\left(median(PDS_j^k) - \overline{\boldsymbol{PDS}_j^k}\right)}{\sum_{j=1}^{n}(k_j - \bar{k})^2} + \frac{PDS_{crack\ treatment}^{90th\ percentile}}{5} - \frac{PDS_{crush\&shape}^{10th\ percentile}}{10} \quad 5.18$$

$$\min \boldsymbol{z}_{\boldsymbol{rigid}} = \frac{\sum_{j=1}^{n}(k_j - \bar{k})\left(median(PDS_j^k) - \overline{PDS_j^k}\right)}{\sum_{j=1}^{n}(k_j - \bar{k})^2} + \frac{PDS_{DG\ and\ JS}^{90th\ percentile}}{5} - \frac{PDS_{reconstruction}^{10th\ percentile}}{10} \quad 5.19$$

where *PDS* is calculated using each weight factor (w_i) and distress values ($\mathbf{X}_{ijk}$), k_j is the fix type category, which was assigned numerically with the crack treatment group being assigned a value of one up to reconstruction, which was assigned the value of 11 for flexible pavement and 5 for rigid pavement. This numerical assignment was done so that a line could be fit using the median PDS value for each fix type as the y-variable and the assignment as the x-variable; the slope of that line is an indication of the magnitude of differences in the PDS between the categories. Note that the choice of numerical assignments to group categories can significantly affect the results of optimization in two ways. First, if unequal spacing of the numerical assignments are selected for each maintenance type (e.g., if double chip seal is assigned a 7 and added HMA is assigned a value of 30), the results will be biased towards those categories that are assigned a higher numerical value. Secondly, the fix type should be ordered based on their expected PDS at the time of the specific maintenance activities. This project assumed (and recommends) equal spacing between numerical values assigned to the fix types. The $\bar{k}$ is the average group value ((k = 11)/2 = 5.5 for flexible and (k=5)/2 = 2.5 for rigid pavements). The objective function seeks to maximize the disparity between the median PDS value for each *k* fix type category. More specifically, the objective function for flexible pavement was set to maximize the 90th percentile PDS value for crack sealing (i.e., noting that crack sealing should occur at high PDS values) and minimizing the 10th percentile PDS value for crush and shape (i.e., noting that crush and shape should occur when the PDS value is low). Many different variables were investigated, such as maximizing the median value of single microsurfacing while minimizing the median value of reconstruction, and the chosen objective function minimized the variability of the boxplots while maximizing the difference in median values. The denominator on the last two terms of equations

5.18 and 5.19 brings the range of values for each term to nearly equivalent values so that one term in the optimization does not dominate. Similarly, the objective function for rigid pavement was set to minimize the 90th percentile PDS value for diamond grinding and joint sealing and minimizing the 10th percentile PDS value for rigid reconstruction. The PDS values at reconstruction were used in the analysis of rigid pavements, they were not used for HMA because crush and shape was much more sensitive to changes in the weight factors.

A boxplot showing the PDS for the different maintenance categories using the original Minnesota weights is shown in Figure 5-9 and Figure 5-10, for flexible and rigid pavements, respectively. In all of these boxplots, the box represents the 25th to 75th percentile, with the whiskers covering approximately the 99th percentile, the asterisks the individual data points that are considered outliers.

After optimization, similar boxplots were generated using the revised weights and they are shown in Figure 5-11 and Figure 5-12, respectively, for flexible and rigid pavements. The original and revised weights are shown in Table 5-21 and Table 5-22, for flexible and rigid pavements, respectively. Please note that the patching for HMA was not originally included in the analysis (per early discussions with MDOT), that is why its coefficient is zero. However, later discussions on patching in rigid pavements lead to inclusion of patching in rigid pavements, that is why it has a coefficient in rigid table. For consistency, patching was put back to the list of distresses in HMA and its coefficient will be decided in the future. Since Corner Crack and Punchouts were not collected by MDOT in the past, their coefficients could not be determined.

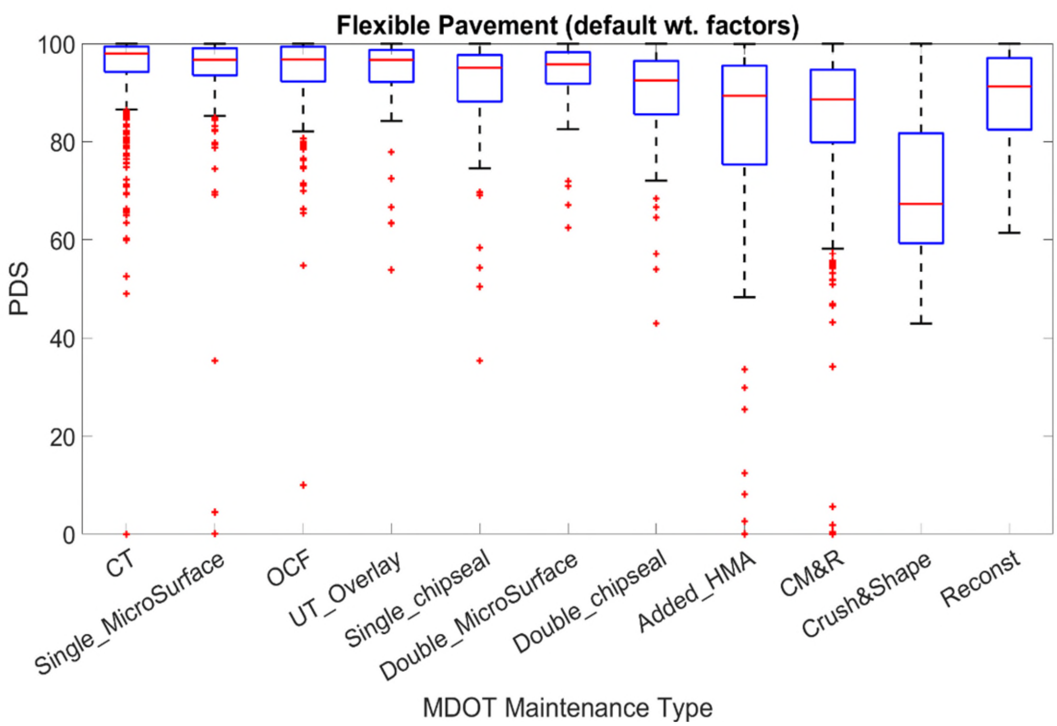


Figure 5-9 PDS boxplot with Minnesota flexible pavement weights

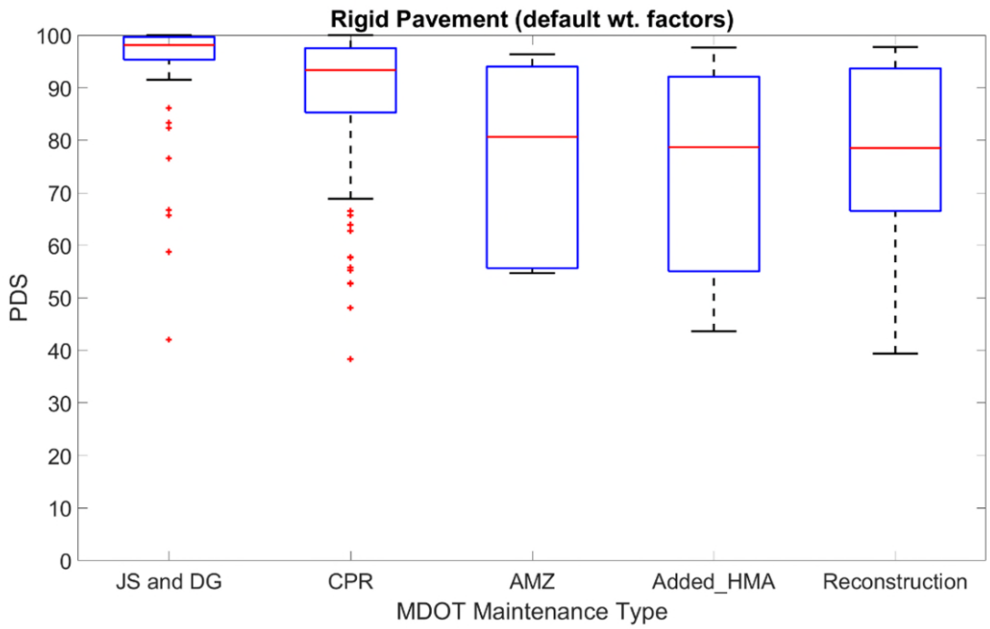


Figure 5-10 PDS boxplot with Minnesota's rigid pavement weights

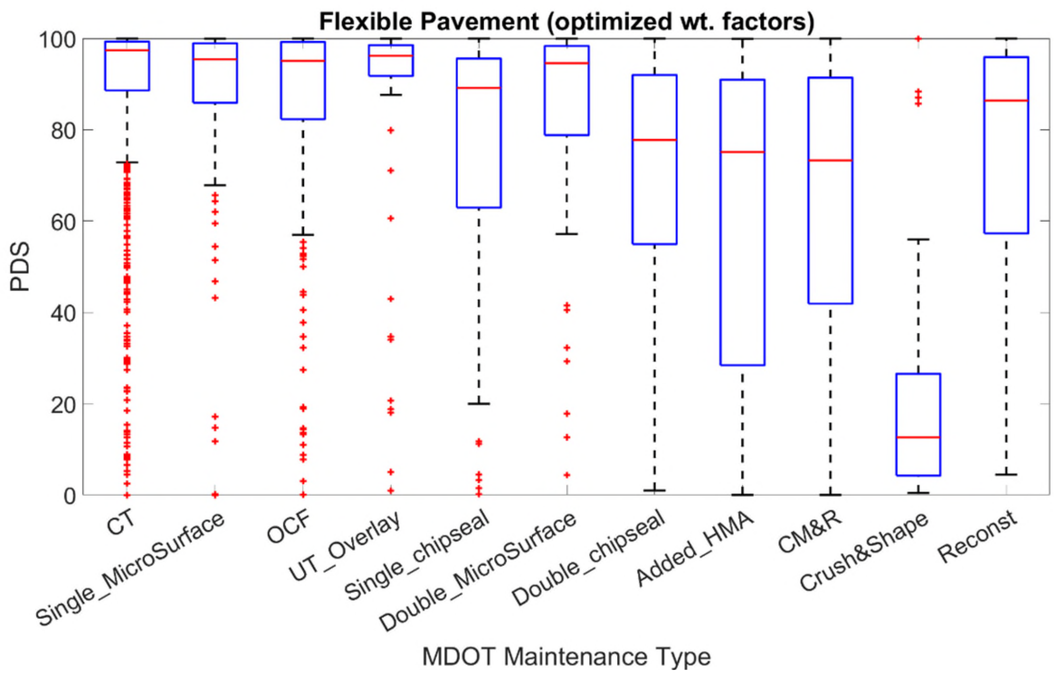


Figure 5-11 PDS boxplot with revised flexible pavement weights

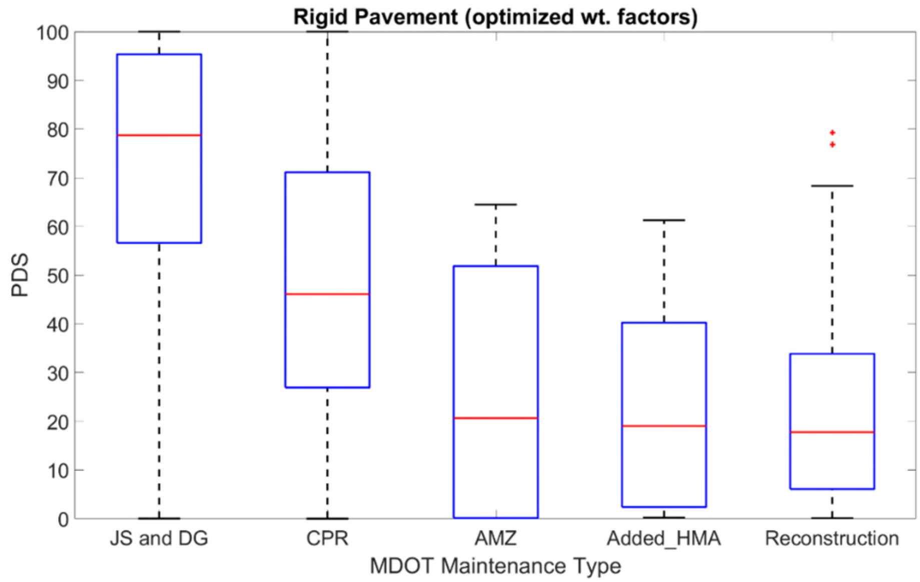


Figure 5-12 PDS boxplot with revised rigid pavement weights

Table 5-21 Flexible pavement Minnesota and revised distress weight factors

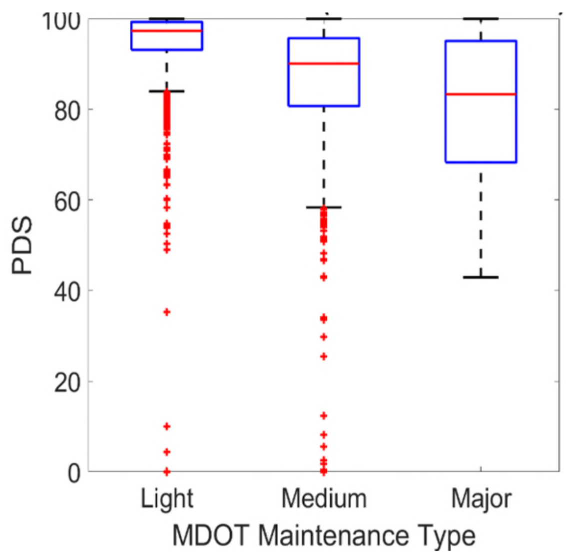
Distress Type	Severity	Minnesota Factor (w_i)	Revised Factor (w_i)
Transverse Crack	Low	0.01	0.017
	Medium	0.1	0.028
	High	0.2	0.884
Longitudinal Wheelpath Crack	Low	0.02	0.011
	Medium	0.03	0.218
	High	0.04	0.831
Longitudinal Center Crack	Low	0.02	0.0088
	Medium	0.03	0.1744
	High	0.04	0.6648
Longitudinal Edge Crack	Low	0.02	0.011
	Medium	0.03	0.031
	High	0.04	0.084
Block Crack	-	0.15	0.943
Raveling	-	0.02	0.490
Bleeding	-	0.01	0.012

Table 5-22 Rigid pavement Minnesota and revised distress weight factors

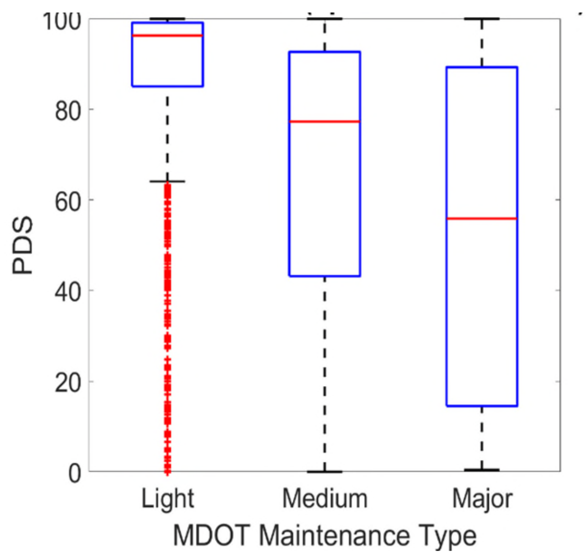
Distress Type	Severity	Minnesota Factor (w_i)	Revised Factor (w_i) (not final)
Transverse Crack	Low	0.01	0.263
	Medium	0.10	0.291
	High	0.20	0.363
Longitudinal Wheelpath Crack	Low	0.02	0.118
	Medium	0.03	0.316
	High	0.04	0.613
Longitudinal Center Crack	Low	0.02	0.094

Distress Type	Severity	Minnesota Factor (w_i)	Revised Factor (w_i) (not final)
	Medium	0.03	0.252
	High	0.04	0.490
Longitudinal Joint Spalling	Low	0.10	0.314
	Medium	0.15	0.419
	High	0.20	0.923
Transverse Joint Spalling	Low	0.10	0.988
	Medium	0.15	1.976
	High	0.20	2.104
Delamination	-	0.07	0.564
Patching	-	0.14	0.315

To better facilitate the boxplot representation, all fix types can be grouped into three categories: preventive maintenance, rehabilitation and reconstruction fixes for flexible and rigid pavements, respectively. As a result, Figure 5-9 through Figure 5-12 can be re-created as Figure 5-13 and Figure 5-14 respectively, for flexible and rigid pavements.



(a)



(b)

Figure 5-13 Combine boxplot for MDOT's flexible pavement maintenance records (light, medium and major) based on PDS (a) with Minnesota wt. factors and (b) with revised wt. factors

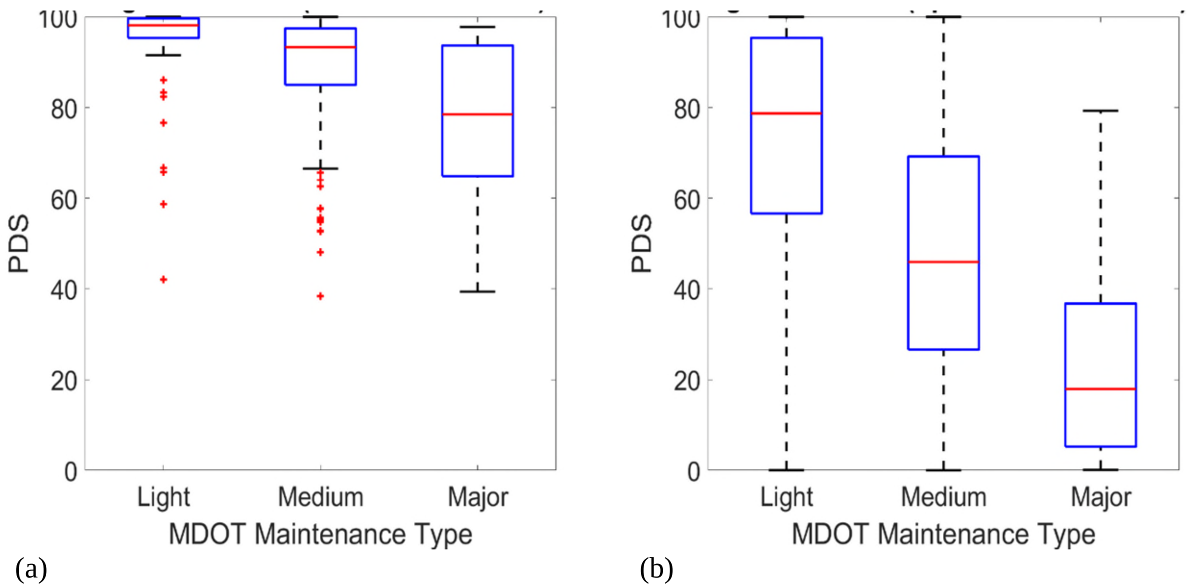


Figure 5-14 Combine boxplot for MDOT's rigid pavement maintenance records (light, medium, and major) based on PDS (a) with Minnesota wt. Factors and (b) with revised wt. factors

5.1.6.2 Evaluation and Finalization of PDS Coefficients

The PDS values based on the calibrated weight factors for both asphalt and rigid pavement were evaluated by MDOT engineers by comparing PDS values with the visual observation of many road segments from seven regions of the MDOT road network. For this, PDS values were calculated based on data in every 0.1-mile and spreadsheets were generated and shared with MDOT engineers. MDOT engineers from different regions reviewed these excel sheets and compared them to the videos of the pavement segments captured at different years. The engineers then made comments on what they think the PDS value should be for various sections. While the opinion of the MDOT engineers showed the PDS values for flexible pavements to be generally reasonable, they noted that the PDS values of rigid pavements were too low. After investigation, it was found that transverse joint spalling had high weights at all three severity levels, and the transverse joint is the most frequently called distress type for rigid pavement in some years. A combination of these two reasons caused the rigid PDS values to be too low. Therefore, another approach of rigid weight factor calibration was adopted so that the rigid PDS values better aligned with the visual observations from MDOT engineers. Transverse joint weight factors were changed so that they are close to the transverse crack weight factors. Also, delamination was given the highest weight following the MDOT engineers' suggestion. After a set of trials, a set of new coefficients were developed, which provided reasonable PDS numbers that matched MDOT comments. These final coefficients are shown in Table 5-23 and Table 5-24.

Table 5-23 Flexible pavement distresses and corresponding weight factors for PDS.

Distress-severity combination (Di)	Distress Type	Severity	Unit	Zone(s)	Weight factor (wi)
D1	Transverse Crack	Low	%	All	0.017

Distress-severity combination (Di)	Distress Type	Severity	Unit	Zone(s)	Weight factor (wi)
D2		Medium	%	All	0.028
D3		High	%	All	0.884
D4	Longitudinal Wheelpath Crack	Low	%	2 and 4	0.011
D5		Medium	%	2 and 4	0.218
D6		High	%	2 and 4	0.831
D7	Longitudinal Center Crack	Low	%	3	0.0088
D8		Medium	%	3	0.1744
D9		High	%	3	0.6648
D10	Longitudinal Edge Crack	Low	%	1 and 5	0.011
D11		Medium	%	1 and 5	0.031
D12		High	%	1 and 5	0.084
D13	Block Crack	-	%	All	0.9434
D14	Raveling+ Potholes	-	%	All	0.4903
D15	Flushing/Bleeding	-	%	All	0.012
D16	Patching	-	%	All	0
Notes: (1) Zones are the five equally spaced regions in each lane, as defined in NCHRP report 1-57A [43] (an example is shown in Figure 5.3). (2) Weight factor for patching is currently zero because of ongoing discussions regarding its inclusion in PDS. A final decision was not made during the project so patching is included in the table and its weight factor can be decided by MDOT in the future.					

Table 5-24 Rigid pavement distresses and corresponding weight factors for PDS.

Distress-severity combination (Di)	Distress Type	Severity	Unit	Zone(s)	Weight factor (wi)
D1	Transverse Crack	Low	%	All	0.0225
D2		Medium	%	All	0.225
D3		High	%	All	0.45
D4	Longitudinal Wheelpath Crack	Low	%	2 and 4	0.045
D5		Medium	%	2 and 4	0.0675
D6		High	%	2 and 4	0.09
D7	Longitudinal Center Crack	Low	%	3	0.036
D8		Medium	%	3	0.054
D9		High	%	3	0.072
D10	Longitudinal Joint Spalling	Low	%	1 and 5	0.225
D11		Medium	%	1 and 5	0.3375
D12		High	%	1 and 5	0.45
D13	Transverse Joint Spalling	Low	%	All	0.0225
D14		Medium	%	All	0.225
D15		High	%	All	0.45
D16	Delamination	-	%	All	0.6
D17	Patching	-	%	All	0.315
D18	Corner Crack	-	%	1 and 5	0
D19	Punchout	-	%	All	0
Notes: (1) Zones are the five equally spaced regions in each lane, as defined in NCHRP report 1-57A [43] (an example is shown in Figure 5.3). (2) Weight factors for corner crack and punchouts are shown					

Distress-severity combination (Di)	Distress Type	Severity	Unit	Zone(s)	Weight factor (wi)
zero because these distresses were not recorded in the past, but they were planned to be included in the future. As shown in the later part of this report, they are indeed included in the Surface Defect Survey (SDS) protocol and their coefficients have been decided and included in the new PDS coefficients for the SDS data.					

5.2 PHASE II EFFORT

Phase II of the project focused on a re-evaluation of both the distress definitions and weighting factors used in the Pavement Distress Score (PDS) calculation. This re-evaluation was prompted by MDOT's adoption of a new distress data collection methodology known as the **Surface Defect Survey (SDS)**. MDOT's implementation of the SDS introduced changes to the types of distresses collected, as well as their formats and measurement protocols, making it necessary to revise the original PDS framework developed in Phase I. As a result, new PDS coefficients were established to align with the SDS-defined distress types. Additionally, the equations previously used to convert raw PD/AD distress measurements into percentage-based values were re-developed to reflect the updated definitions and formats of the SDS data.

Another critical task in Phase II involved ensuring continuity between historical and newly collected data. Since MDOT expressed interest in generating **historical PDS values**, it became necessary to translate legacy PD/AD (Principal Distress / Associated Distress) data into the SDS-equivalent format. This required the development of a mapping strategy to determine which combinations of PD/AD corresponded to each of the newly defined SDS distress categories.

This section describes the work undertaken to implement these changes, including the methodology for redefining distress categories, updating the PDS formula, and performing the historical data conversion to ensure consistency across MDOT's pavement condition records.

5.2.1 Surface Defect Survey (SDS) – Flexible Pavements

Table 5-25 presents the list of flexible pavement distress types relevant to the PDS that are collected by MDOT as part of the Surface Defect Survey (SDS) methodology. (SDS data availability begins with year 2021.) Descriptions of each of these are listed below:

- **LCUS Len Z1–Z5 (Low/Mod/High):** Total length (in feet) of unsealed longitudinal **cracks** in Zones 1 through 5, classified by severity:
  - Low**:** Width < 0.25"
  - Moderate**:** Width between 0.25" and 0.50"
  - High**:** Width > 0.50"
- **LCS Len Z1–Z5:** Total length (in feet) of sealed longitudinal cracks in Zones 1 through 5.

- **TCUSFL Len (Low/Mod/High):** Total length (in feet) of unsealed transverse cracks, classified by severity:
  - Low**:** Width < 0.25"
  - Moderate**:** Width between 0.25" and 0.50"
  - High**:** Width > 0.50"
- **TCSFL Len:** Total length (in feet) of sealed transverse cracking.
- **PH Area:** Total area (in square feet) of all potholes.
- **ALLIG Area Z1–Z5 (Low/Mod/High):** Total area (in square feet) of alligator cracking in Zones 1 through 5, classified by severity:
  - Low severity, Moderate severity, and High severity
- **Rav Area:** Total area (in square feet) of raveling.
- **Bleed Area:** Total area (in square feet) of bleeding.

Table 5-25 Flexible pavement distresses in the Surface Defect Survey and PDS coefficients

SDS Attribute	PDS Coefficient (w_i)	Divider	PDS Coefficient-old (w_{i-old})
LCUS_Len_Z1_Low	0.0055	2	0.011
LCUS_Len_Z1_Mod	0.0155	2	0.031
LCUS_Len_Z1_High	0.042	2	0.084
LCUS_Len_Z2_Low	0.0055	2	0.011
LCUS_Len_Z2_Mod	0.109	2	0.218
LCUS_Len_Z2_High	0.4155	2	0.831
LCUS_Len_Z3_Low	0.0088	1	0.0088
LCUS_Len_Z3_Mod	0.1744	1	0.1744
LCUS_Len_Z3_High	0.6648	1	0.6648
LCUS_Len_Z4_Low	0.0055	2	0.011
LCUS_Len_Z4_Mod	0.109	2	0.218
LCUS_Len_Z4_High	0.4155	2	0.831
LCUS_Len_Z5_Low	0.0055	2	0.011
LCUS_Len_Z5_Mod	0.0155	2	0.031
LCUS_Len_Z5_High	0.042	2	0.084
LCS_Len_Z1	0.00275	4	0.011
LCS_Len_Z2	0.00275	4	0.011
LCS_Len_Z3	0.0044	2	0.0088
LCS_Len_Z4	0.00275	4	0.011
LCS_Len_Z5	0.00275	4	0.011
TCUSFL_Len_Low	0.017	1	0.017
TCUSFL_Len_Mod	0.028	1	0.028
TCUSFL_Len_High	0.884	1	0.884
TCSFL Len	0.0085	2	0.017
Patch Area Conc	0.0	1	0.0
Patch Area Asphalt	0.0	1	0.0
PH_Area	0.4903	1	0.4903
ALLIG_Area_Z1_Low	0.00825	2	0.0165
ALLIG_Area_Z1_Mod	0.02325	2	0.0465
ALLIG_Area_Z1_High	0.063	2	0.126
ALLIG_Area_Z2_Low	0.00825	2	0.0165
ALLIG_Area_Z2_Mod	0.1635	2	0.327
ALLIG_Area_Z2_High	0.62325	2	1.2465
ALLIG_Area_Z3_Low	0.0132	1	0.0132
ALLIG_Area_Z3_Mod	0.2616	1	0.2616
ALLIG_Area_Z3_High	0.9972	1	0.9972
ALLIG_Area_Z4_Low	0.00825	2	0.0165
ALLIG_Area_Z4_Mod	0.1635	2	0.327
ALLIG_Area_Z4_High	0.62325	2	1.2465
ALLIG_Area_Z5_Low	0.00825	2	0.0165
ALLIG_Area_Z5_Mod	0.02325	2	0.0465
ALLIG_Area_Z5_High	0.063	2	0.126
Rav_Area	0.4903	1	0.4903
Bleed_Area	0.012	1	0.012

SDS Attribute	PDS Coefficient (w_i)	Divider	PDS Coefficient-old ($w_{i\text{-}old}$)
Notes: LCUS = Longitudinal Cracks – Unsealed, LCS = Longitudinal Cracks – Sealed, TCUSFL = Transverse Cracks – Unsealed, TCS - Transverse Cracks – Sealed, PH = Potholes, ALLIG = Alligator Cracking, Rav = Raveling, Bleed = Bleeding.			

It should be noted that although the Surface Defect Survey (SDS) includes additional distress measures beyond those listed in Table 5-25, only the distress types relevant to the Pavement Distress Score (PDS) are shown. The excluded items are either duplicate measures reported in different units or values derived by summing other distress types already included in the table. Patching, while now reported more consistently in the SDS dataset, was not included in the current PDS calculation because it was not sufficiently represented in the legacy PD/AD datasets used for model development. However, patching may be considered for inclusion and weighting in future updates to the PDS framework as more consistent data become available.

Table 5-25 also displays the **PDS coefficients** used in the score calculation for each distress type. The column labeled **"PDS Coefficient-old"** refers to the original coefficients established during Phase I of the project. To update these coefficients for use with SDS data, a **"Divider"** value was applied. The updated coefficients are shown in the **"PDS Coefficient"** column and are calculated by dividing the old coefficient by the corresponding Divider value:

$$PDS\ Coefficient = \frac{PDS\ Coefficient - old}{Divider} \qquad 5.20$$

The **Divider** column contains one of three possible values—**1**, **2**, or **4**—each with a specific interpretation:

- **Divider = 1**: The original Phase I coefficient is retained without any change.
- **Divider = 2**: Applied to longitudinal **edge crack** (Zones 1 and 5), **wheelpath crack** (Zones 2 and 4) and **alligator crack** (Zones 1, 2, 4 and 5). In Phase II, the PDS equations were modified so that the lengths of cracks in these paired zones are summed and then averaged (divided by two). To simplify the equations and make them consistent across all zones, the coefficient was halved. This adjustment allows the use of a unified formula for all length-based distresses in all Zones:

$$Distress\ (\%) = \frac{Distress\ length\ (ft)}{Length\ of\ section\ (ft)} \times 100. \qquad 5.21$$

  Divider=2 also applies to **sealed cracks** such as LCS and TCSFL. Since sealed cracks are considered less severe than unsealed cracks, their coefficients are reduced by half.

- **Divider = 4**: Applied when **sealed cracks** are located in Zones 2 or 4 (wheelpath) or Zones 1 and 5 (edge). Because these sealed cracks are also located in zones where lengths are averaged (as explained above), they are divided by two again, resulting in a total divider of 4.

It should be noted that the coefficients for alligator cracking were established by multiplying the corresponding longitudinal cracking coefficients by a factor of 1.5, across all severity levels and zones. This adjustment was made based on extensive discussions and meetings with MDOT engineers, who determined that alligator cracking—being a more advanced and structurally significant form of distress—should carry greater weight in the Pavement Distress Score (PDS) calculation than simple longitudinal cracking. The 1.5 multiplier was selected to reflect this increased severity while maintaining consistency within the overall weighting framework.

5.2.2 Surface Defect Survey (SDS) – Rigid Pavements

Table 5-26 shows the list of rigid pavement distress types relevant to the PDS. Descriptions of each of these are listed below:

- **LCUS Len Z2–Z4 (Low/Mod/High):** Total length (in feet) of unsealed longitudinal cracks in Zones 2 through 4, categorized by width:
    - Low: Width < 0.25"
    - Moderate: Width between 0.25" and 0.50"
    - High: Width > 0.50"
- **LCS Len Z2–Z4:** Total length (in feet) of sealed longitudinal cracks in Zones 2 through 4.
- **TCUSFL Len (Low/Mod/High):** Total length (in feet) of unsealed transverse cracks, categorized by width:
    - Low: Width < 0.25"
    - Moderate: Width between 0.25" and 0.50"
    - High: Width > 0.50"
- **TCSFL Len:** Total length (in feet) of sealed transverse cracking.
- **Patch Area Conc / Patch Area Asphalt:** Total area (in square feet) of concrete or asphalt patching, respectively.
- **PH Area:** Total combined area (in square feet) of all potholes.
- **TJ Cnt (Low/Mod/High):** Number of transverse joints with spall width:
    - Low: < 3"
    - Moderate: 3" – 6"
    - High: > 6"
- **LJ Len Z1 and Z5 (Low/Mod/High):** Total length (in feet) of longitudinal joints in Zones 1 and 5:
    - Low: Spall width < 3"
    - Moderate: Spall width 3" – 6"
    - High: Spall width > 6"

- **CB Cnt (Low/Mod/High):** Number of corner breaks, categorized by LTPP-defined severity (Low, Moderate, or High).
- **Punch Area:** Total combined area (in square feet) of all punchouts.

Table 5-26 Rigid pavement distresses in the Surface Defect Survey and PDS coefficients

SDS Attribute	PDS Coefficient (w_i)	Divider	PDS Coefficient-old ($w_{i\text{-}old}$)
LCUS Len Z2 Low	0.0225	2	0.045
LCUS Len Z2 Mod	0.03375	2	0.0675
LCUS Len Z2 High	0.045	2	0.09
LCUS Len Z3 Low	0.036	1	0.036
LCUS Len Z3 Mod	0.054	1	0.054
LCUS Len Z3 High	0.072	1	0.072
LCUS Len Z4 Low	0.0225	2	0.045
LCUS Len Z4 Mod	0.03375	2	0.0675
LCUS Len Z4 High	0.045	2	0.09
LCS Len Z2	0.01125	4	0.045
LCS Len Z3	0.018	2	0.036
LCS Len Z4	0.01125	4	0.045
TCUSFL Len Low	0.0225	1	0.0225
TCUSFL Len Mod	0.225	1	0.225
TCUSFL Len High	0.45	1	0.45
TCSFL Len	0.01125	2	0.0225
Patch Area Conc	0.315	1	0.315
Patch Area Asphalt	0.315	1	0.315
PH Area	0.6	1	0.6
TJ Cnt Low	0.0225	1	0.0225
TJ Cnt Mod	0.225	1	0.225
TJ Cnt High	0.45	1	0.45
LJ Len Z1 Low	0.1125	2	0.225
LJ Len Z1 Mod	0.16875	2	0.3375
LJ Len Z1 High	0.225	2	0.45
LJ Len Z5 Low	0.1125	2	0.225
LJ Len Z5 Mod	0.16875	2	0.3375
LJ Len Z5 High	0.225	2	0.45
CB Cnt Low	0.15	1	0.15
CB Cnt Mod	0.4	1	0.4
CB Cnt High	0.6	1	0.6
Punch Area	0.6	1	0.6
Notes: LCUS = Longitudinal Cracks – Unsealed, LCS = Longitudinal Cracks – Sealed, TCUSFL = Transverse Cracks – Unsealed, TCS - Transverse Cracks – Sealed, LJ = Longitudinal Joint Spalling			

The description of the **Divider** column in Table 5-26 is the same as the one given in the previous section for flexible pavements.

5.2.3 Conversion of PD/AD data to the equivalent SDS data

As previously noted, MDOT requested the research team to convert historical PD/AD (Principal Distress / Associated Distress) data into an equivalent SDS-compatible format. This conversion was essential for applying the updated PDS coefficients shown in Table 5-25 and Table 5-26 to compute Pavement Distress Scores for years up to 2019, when MDOT's earlier data collection system was still in use.

Table 5-27 and Table 5-28 shows the correspondence between SDS attributes and PD/AD code combinations for **flexible** and **rigid** pavements, respectively. These mappings were used to compute SDS-equivalent distress values in percentage units, enabling direct input into the current PDS formula.

It is noted that the following equations were used to convert the PD/AD data to PDS data:

- For all count-based records (i.e., transverse cracking, transverse joint in concrete):

$$Distress\ (\%) = \frac{Distress\ (count)}{N_{max}} \times 100 \tag{5.22}$$

  where:

$$N_{max} = \frac{Length\ of\ section\ (miles) \times 5280\ (ft/mile)}{Distress\ spacing\ (ft)} \tag{5.23}$$

  Here, N_{max} represents the theoretical maximum number of distresses (e.g., transverse cracks) or number of joints over a given section length, and *Distress Spacing* refers to the assumed typical spacing between distresses. For asphalt pavements, a distress spacing of 10 feet is used for thermal cracking, and for concrete pavements, a spacing of 15 feet is used for transverse joints.

- For all the length-based records, (i.e., longitudinal cracks in all zones, sealed or unsealed, alligator cracks in all zones, raveling, bleeding, patching, longitudinal joint in concrete):

$$Distress\ (\%) = \frac{Distress\ length\ (ft)}{Length\ of\ section\ (ft)} \times 100 \tag{5.24}$$

Table 5-27 Correspondence between SDS attribute and PD/AD combinations for <u>flexible</u> pavements

SDS Attribute (percent)	Principal Distress (PD) Codes	Associated Distresses (AD)
LCUS_Perc_Z1_Low	201, 236, 721	For PDs 201 and 721 = (5,0); For PD 236 = (1,0)
LCUS_Perc_Z1_Mod		For PDs 201 and 721 = (6,0); For PD 236 = (2,0)
LCUS_Perc_Z1_High		For PDs 201 and 721 = (7,0); For PD 236 = (3,0)
LCUS_Perc_Z2_Low	205, 725	(0,0), (5,0)
LCUS_Perc_Z2_Mod		(0,0), (6,0)
LCUS_Perc_Z2_High		(0,0), (7,0)
LCUS_Perc_Z3_Low	202, 218,722	(0,0), (5,0)
LCUS_Perc_Z3_Mod		(0,0), (6,0)
LCUS_Perc_Z3_High		(0,0), (7,0)
LCUS_Perc_Z4_Low	204, 724	(0,0), (5,0)
LCUS_Perc_Z4_Mod		(0,0), (6,0)
LCUS_Perc_Z4_High		(0,0), (7,0)
LCUS_Perc_Z5_Low	203, 237, 723	For PDs 203 and 723 = (5,0); For PD 237 = (1,0)
LCUS_Perc_Z5_Mod		For PDs 203 and 723 = (6,0); For PD 237 = (2,0)
LCUS_Perc_Z5_High		For PDs 203 and 723 = (7,0); For PD 237 = (3,0)
LCS_Perc_Z1	201, 721	For PDs 201 and 721 = (0,0), (1,0), (2,0), (3,0), (4,0)
LCS_Perc_Z2	205, 725	(0,0), (1,0), (2,0), (3,0), (4,0)
LCS_Perc_Z3	202, 218, 722	(0,0), (1,0), (2,0), (3,0), (4,0)
LCS_Perc_Z4	204, 724	(0,0), (1,0), (2,0), (3,0), (4,0)
LCS_Perc_Z5	203, 723	For PDs 203 and 723 = (0,0), (1,0), (2,0), (3,0), (4,0)
TCUSFL_Perc_Low	101, 103, 104, 110, 114, 701, 703, 704	(5,2), (5,3), (5,4), (6,2), (6,3)
TCUSFL_Perc_Mod	103, 104, 110, 703, 704	(0,0), (6,4), (7,2), (7,3), (7,4)
TCUSFL_Perc_High		(0,0), (8,2), (8,3), (8,4)
TCSFL_Perc	101, 103, 104, 110, 114, 701, 703, 704	(0,0), (1,1), (2,1), (3,1), (4,1)
ALLIG_Perc_Z2_High	210, 221, 224, 235, 731	(0,0), (3,0), (1, 5), (2, 4), (2, 5)
ALLIG_Perc_Z2_Low		(0,0), (1,0), (1, 2), (2, 2)
ALLIG_Perc_Z2_Mod		(0,0), (2,0), (1, 3), (1, 4), (2, 3)
ALLIG_Perc_Z4_High	220, 222, 234, 730	(0,0), (3,0), (1, 5), (2, 4), (2, 5)
ALLIG_Perc_Z4_Low		(0,0), (1,0), (1, 2), (2, 2)
ALLIG_Perc_Z4_Mod		(0,0), (2,0), (1, 3), (1, 4), (2, 3)
Rav_Perc	405	(0,0)
Bleed_Perc	406	(0,0)
Patch_Perc_Conc	326	(0, 0), (1, 1), (1, 2), (1, 3), (2, 1), (2, 2), (2, 3), (3, 1), (3, 2), (3, 3), (4, 1), (4, 2), (4, 3), (5, 1), (5, 2), (5, 3)

SDS Attribute (percent)	Principal Distress (PD) Codes	Associated Distresses (AD)
Patch_Perc_Asphalt	327	(0, 0), (1, 1), (1, 2), (1, 3), (2, 1), (2, 2), (2, 3), (3, 1), (3, 2), (3, 3), (4, 1), (4, 2), (4, 3), (5, 1), (5, 2), (5, 3)
Note: Z = Zone		

Table 5-28 Correspondence between SDS attribute and PD/AD combinations for <u>rigid</u> pavements

SDS Attribute (percent)	Principal Distress (PD) Codes	Associated Distresses (AD)
LCUS_Perc_Z2_Low	206, 214, 215, 229, 232, 739, 742	(0,0), (5,0)
LCUS_Perc_Z2_Mod		(0,0), (6,0)
LCUS_Perc_Z2_High		(0,0), (7,0)
LCUS_Perc_Z3_Low	219, 228, 231, 738, 741	(0,0), (5,0)
LCUS_Perc_Z3_Mod		(0,0), (6,0)
LCUS_Perc_Z3_High		(0,0), (7,0)
LCUS_Perc_Z4_Low	207, 212, 213, 227, 230, 737, 740	(0,0), (5,0)
LCUS_Perc_Z4_Mod		(0,0), (6,0)
LCUS_Perc_Z4_High		(0,0), (7,0)
LCS_Perc_Z2	206, 214, 215, 229, 232, 739, 742	(0,0), (1,0), (2,0), (3,0), (4,0)
LCS_Perc_Z3	219, 228, 231, 738, 741	(0,0), (1,0), (2,0), (3,0), (4,0)
LCS_Perc_Z4	207, 212, 213, 227, 230, 737, 740	(0,0), (1,0), (2,0), (3,0), (4,0)
TCUSFL_Perc_Low	102, 105, 107, 712, 713, 112, 113	(0,0), (5,2), (5,3), (5,4), (5,5), (6,2), (7,2), (8,2)
TCUSFL_Perc_Mod		(0,0), (6,3), (6,4), (6,5), (7,3), (8,3)
TCUSFL_Perc_High		(0,0), (7,4), (7,5), (8,4), (8,5)
TCSFL_Perc		(0,0), (1,1), (2,1), (3,1), (4,1)
Patch_Perc_Conc	326	(0, 0), (1, 1), (1, 2), (1, 3), (2, 1), (2, 2), (2, 3), (3, 1), (3, 2), (3, 3), (4, 1), (4, 2), (4, 3), (5, 1), (5, 2), (5, 3)
Patch_Perc_Asphalt	327	(0, 0), (1, 1), (1, 2), (1, 3), (2, 1), (2, 2), (2, 3), (3, 1), (3, 2), (3, 3), (4, 1), (4, 2), (4, 3), (5, 1), (5, 2), (5, 3)
TJ_Perc_Low	106, 706	(0,0), (2,2), (2,3), (2,4), (2,5)
TJ_Perc_Mod		(0,0), (3,2), (3,3), (3,4), (4,2), (5,2)
TJ_Perc_High		(0,0), (3,5), (4,3), (4,4), (4,5), (5,3), (5,4), (5,5)
LJ_Perc_Z1_Low	208	(0,0), (2,0)
LJ_Perc_Z1_Mod		(0,0), (3,0)
LJ_Perc_Z1_High		(0,0), (4,0)
LJ_Perc_Z5_Low	209	(0,0), (2,0)
LJ_Perc_Z5_Mod		(0,0), (3,0)
LJ_Perc_Z5_High		(0,0), (4,0)

SDS Attribute (percent)	Principal Distress (PD) Codes	Associated Distresses (AD)
Note: Z = Zone		

6 TASK 4: PERFORMANCE MODELING FOR PDS

Performance modeling is integral to the PMS (Victoria Felker et al. 2004). Performance models are used for future condition assessment, budget allocation, and work planning for road networks. Therefore, an accurate performance modeling approach is crucial for state DOTs. Due to the high variability of road condition data, typically, state DOTs develop their performance models based on pavement families (Pantuso et al. 2019) at the network level. Pavement families represent pavement sections with similar characteristics such as performance and surface type.

There are two levels of performance curves: site-specific (i.e., project-level) and default (i.e., network-level) curves. Site-specific curves are based on previously observed performance data for pavement sections, considering specific characteristics such as pavement structure, traffic loads, and environmental factors. However, constructing site-specific curves can be challenging due to the lack of consistent data trends and insufficient data. When no previous data is available, state agencies opt for default curves (Abu-Lebdeh et al. 2003). While less accurate than site-specific curves, default curves provide helpful information when specific data are unavailable.

To develop reliable pavement performance models, an adequate collection of distress data, pavement age, traffic count, and other pavement-related structural information is necessary (Peraka and Biligiri 2020). Accurate performance modeling can optimize budget allocation and pavement maintenance strategies using a systematic data collection and analysis approach, ensuring road network operation. This chapter outlines performance modeling for PDS and the fix life estimation method for different MDOT surface types.

6.1 MODELING APPROACH

There are mainly two types of pavement performance modeling: (i) deterministic and (ii) probabilistic. Deterministic models predict a single rating value or when a pavement section will reach its threshold value. Most state agencies prefer this approach because it is easy to interpret and can be easily implemented into a pavement management system (PMS) (Chen and Mastin 2016; Wolters and Zimmerman 2010). Deterministic models help predict pavement conditions and identify areas where maintenance and rehabilitation activities are needed.

On the other hand, probabilistic models predict the probability of a pavement section deteriorating from one level to another. This approach considers the variability of pavement conditions and the uncertainty associated with future deterioration rates.

This study evaluated several deterministic performance models, including logistic growth curve and the Gompertz mode, which were options in MDOT’s existing modeling software. The other three models are the Asymmetric Sigmoid (Rowe et.al 2009), New Jersey DOT model (NJDOT), and North Carolina DOT’s power model (NCDOT). It is important to note that MDOT’s logistic growth curve and Gompertz model, which historically were on a scale starting at 0, were modified such that the new condition score, i.e., PDS, would provide a performance curve on a scale of 100 (perfect condition) to 0 (worst condition).

All models are a function of pavement age (i.e., years since the last major rehabilitation or reconstruction happened). Other models also available in the literature are a function of additional independent variables (e.g., traffic, pavement structural condition, etc.). However, in the MDOT's PMS database, this information is missing or not consistently found. Therefore, models that are a function of only age are considered in this study and are mentioned below.

$$PDS_{Logistic} = 100 - b_1([\frac{(b_1 + b_2)}{b_1 + b_2 e^{-b_3 t}}] - 1) \quad 6.1$$

$$PDS_{Gompertz} = 100 - ((b_1 + b_2)\left(\frac{b_1}{b_1 + b_2}\right)^{exp(-b_3 t)})) - b_1) \quad 6.2$$

where, $PDS_{Logistic}$= PDS calculated based on MDOT's logistic model, $PDS_{Gompertz}$ = PDS calculated based on MDOT's Gompertz model, b_1 = potential initial PDS, b_2 = limiting PDS, t = age in years, and b_3 = deterioration pattern index

$$PDS_{NJDOT} = 100 - e^{(b_1 - b_2 * b_3^{\ln\left(\frac{1}{t}\right)})} \quad 6.3$$

where, PDS_{NJDOT} = PDS calculated based on New Jersey DOT's model, t = age in years, and b_1, b_2, b_3 = model coefficients

$$PDS_{NCDOT} = 100 - (b_1 + b_2 * t^{b_3}) \quad 6.4$$

where, PDS_{NCDOT} = PDS calculated based on North Carolina DOT's model, t = age in years, b_1, b_2, b_3 = model coefficients.

$$PDS_{ASigmoid} = b_1 + \frac{b_2 - b_1}{[1 + b_5 e^{(b_3 + b_4 \cdot t)}]^{1/b_5}} \quad 6.5$$

where, $PDS_{ASigmoid}$= PDS calculated based on the Asymmetric Sigmoid model, t = age in years, and b_1, b_2, b_3, b_4 = model coefficients.

Similar to other state Departments of Transportation (Khattak et al. 2008; Stephanos et al. 2002; Keleman et al. 2005), MDOT categorized its pavements into distinct families to develop performance (family) curves based on different *parent fix* types. The term *parent fix* refers to the specific type of treatment or rehabilitation applied to a pavement section, at which point the pavement's age is reset to zero. After a parent fix, the section is treated as a new pavement, typically assigned same set of identifiers such as Control Section (CS), Beginning Mile Post (BMP), Ending Mile Post (EMP), and Direction (DIR).

The following parent fix types were each modeled separately using Pavement Distress Score (PDS) data:

1. Multi-Course Overlay HMA

2. HMA Reconstruction
3. HMA over Crush & Shape HMA
4. HMA over Rubblized Concrete
5. Concrete Reconstruction
6. Concrete Overlay (Unbonded)
7. HMA over Asphalt Stabilized Crack Relief Layer (ASCRL)
8. Thin Concrete Overlay

6.1.1 MODELING GROUPS OF PAVEMENT SEGMENTS IN MDOT FAMILIES

Pavements are typically classified into three families: Family 1, Family 2, and Family 3, representing good, fair, and poor pavement conditions, respectively. However, MDOT has found it necessary to utilize 4 or 5 families for a few of its fix types. For grouping pavement sections into families, MDOT took their DI values before any major maintenance activity was applied and then grouped different pavement sections based on DI magnitude and similar DI trends. For instance, if a pavement deteriorated early, it was placed in the poor family group or Family 3.

To model the Pavement Distress Score (PDS), individual CSV (Comma-Separated Values) files were initially created for each parent fix type. A list of the input CSV files is shown in Figure 6-1. These files contain section-level data for various pavement family groups, including attributes such as pavement age, and corresponding Old DI and PDS values. All PDS data collected after any type of maintenance activity for a given pavement section were excluded to eliminate their influence on modeling the reduction of PDS over time.

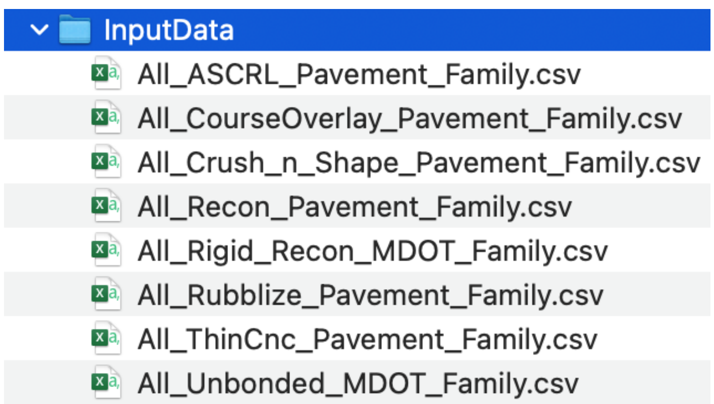


Figure 6-1 A snapshot of a list of CSV files developed for modeling PDS

Figure 6-2 shows a snapshot of an example CSV file (opened in MS Excel) for the parent fix type of HMA crush and shape pavement. It is noted that reported PDS values are on a scale of 100 (perfect condition) to 0 (worst condition).

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	NEW_OLD_ID	Age	DI	FAMILY	REGION	ROUTE	CS	JN	BMP	EMP	DIR	LENGTH	OPENED	PDS
2	1N	13	6.0	1	North	I-75 NB	69013	5789	0	12.616	I	12.616	1980	94.8
3	1N	15	6.8	1	North	I-75 NB	69013	5789	0	12.616	I	12.616	1980	86.9
4	1S	13	2.7	1	North	I-75 SB	69013	5789	0	12.65	D	12.65	1980	99.5
5	1S	15	5.6	1	North	I-75 SB	69013	5789	0	12.65	D	12.65	1980	92.8
6	3S	13	3.4	2	North	I-75 SB	69014	5789	0	0.51	D	0.51	1980	98.7
7	3S	15	15.6	2	North	I-75 SB	69014	5789	0	0.51	D	0.51	1980	82.5
8	5N	8	8.9	2	North	I-75 NB	72061	15887	7.519	13.323	I	5.804	1985	98.0
9	5N	10	9.3	2	North	I-75 NB	72061	15887	7.519	13.323	I	5.804	1985	98.2
10	5N	12	16.3	2	North	I-75 NB	72061	15887	7.519	13.323	I	5.804	1985	97.5
11	5N	14	14.9	2	North	I-75 NB	72061	15887	7.519	13.323	I	5.804	1985	98.1
12	5S	8	3.1	3	North	I-75 SB	72061	15887	7.473	13.32	D	5.847	1985	99.6
13	5S	10	19.4	3	North	I-75 SB	72061	15887	7.473	13.32	D	5.847	1985	80.3

Figure 6-2 An example of the developed database for modeling different pavement family groups. Note: CS = control section, JN = job number, BMP = beginning mile post, EMP = end mile post, OPENED = opened to traffic

The negative binomial (NB) distribution was used in PDS modeling to express the pavement deterioration process. The negative binomial distribution is preferred over other methods because it accounts for the overdispersion present in pavement distress data, which means that the variance of the data is greater than the mean (Pantuso et al. 2019; Katicha et al. 2016; Bryce et al. 2019). The negative binomial (NB) distribution can better capture the variability and heterogeneity of pavement distress data compared to traditional distributions such as the Poisson distribution, which assumes that the variance is equal to the mean. In the NB distribution, the rate of deterioration of pavement segments is represented by a Gamma distribution, which accounts for the variability in their rates. Figure 6-3 clearly shows why negative binomial is the best distribution for network-level PDS data modeling consideration. The example plot is shown for Family 2 of the crush and shape pavement family type.

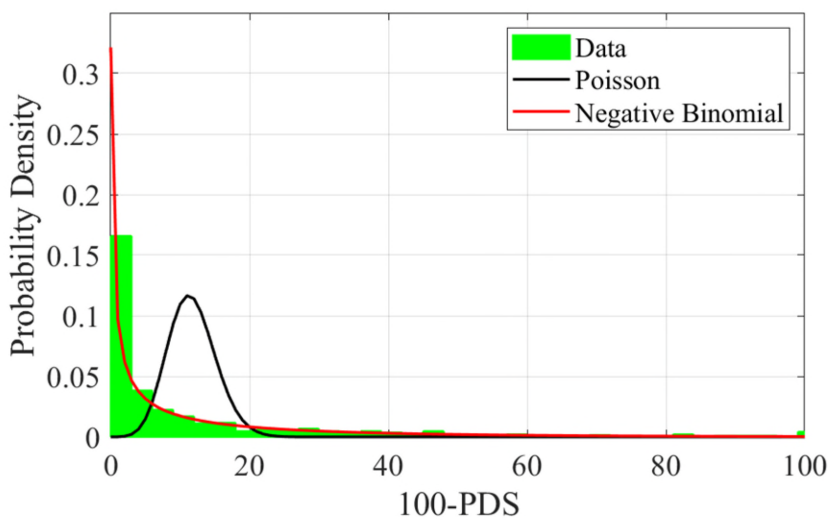


Figure 6-3 PDS data distribution for crush and shape Family 2

Once the distribution of PDS data is determined, the likelihood function is used in the PDS model predictions. The likelihood is a powerful statistical method that can be applied to a wide range of probability distributions, including the NB distribution. It represents the probability that the data fits the model (which should be maximized for the best fit). The log-likelihood, the logarithm of the likelihood, is often used because it simplifies the calculation by converting the product of probabilities into a summation of logarithms. The primary objective is to increase the likelihood of observing the data by adjusting the parameters in the link function, which is defined as 100 minus the performance model. In other words, the goal of getting maximum likelihood is to find the parameters that make the observed data most likely to have been generated by a particular probability distribution, i.e., NB distribution in this study.

The 'find minimum of constrained (fmincon)' optimization function in MATLAB was used to maximize the log-likelihood function. This function utilizes an iterative algorithm based on the interior-point method to find the optimal values of decision variables that minimize the objective function, subject to constraints. The constraints, i.e., the minimum and maximum boundaries of the coefficients of each model are listed in Table 6-1. Initially, an initial set of model coefficients was specified (those listed in Table 6-1), and then the MATLAB fmincon function was used with a range of coefficient boundaries (those listed in Table 6-1) to search for the optimal coefficient set for each pavement family and model. The goal was to find the set of coefficients that provided the maximum likelihood. In addition to the negative binomial, minimum absolute difference of the median values of PDS of a pavement segment at each time (year) was also implemented in the MATLAB algorithm. Once the optimal set of coefficients was obtained, performance model curves were developed for each model and pavement family group.

Table 6-1 Constraints and initial values of the coefficients for each PDS model

Model	Coefficient	Initial	Min	Max
ASigmoid	b1	0	0	0
	b2	100	100	100
	b3	-10	-20	-7
	b4	1	0.5	4
	b5	1	0.5	10
Logistic	b1	0.05	0.001	0.8
	b2	100	100	100
	b3	0.3	0.1	1.5
Gompertz	b1	1	0.1	2
	b2	100	50	110
	b3	0.2	0.001	0.2
NJDOT	b1	4	0	10
	b2	15	0	100
	b3	5	0	20
NCDOT	b1	0	0	0
	b2	1	0.1	2
	b3	1.5	0.5	1.8

6.1.1.1 Asphalt Pavement Modeling (with MDOT Family groups)

Pavement sections, for each parent fix type, were grouped based on good/fair/poor families originally developed by MDOT using the DI. Then, each group, herein called family, was modeled individually using each of the models described above. PDS modeling for pavement type 'HMA over Crush and Shape HMA' is shown in Figure 6-4. To evaluate the goodness-of-fit statistics for all models, two parameters, coefficient of determination (R^2) and root mean square error (RMSE) of the measured and predicted PDS values from different models, are shown in these performance plots. RMSE shows how far measured values are from the regression line. Therefore, it is expected to get a smaller number of RMSE, representing that predicted observations are closer to those measured observations. The RMSE is shown as E (for brevity) in the legends of the figures (for example, see Figure 6-4).

Given the high variability in the measured PDS, in some cases, one performance model may perform better; in other cases, the same performance model may be the worst. Therefore, visual observations and engineering judgment may be necessary when choosing one performance model over others. Similar analyses were performed for HMA Reconstruction (Figure 6-5), Multi-Course Overlay (Figure 6-6), HMA over Rubblized Concrete (Figure 6-7) and HMA over ASCRL (Figure 6-8).

6.1.1.2 Concrete Pavement Modeling (with MDOT Family groups)

The same analysis described in the previous section was performed for concrete pavements using the families originally developed based on DI. The results are shown in Figure 6-9, Figure 6-10 and Figure 6-11 for the surface types 'Concrete Reconstruction' , 'Concrete Overlay (Unbonded)', and ‘Thin Concrete Overlay, respectively. Each of the subfigures shows different models for different families (Family 1, Family 2 ...etc.). As shown, reasonable R^2 and RMSE values are observed for each model.

6.1.1.3 Fix Life Estimation

The term "pavement fix life" refers to the period between when a pavement surface is first constructed or rehabilitated to when it reaches a point where major rehabilitation or reconstruction is the appropriate action. It is important to point out that this is the projected time a fix type is expected to last without maintenance. The length of the pavement fix life depends on several factors, including the initial design and construction quality and the amount and type of traffic using the pavement. To calculate the pavement fix life, MDOT uses a composite curve that combines all the individual family curves described in the previous chapter. The composite curve is generated by calculating the Composite Pavement Distress Score (CPDS) using a weighted average of the total section length of each pavement family.

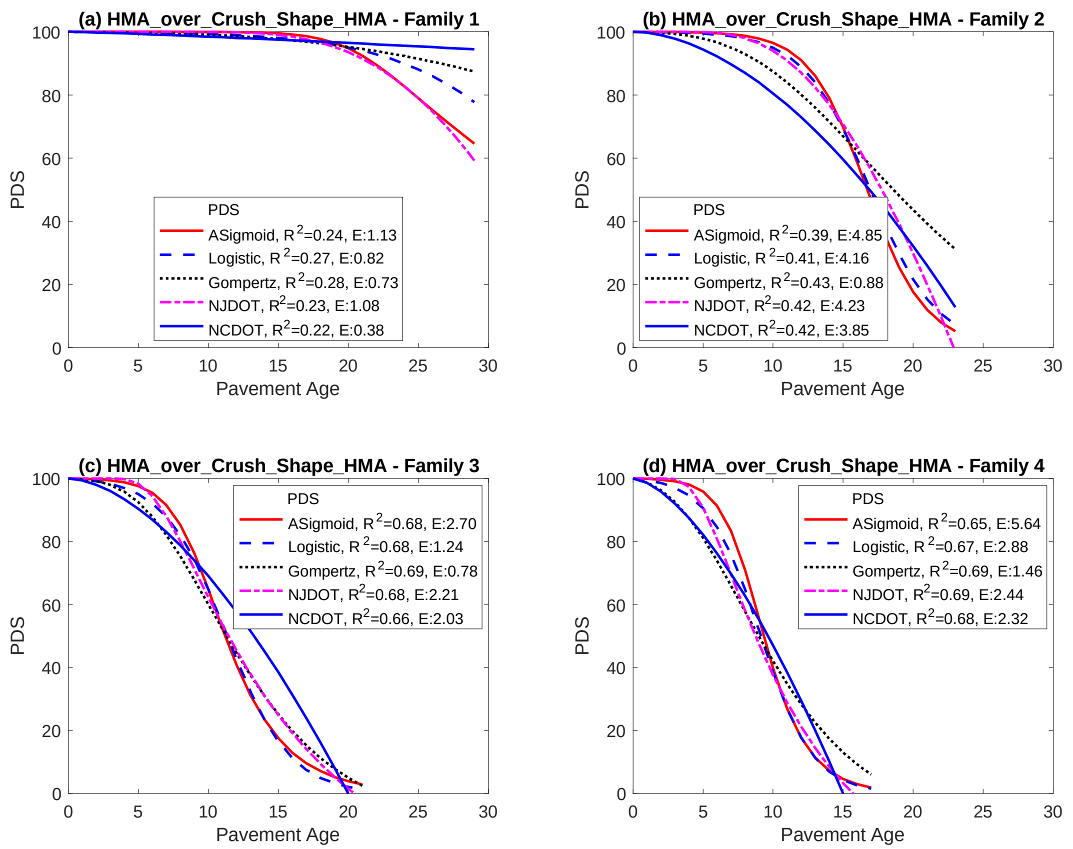


Figure 6-4 PDS modeling based on MDOT families for parent fix type: HMA over Crush and Shape HMA.

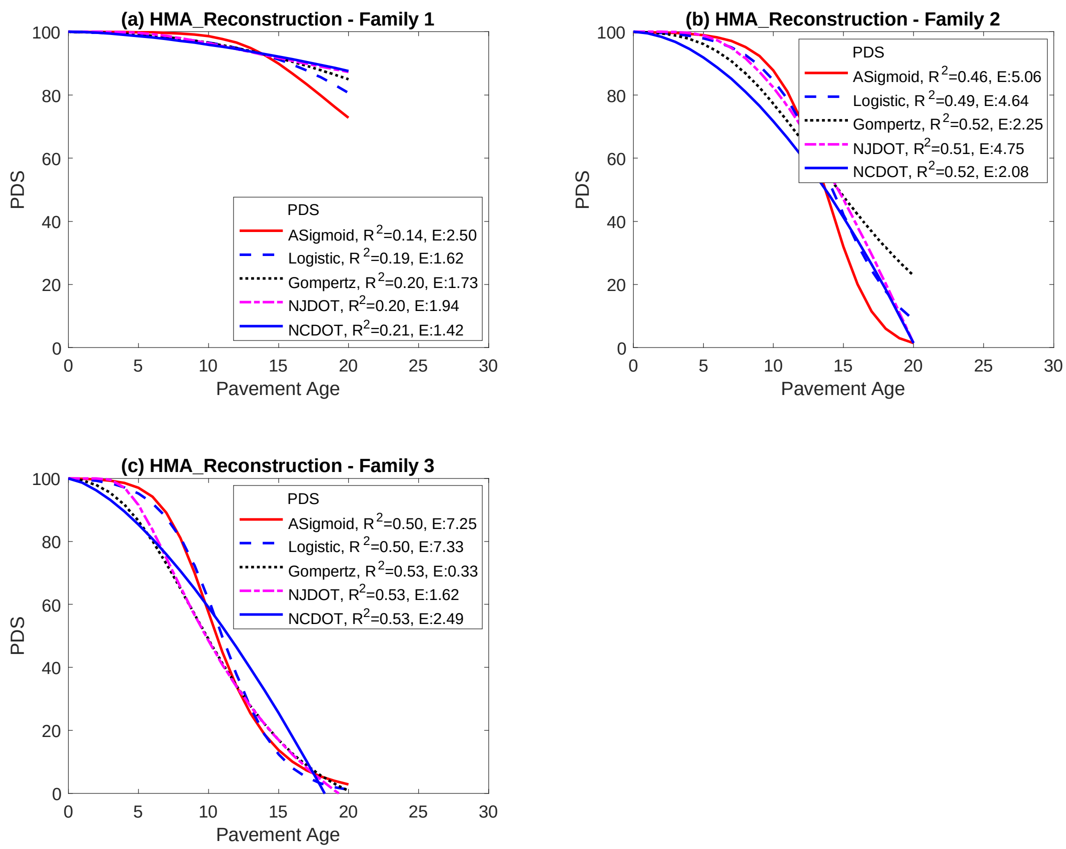


Figure 6-5 PDS modeling based on MDOT families for parent fix type: HMA Reconstruction.

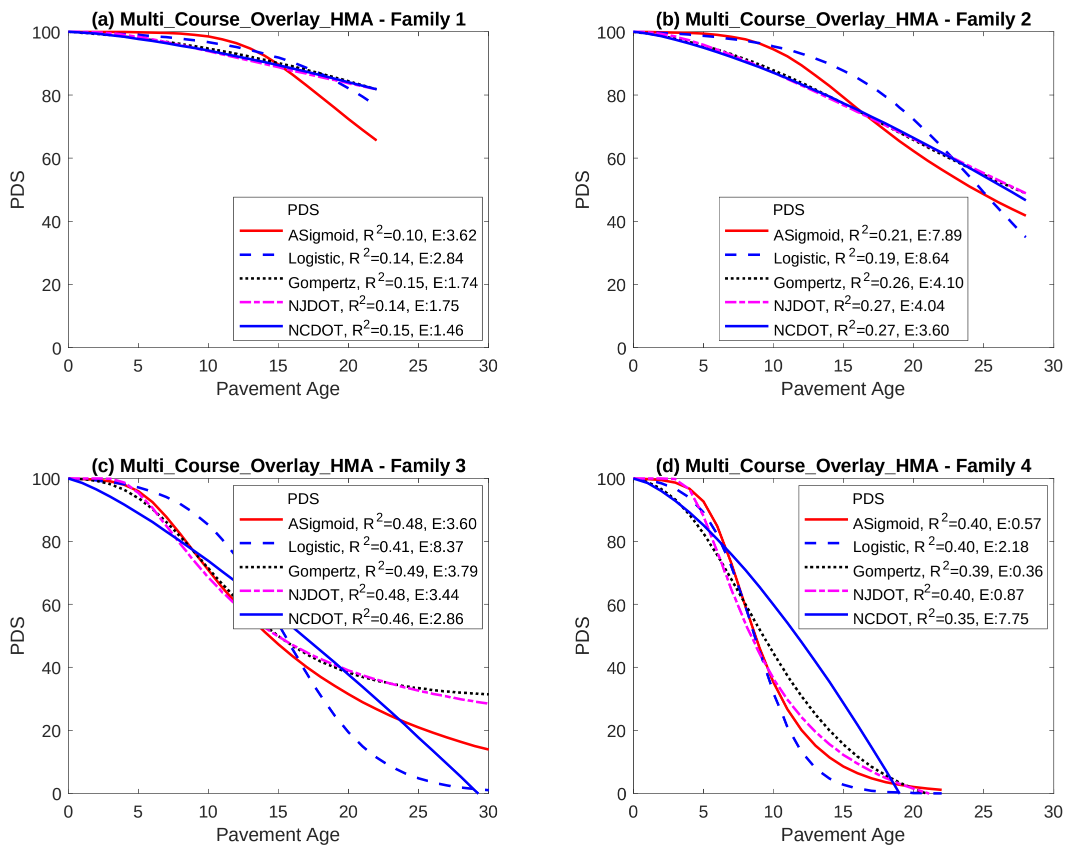


Figure 6-6 PDS modeling based on MDOT families for parent fix type: Multi Course Overlay.

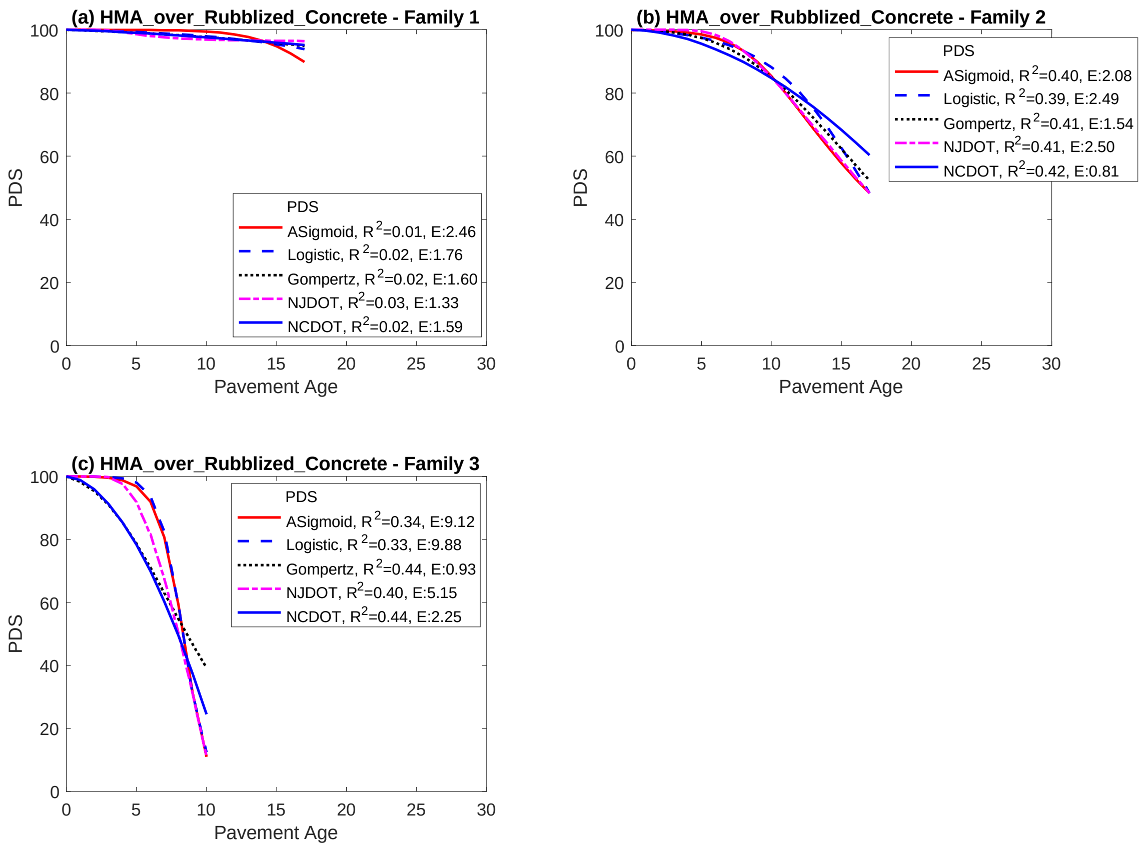


Figure 6-7 PDS modeling based on MDOT families for parent fix type: HMA over Rubblized Concrete.

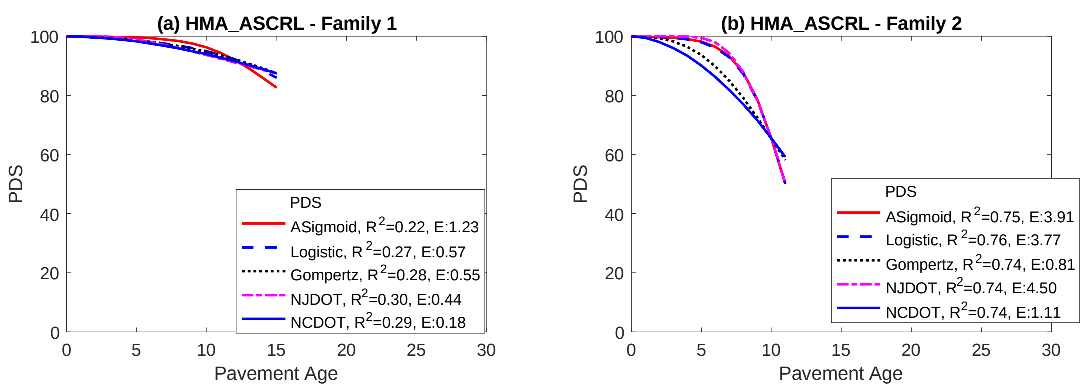


Figure 6-8 PDS modeling based on MDOT families for parent fix type: HMA over Asphalt Stabilized Crack Relief Layer (ASCRL).

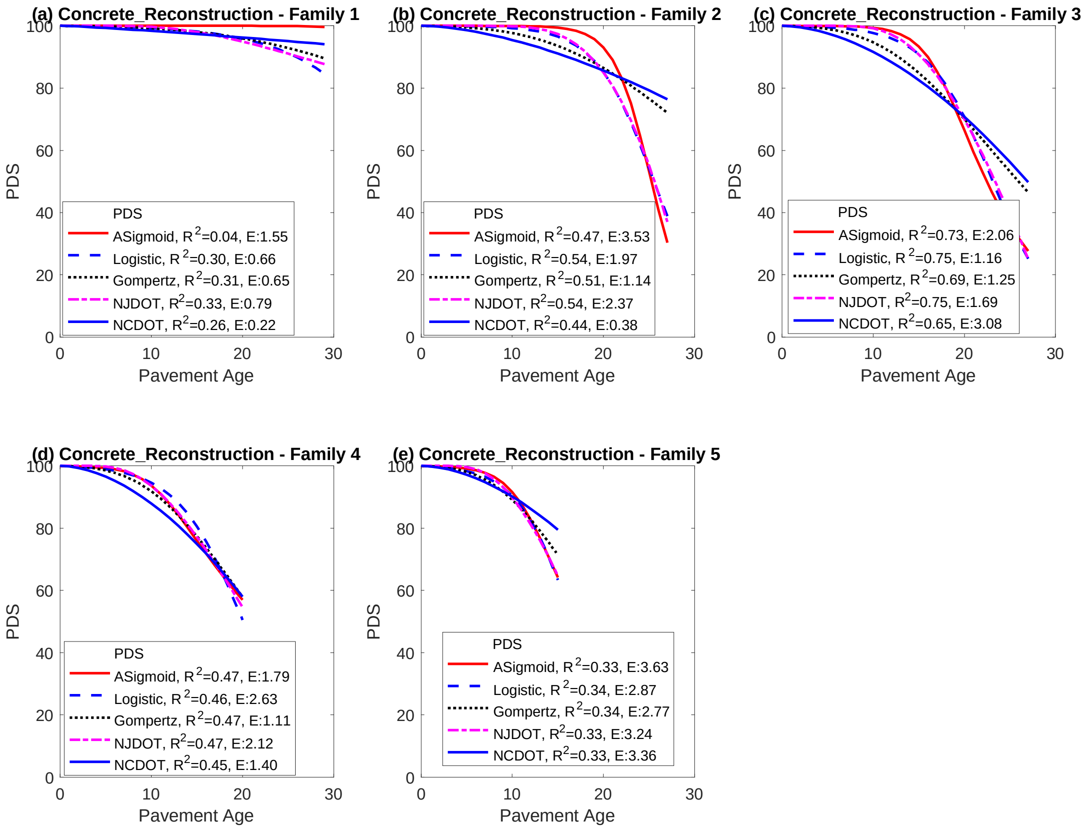


Figure 6-9 PDS modeling based on MDOT families for parent fix type: Concrete Reconstruction

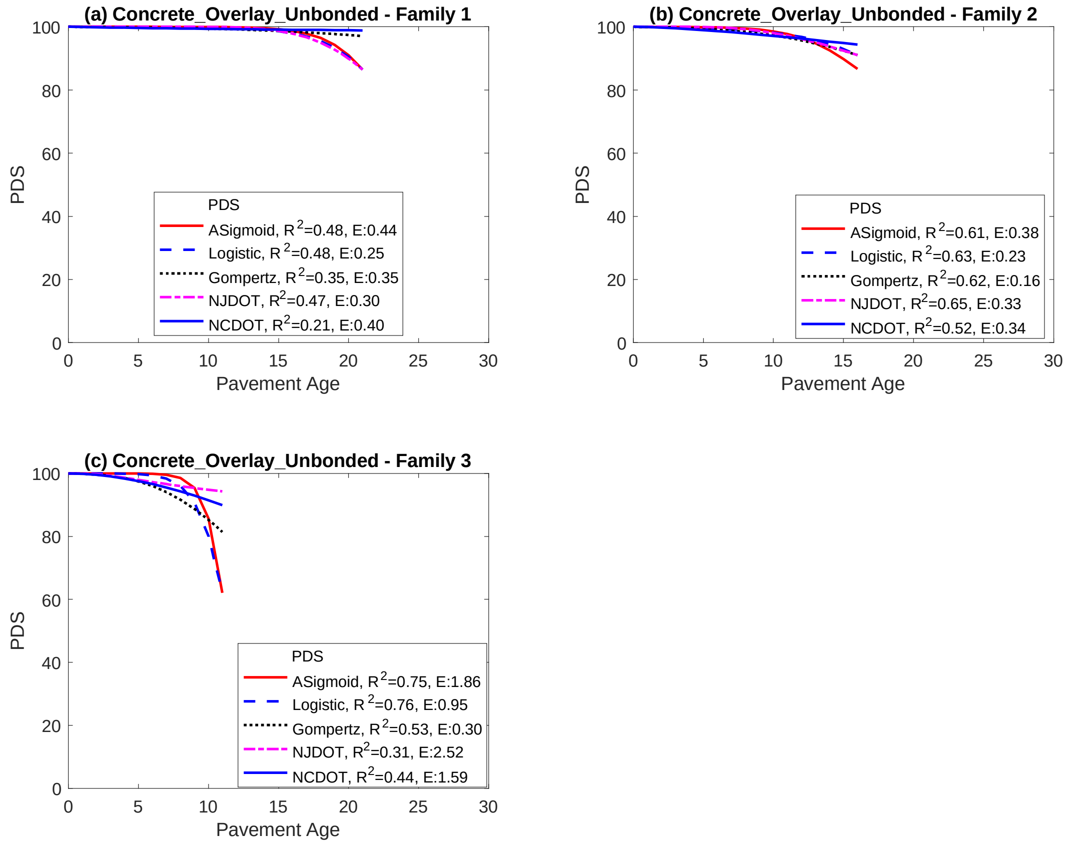


Figure 6-10 PDS modeling based on MDOT families for parent fix type: Concrete Overlay (Unbonded)

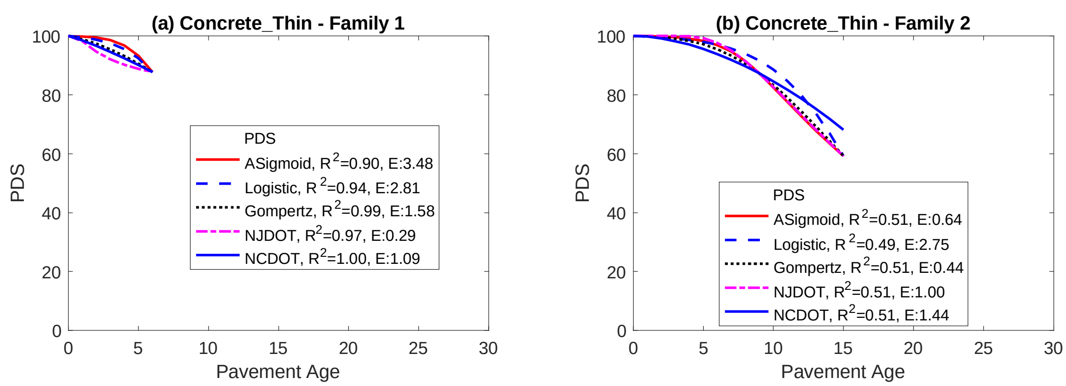


Figure 6-11 PDS modeling based on MDOT families for parent fix type: Thin Concrete Overlay

Once the composite curve reaches a threshold value of 50, the pavement fix life is calculated up to that point since the pavement was first opened to traffic. The CPDS can be mathematically calculated using Equation 6.6.

$$Composite\ PDS = \frac{PDS(age, family_1) \times L_1 \ + \ PDS(age, family_2) \times L_2 + \cdots\cdots + \ PDS(age, family_n) \times L_n}{L_1 \ + \ L_2 + \cdots\cdots + \ L_n} \qquad 6.6$$

where, PDS (age, family) is the PDS for a particular family of distress at a given age, L is the total length of the pavement segments in the corresponding family, and subscripts 1, 2, and … n refer to the number of different families that MDOT follows.

Table 6-2 presents the total pavement section length for each pavement family for all asphalt and rigid pavement surface types. It can be observed that only rigid reconstruction was classified into five families. In most cases, Family 1 (i.e., good condition pavement group) represents the largest length for a particular surface type. As a result, it can be expected that the PDS composite curve will tend to shift towards the Family 1 curve.

Table 6-2 Total section length for the MDOT's DI-based pavement families

Surface type	Family1 (miles)	Family2 (miles)	Family3 (miles)	Family4 (miles)	Family5 (miles)
HMA over Crush & Shape HMA	723	568	252	246	-
HMA Reconstruction	314	199	106	-	-
Multi Course Overlay HMA	578	950	820	419	-
HMA over Rubblized Concrete	222	158	96	-	-
HMA over Asphalt Stabilized Crack Relief Layer (ASCRL)	161	13	-	-	-
Concrete Reconstruction	781	311	112	168	188
Concrete Overlay (Unbonded)	83	154	41	-	-
Thin Concrete Overlay	1.5	8	-	-	-

Figure 6-12 through Figure 6-16 show all family curves alongside composite curves for different surface types and models. Also, fix life for each surface type and model is reported when the PDS composite curve reaches a threshold value of 50.

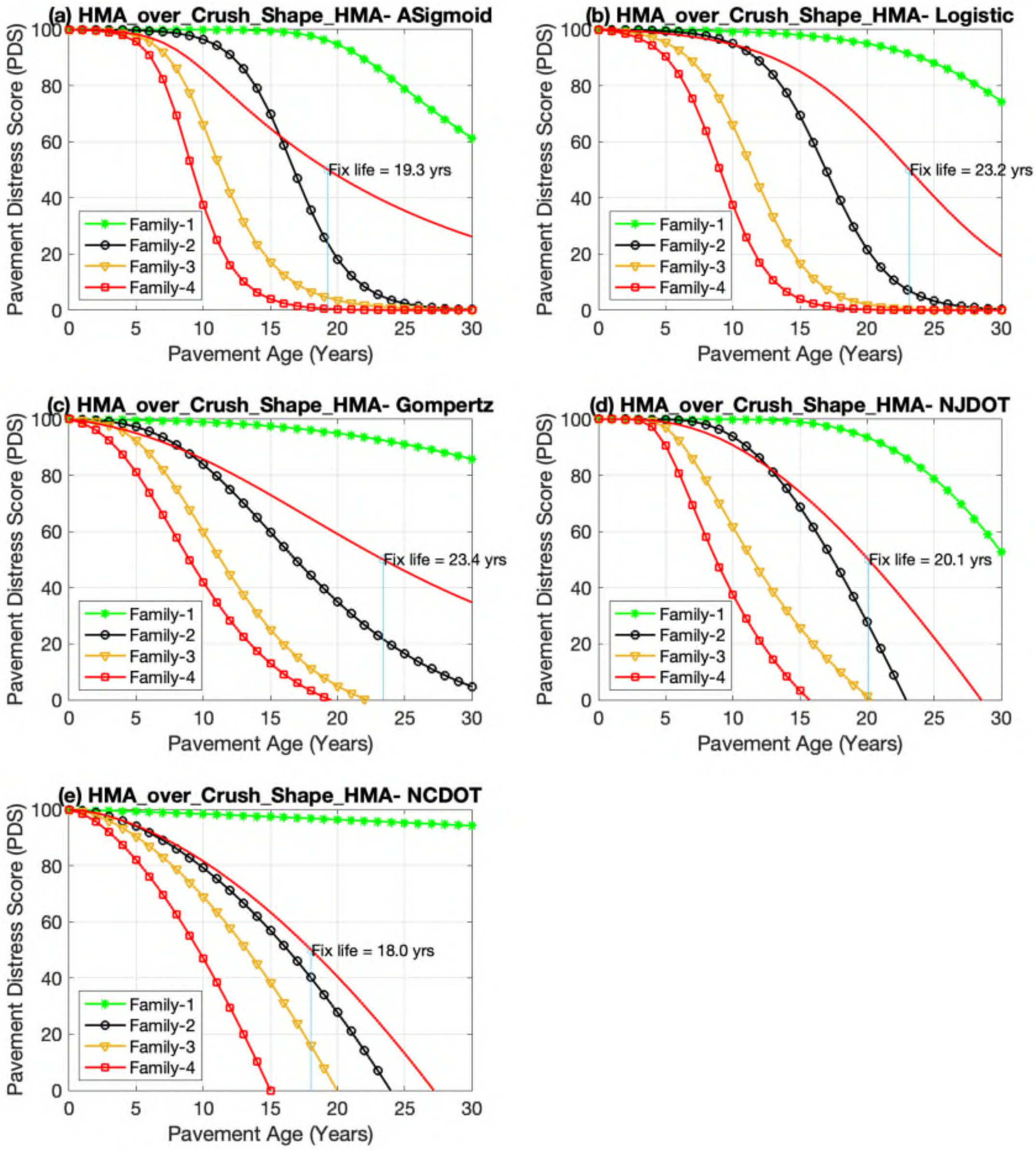


Figure 6-12 PDS composite curves with MDOT families for HMA over Crush & Shape HMA

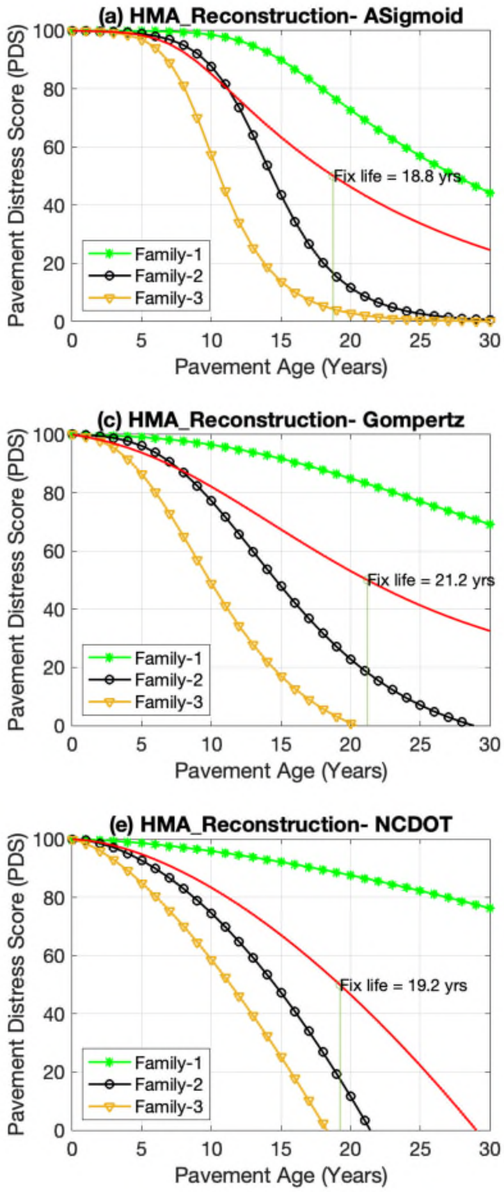


Figure 6-13 PDS composite curves with MDOT families for HMA Reconstruction

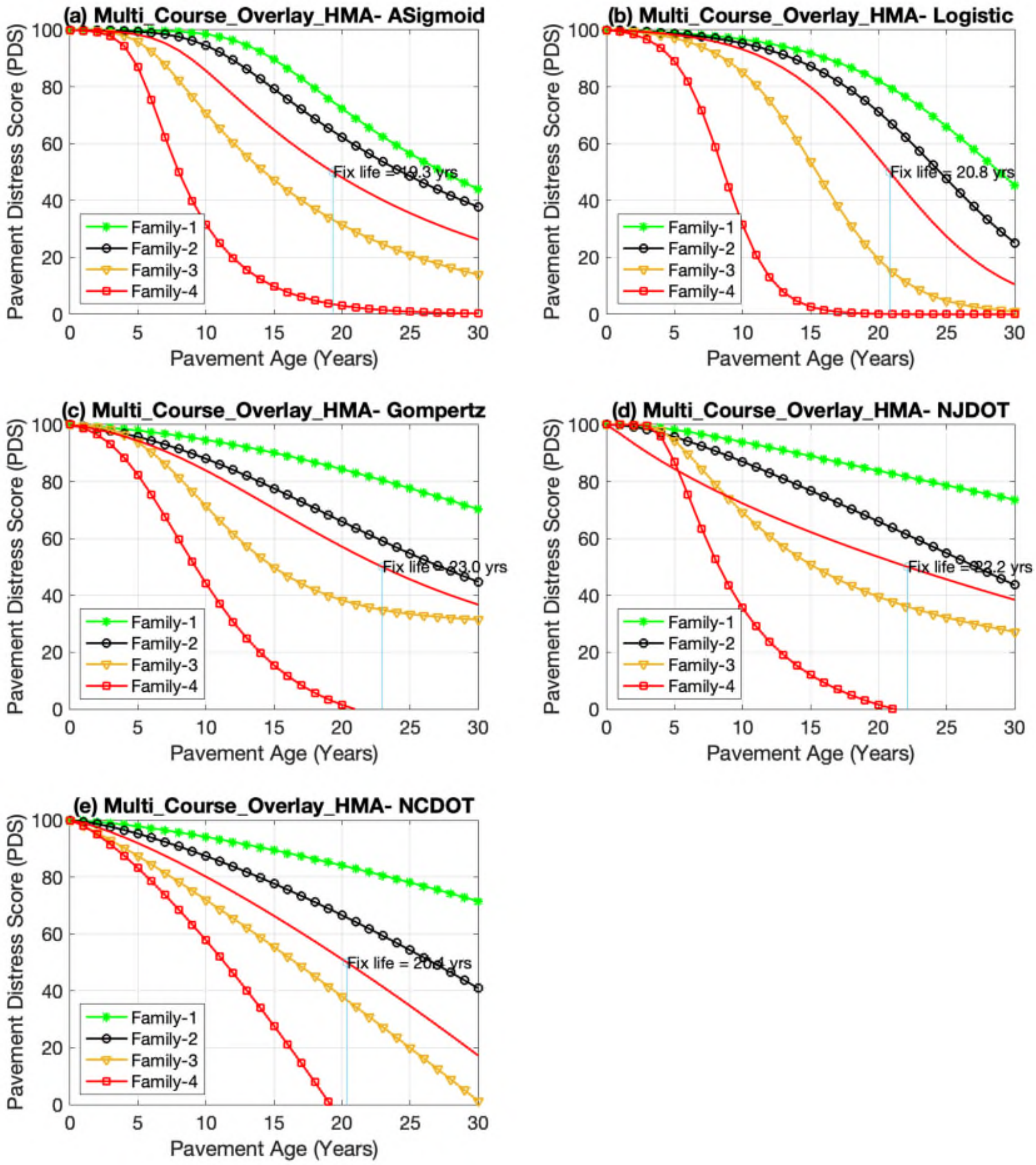


Figure 6-14 PDS composite curves with MDOT families for Multi Course Overlay HMA

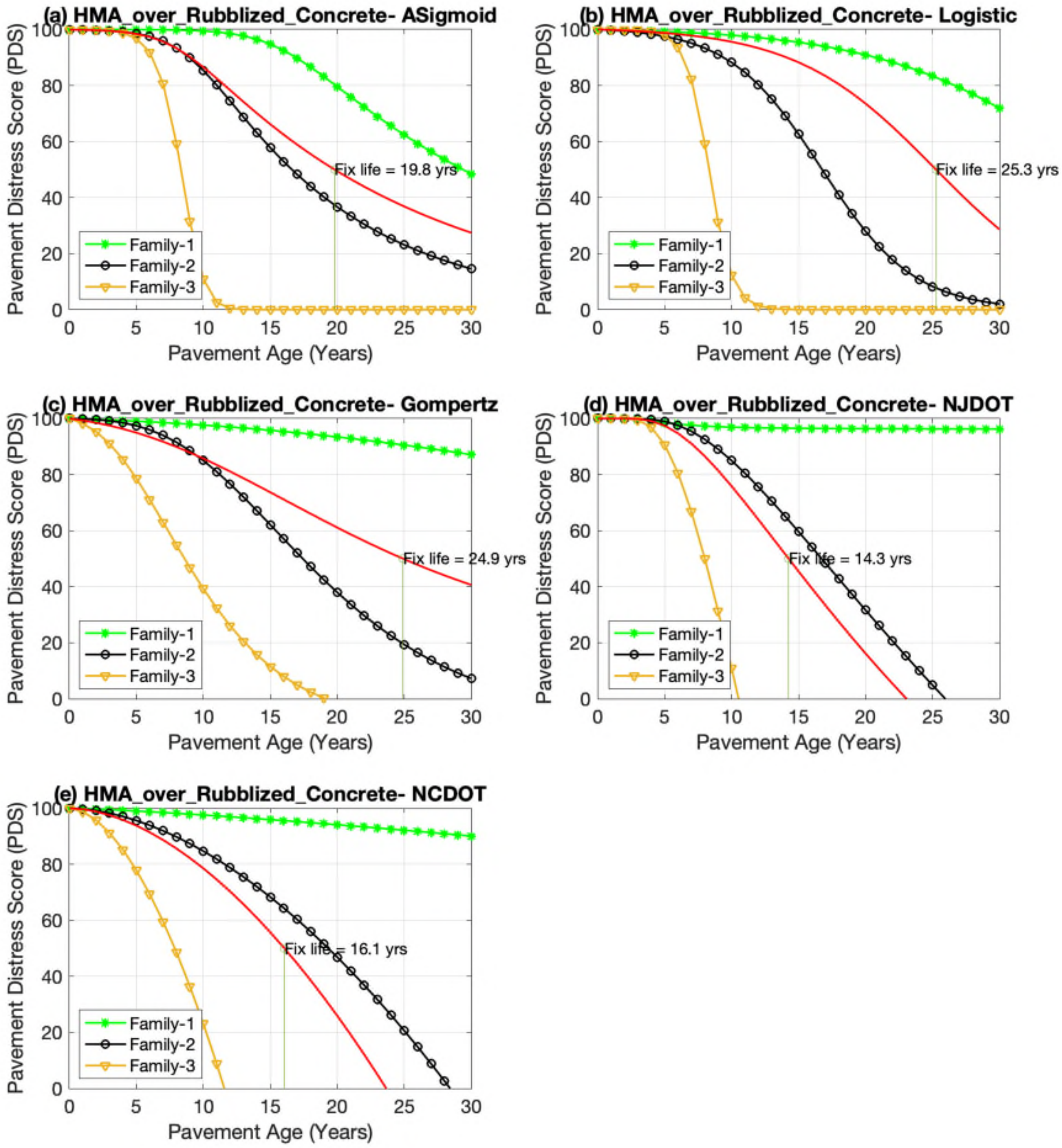


Figure 6-15 PDS composite curves with MDOT families for HMA Over Rubblized Concrete

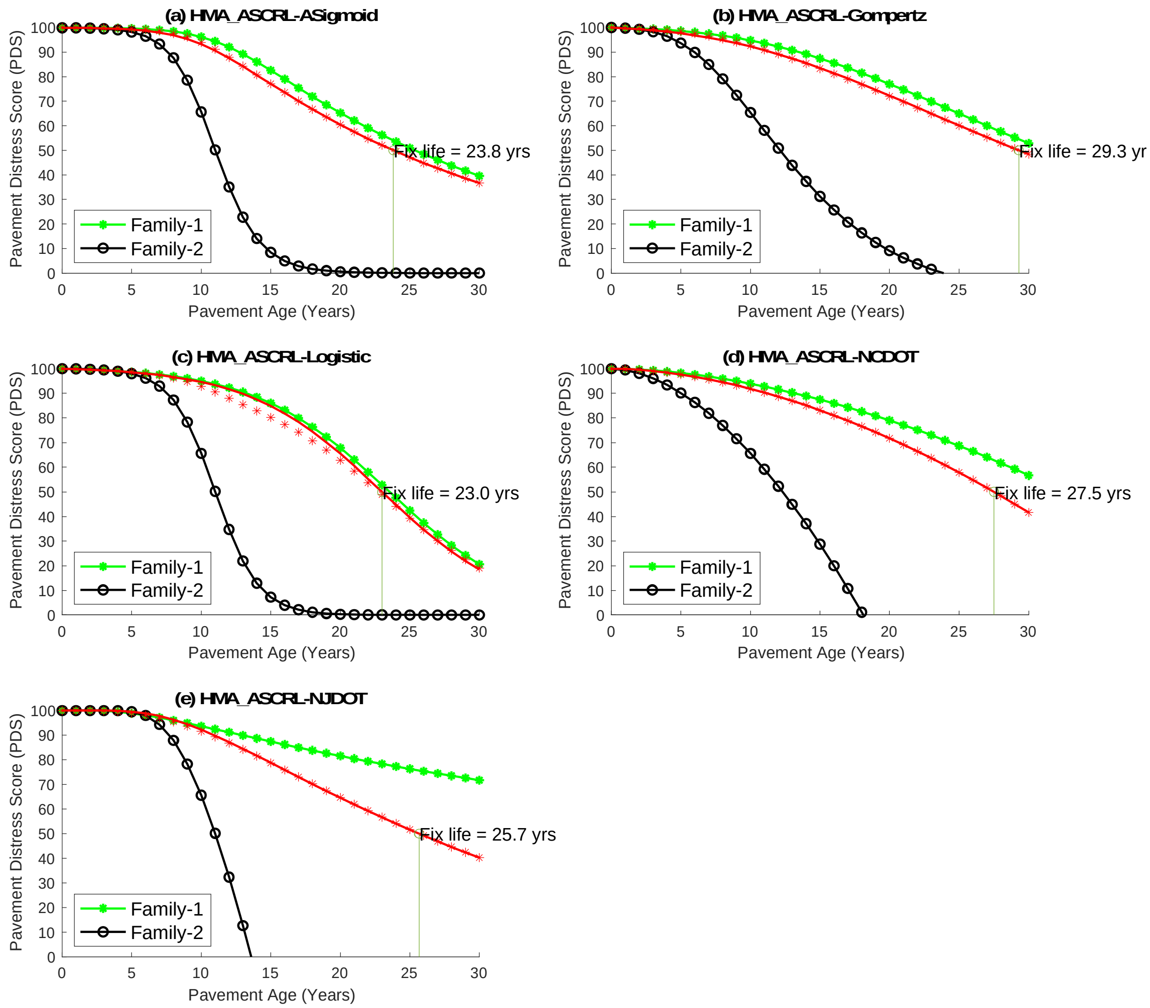


Figure 6-16 PDS composite curves with MDOT families for HMA over Asphalt Stabilized Crack Relief Layer (ASCRL)

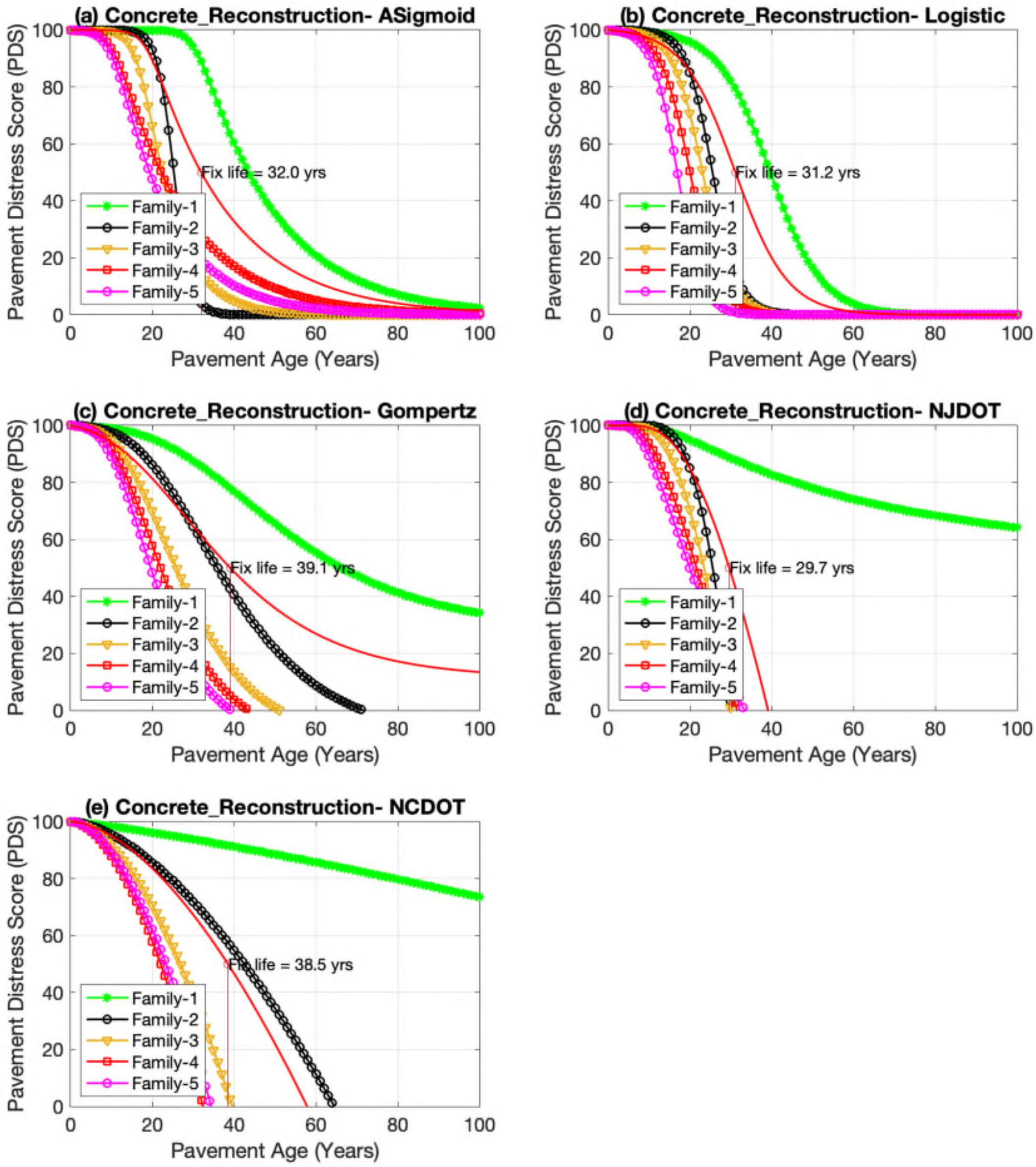


Figure 6-17 PDS composite curves with MDOT families for Concrete Reconstruction

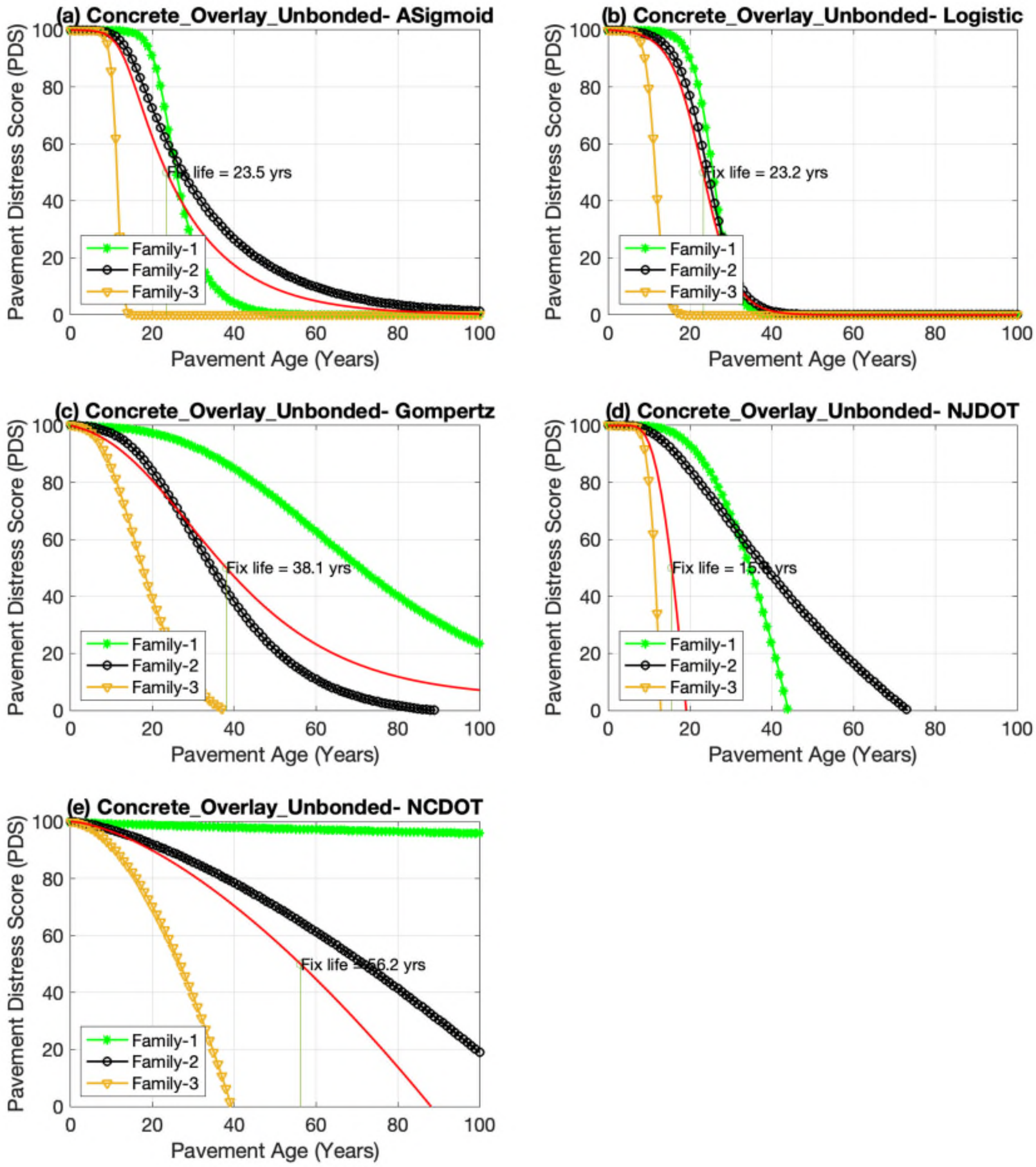


Figure 6-18 PDS composite curves with MDOT families for Concrete Overlay (Unbonded)

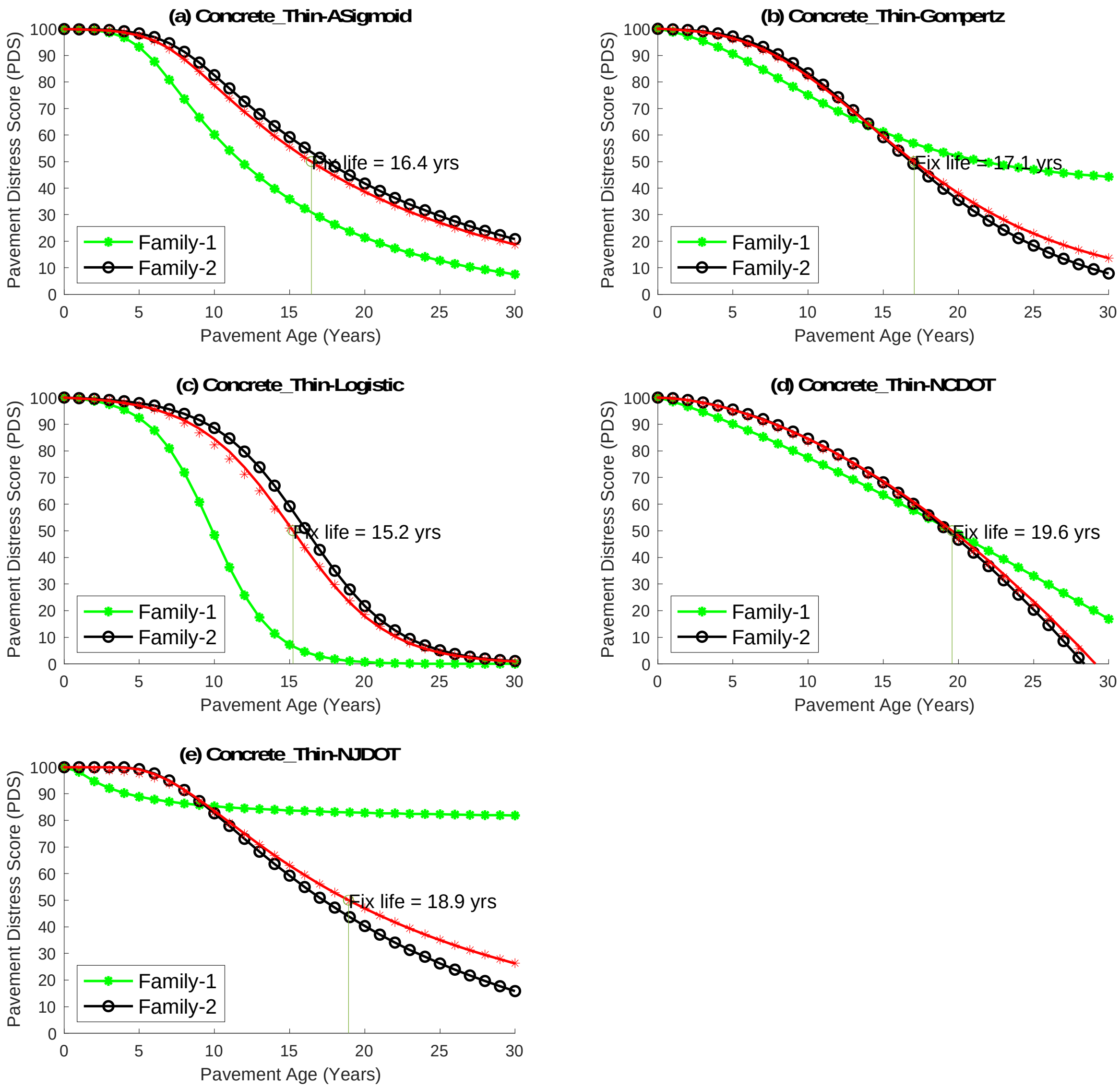


Figure 6-19 PDS composite curves with MDOT families for Thin Concrete Overlay

Table 6-3 shows the fix lives of each surface type for flexible and rigid pavements calculated from the composite curves mentioned above. In Table 6-3, MDOT's current fix lives based on DI for these parent fix types are also reported. With the consensus of region engineers, MDOT determined the existing fix lives based on past DI performance curves and engineering judgment. As shown in Table 6-3, Asymmetric Sigmoid (ASigmoid) and Logistic models produce fix life estimates that align closely with expected pavement performance trends and MDOT's historical experience, making them the most consistent with engineering judgment and past observations. The coefficients of the composite curves for each model are shown in Table 6-4

Table 6-3 PDS-based fix lives computed using MDOT families

Parent Fix Types	ASigmoid	Gompertz	Logistic	NCDOT	NJDOT	MDOT[1]
HMA over Crush & Shape HMA	19	23	23	18	20	19
HMA Reconstruction	19	21	21	19	19	18
Multi-Course Overlay HMA	19	23	21	20	22	21
HMA over Rubblized Concrete	20	25	25	16	14	16
HMA over ASCRL	24	29	23	28	26	33
Concrete Reconstruction	32	39	31	39	30	26
Concrete Overlay Unbonded	24	38	23	56	16	19
Thin Concrete Overlay	16	17	15	20	19	17

Note: [1]This row shows MDOT's existing fix lives based on DI.

Table 6-4 Coefficients of the composite curves for each model

Model	Coefficient	HMA Reconstruction	Multi Course Overlay HMA	HMA over Crush Shape HMA	HMA over Rubblized Concrete	HMA over ASCRL	Concrete Reconstruction	Concrete Overlay Unbonded	Thin Concrete Overlay
ASigmoid	b1	0	0	0	0	0	0	0	0
	b2	100	100	100	100	100	100	100	100
	b3	-7.2	-7	-7.01	-7	-7.28	-11.62	-8.39	-7.08
	b4	0.63	0.6	0.6	0.59	0.5	0.5	0.5	0.70
	b5	9.98	10	9.99	10	10	9.56	7.85	9.72
Logistic	b1	0.8	0.8	0.8	0.8	0.8	0.8	0.27	0.80
	b2	100	100	100	100	100	100	100	100
	b3	0.23	0.23	0.21	0.19	0.21	0.16	0.25	0.32
Gompertz	b1	1.99	2	2	2	0.77	1.3	1.64	0.17
	b2	84.97	82.75	96.96	82.29	96.2	88.69	95.82	97.39
	b3	0.09	0.09	0.08	0.08	0.07	0.05	0.05	0.13
NJDOT	b1	5.93	8.63	9.59	5.97	5.22	8.47	7.77	4.77
	b2	13.68	7.47	17.39	19.86	27.44	34.07	55.65	39.47
	b3	1.91	1.16	1.45	2.35	2.55	1.81	2.64	3.67
NCDOT	b1	0	0	0	0	0	0	0	0
	b2	0.35	1	0.37	0.35	0.13	0.1	0.1	0.28
	b3	1.68	1.3	1.69	1.79	1.79	1.7	1.54	1.75

6.2 NEW MODELING APPROACH

MDOT's current approach requires the engineers to classify the pavements into multiple families, fit the chosen model to each family, and then get the composite model based on the weighted average of the curves of the families. Alternatively, one can fit the model to each pavement segment and then calculate the weighted average of all pavement segments. To accomplish this, an algorithm was written in MATLAB. In addition, the form of the equation needs to be carefully chosen so that some of the early age and/or good-performing pavements do not lead to fix or service lives that are infinitely large. Based on experience, no pavement can last forever, no matter how well it is designed and constructed. For this approach, the two most promising models, Asymmetric Sigmoid (ASigmoid) and Logistic models, are presented herein.

In the new modeling approach, the chosen model is fit to the PDS data of each pavement segment. An example is shown in Figure 6-20 for ASigmoid fit for a pavement segment.

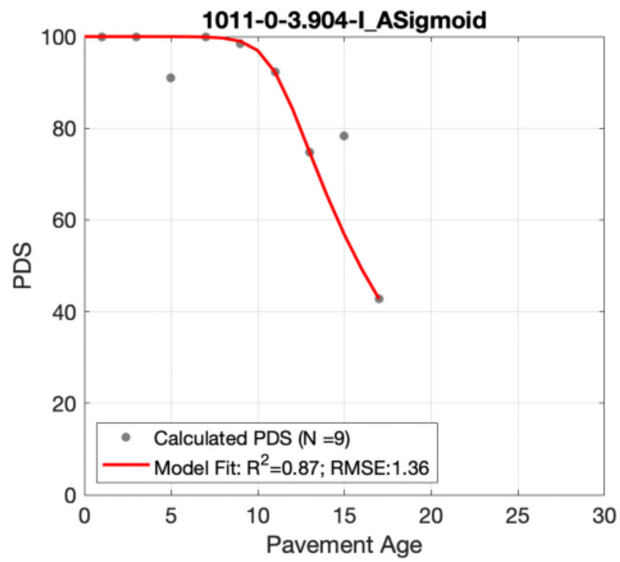


Figure 6-20 Sigmoid fit to one of the pavement segments

Once individual fits of all segments of a fix type were obtained, a weighted average of all curves at each year was computed using the following formula:

$$PDS_{avg}(t) = \frac{\sum_{n=1}^{N_s} L_n \cdot PDS_n(t)}{\sum_{n=1}^{N_s} L_n} \qquad 6.7$$

where, $PDS_{avg}(t)$= weighted average PDS at time t, t = age in years, L_n and $PDS_n(t)$ are length and PDS of nth pavement segment respectively, and N_s is the number of pavement segments.

Figure 6-21 shows all the PDS data points (dot ('.') makers in the figure) and the Logistic and ASigmoid fit (thin lines with different colors) for the surface type: HMA Reconstruction. Figure 6-21 also shows the PDS_{avg} curve, which is shown with red '*' markers. Once the PDS_{avg} curve is obtained, another Logistic or ASigmoid is fit to this curve (thick red line in Figure 6-21) to obtain the composite model coefficients for this surface type. This composite model coefficients can be used to estimate the fix life, and it can also be used in sawtooth graphs to compute the service lives. Similar analyses were done for the other HMA surface types, and their curves are shown in Figure 6-22 through Figure 6-25.

One observation from Figure 6-21 through Figure 6-25 is that the Logistic curve does not fit the average PDS values (red '*' markers) very well. This is because the Logistic is a symmetrical sigmoid, whereas the composite average PDS values are asymmetric. As a result, the symmetric Logistic curve fit to asymmetric PDS average values is not very good. This problem does not exist in the ASigmoid curve because it is an asymmetric equation, and the fit to the average PDS values is very good. Therefore, using the ASigmoid curve in the new method is preferred.

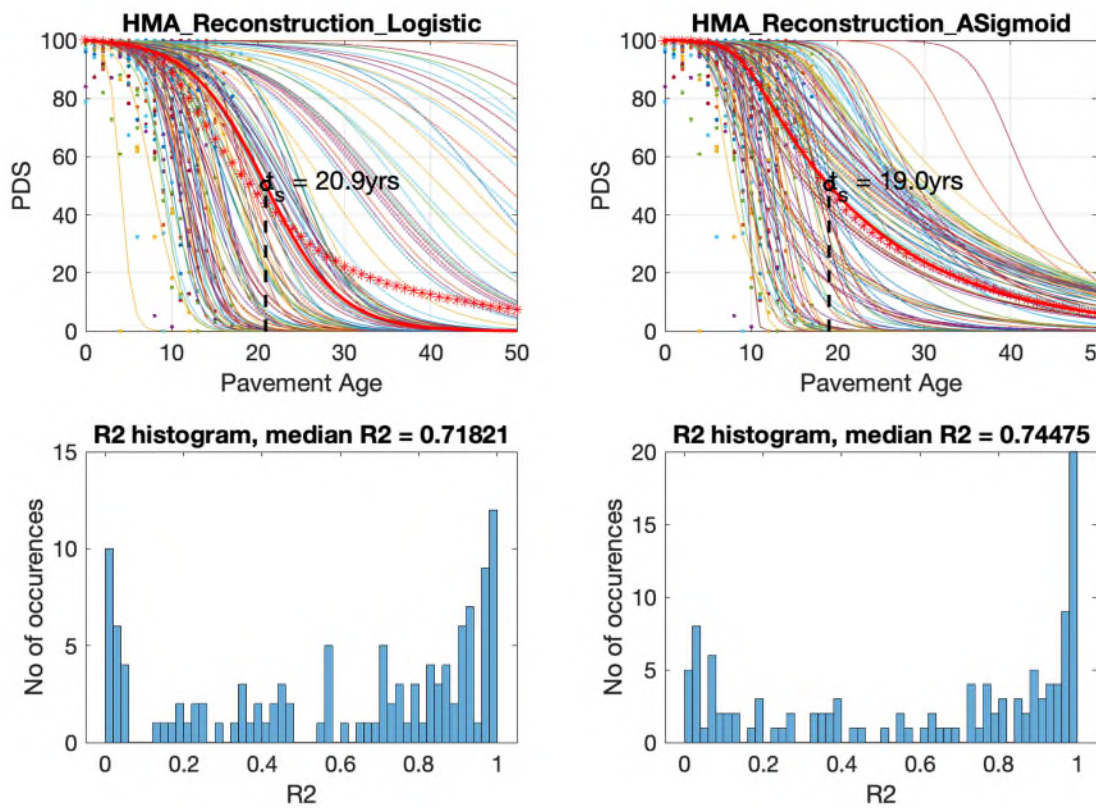


Figure 6-21 Logistic and Asymmetric Sigmoid fits to the PDS data of each pavement segment and resulting composite curve for surface type: HMA Reconstruction

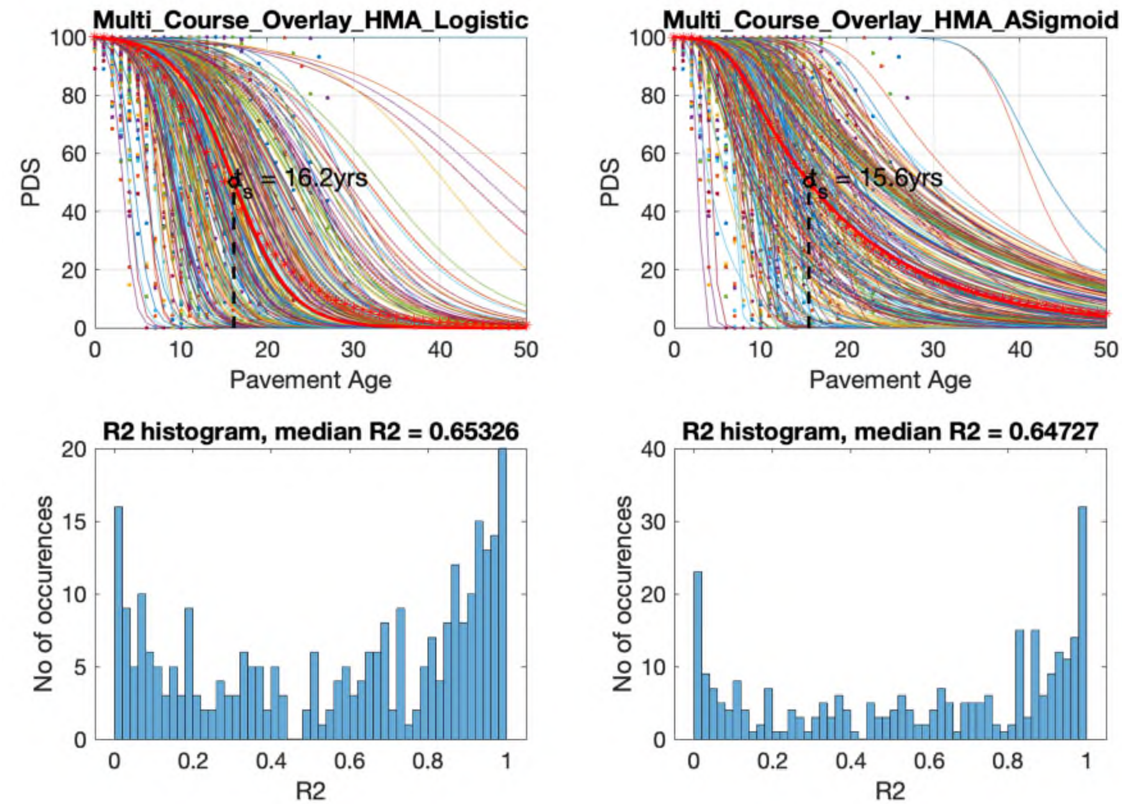


Figure 6-22 Logistic and Asymmetric Sigmoid fits to the PDS data of each pavement segment and resulting composite curve for surface type: Multi Course Overlay HMA

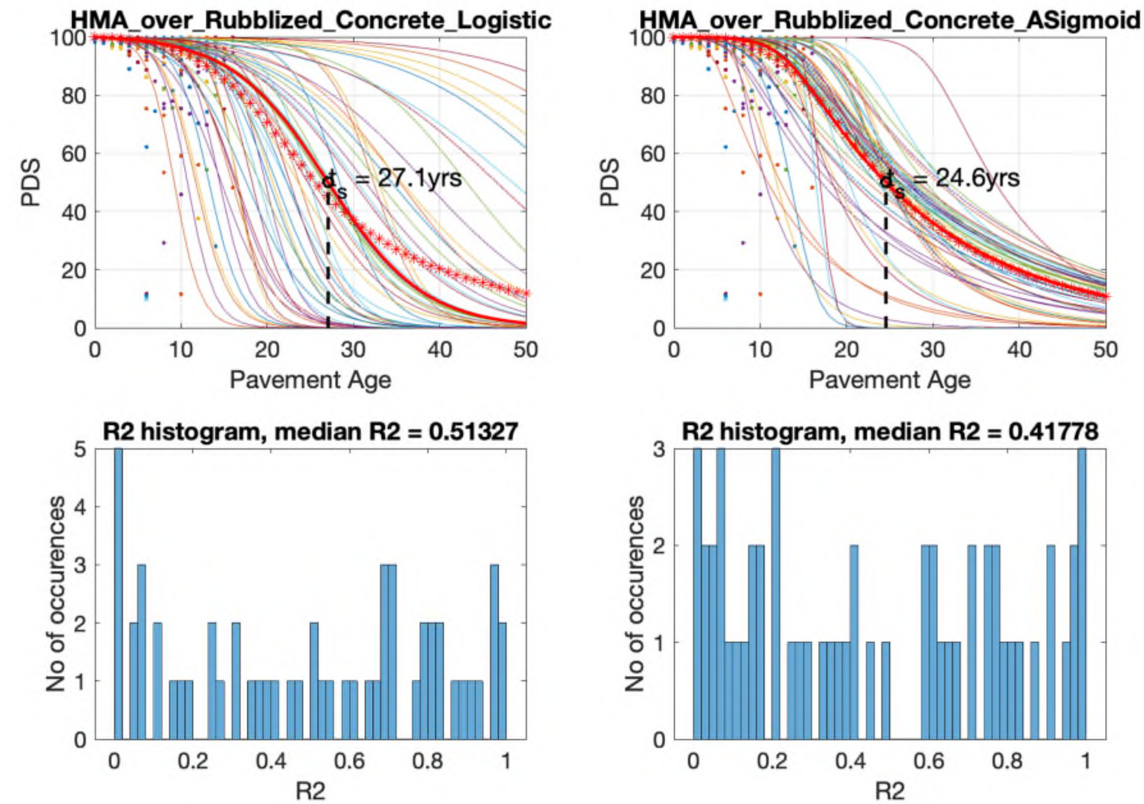


Figure 6-23 Logistic and Asymmetric Sigmoid fits to the PDS data of each pavement segment and resulting composite curve for surface type: HMA over Rubblized Concrete

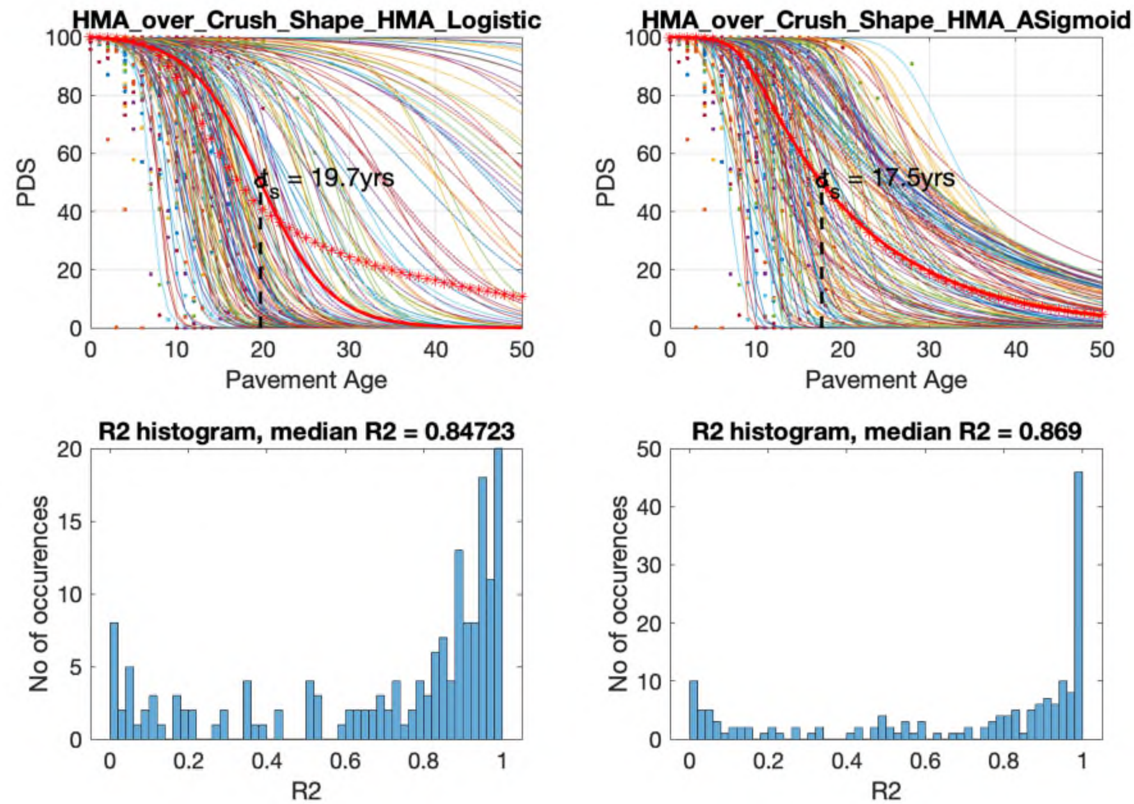


Figure 6-24 Logistic and Asymmetric Sigmoid fits to the PDS data of each pavement segment and resulting composite curve for surface type: HMA over Crush and Shape HMA

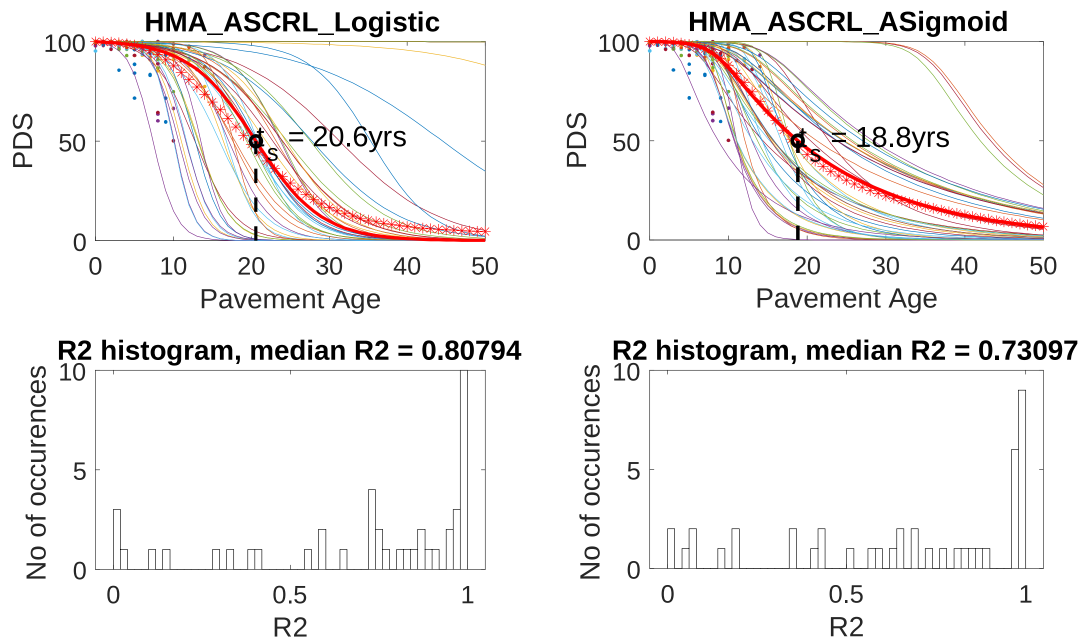


Figure 6-25 Logistic and Asymmetric Sigmoid fits to the PDS data of each pavement segment and resulting composite curve for surface type: HMA over ASCRL

The results of the fits for the concrete pavements are shown in Figure 6-26 , Figure 6-27 and Figure 6-28 for concrete reconstruction, concrete unbonded overlay and thin concrete overlay parent fix types, respectively. Similar observations can be made with these figures where the ASigmoid is a better model for the new approach.

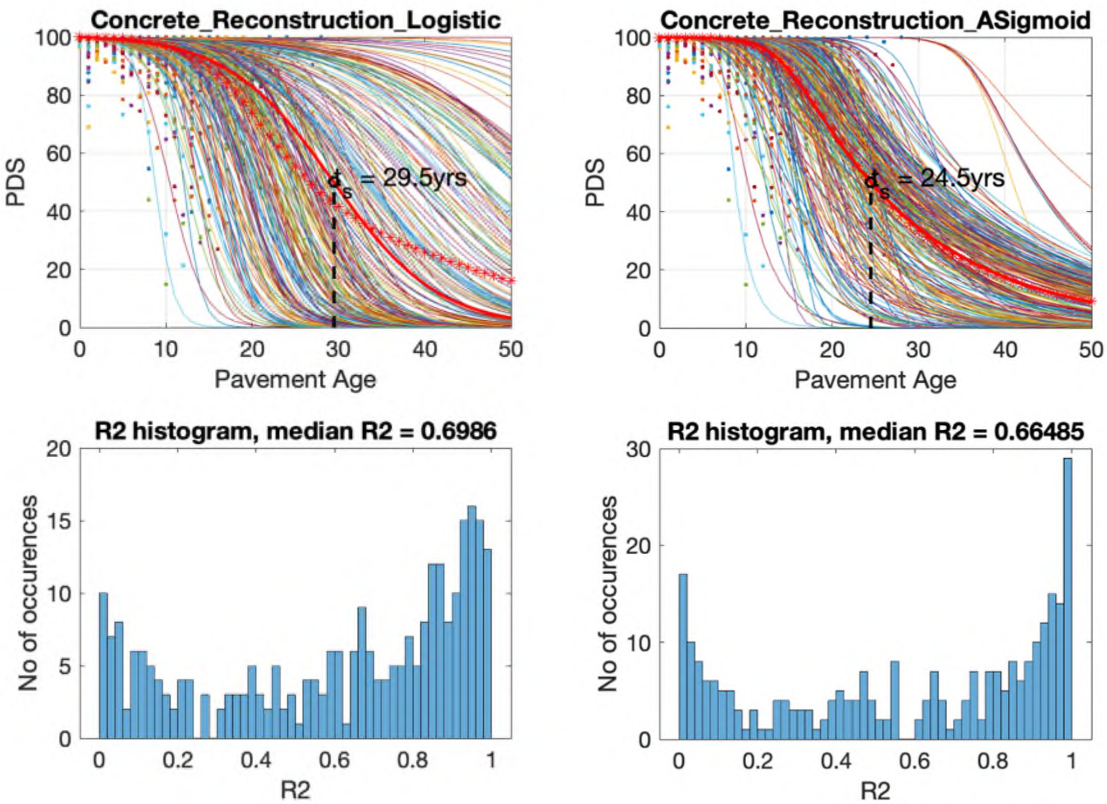


Figure 6-26 Logistic and Asymmetric Sigmoid fits to the PDS data of each pavement segment and resulting composite curve for surface type: Concrete Reconstruction

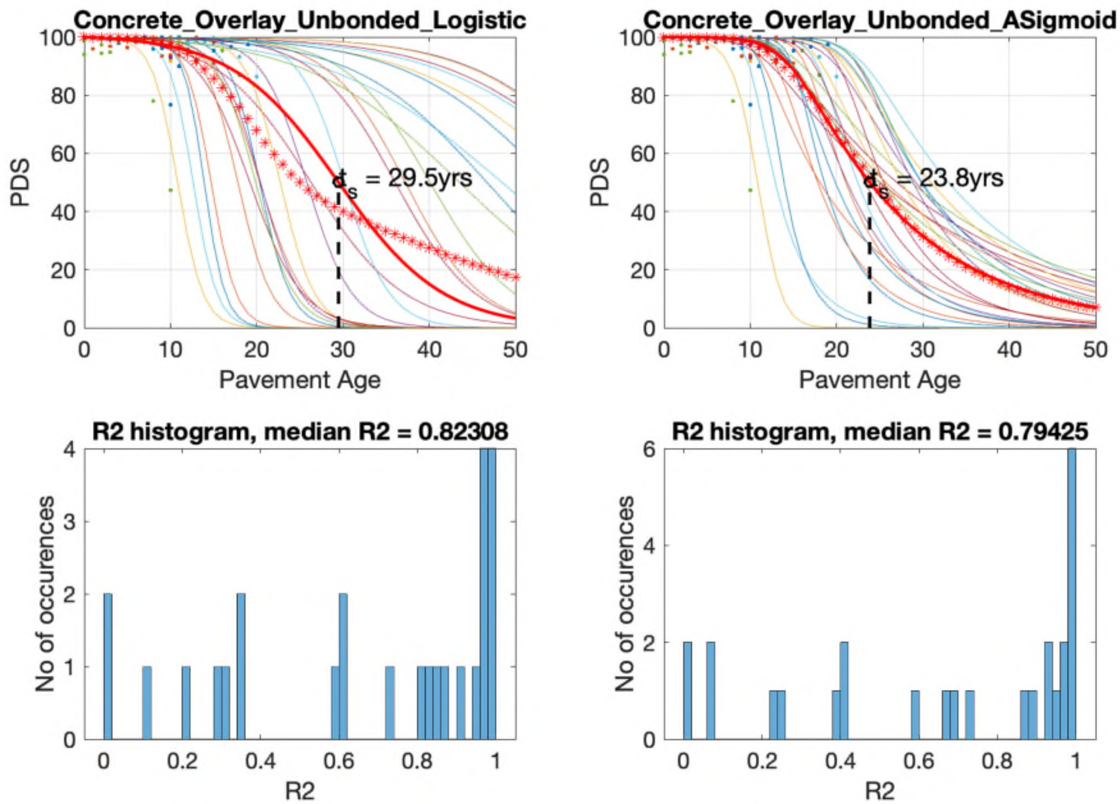


Figure 6-27 Logistic and Asymmetric Sigmoid fits to the PDS data of each pavement segment and resulting composite curve for surface type: Concrete Overlay (Unbonded)

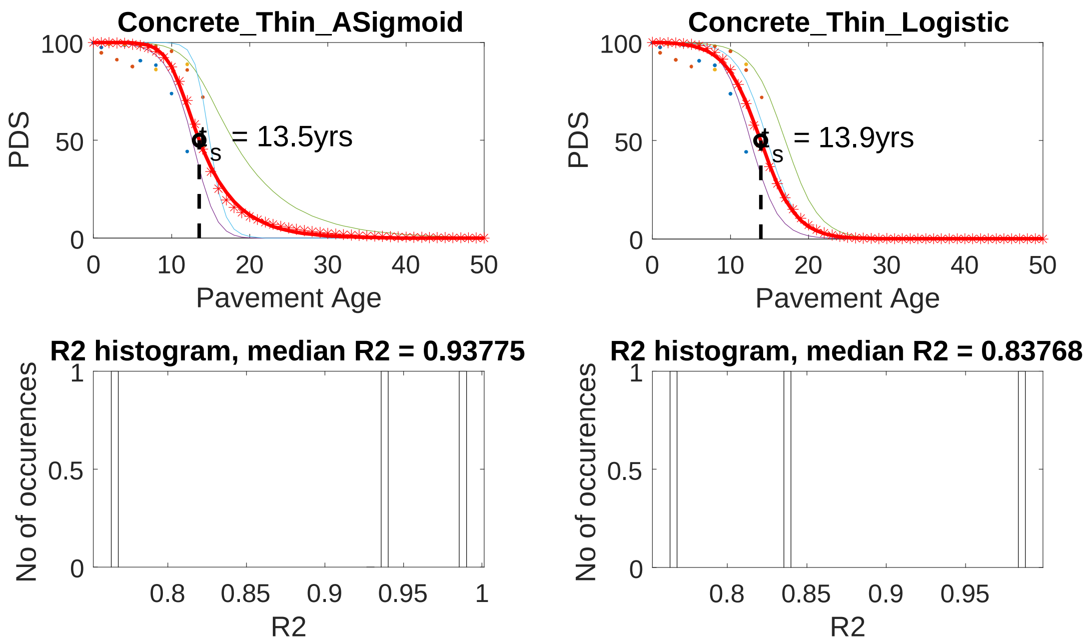


Figure 6-28 Logistic and Asymmetric Sigmoid fits to the PDS data of each pavement segment and resulting composite curve for surface type: Thin Concrete Overlay

Table 6-5 shows the PDS-based fix lives computed using the new method described above for flexible and rigid pavements. Table 6-6 shows the coefficients of the ASigmoid and Logistic curves for the composite PDS. One can observe that b1 and b2 values of ASigmoid are 0 and 100, respectively. This was done to ensure that PDS's minimum and maximum values are 0 and 100, respectively. Similarly, b2 value of the Logistic curve is 100, ensuring that the PDS's minimum value is zero.

Table 6-5 PDS-based fix lives computed using the new method

Surface	ASigmoid	Logistic	MDOT(1)
HMA over Crush & Shape HMA	16	16	19
HMA Reconstruction	19	21	18
Multi-Course Overlay HMA	18	20	21
HMA over Rubblized Concrete	25	27	16
HMA over ASCRL	19	21	33
Concrete Reconstruction	24	30	26
Concrete Overlay Unbonded	25	29	19
Thin Concrete Overlay	14	14	17

Note: (1) This column shows MDOT's existing fix lives based on DI.

Table 6-6 Coefficients of the composite curves for each model for the new method

Model	Coef.	HMA Reconstruction	Multi Course Overlay HMA	HMA over Crush Shape HMA	HMA over Rubblized Concrete	HMA over ASCRL	Concrete Reconstruction	Concrete Overlay Unbonded	Thin Concrete Overlay
ASigmoid	b1	0	0	0	0	0	0	0	0
	b2	100	100	100	100	100	100	100	100
	b3	-8.11	-8.25	-7	-8.63	-7.6932	-9.16	-9.21	-9.84
	b4	0.67	0.71	0.74	0.5	0.65	0.5	0.5	0.8
	b5	9.93	9.43	9.99	8.34	9.91	7.38	6.66	3.57
Logistic	b1	0.799	0.799	0.7989	0.7998	0.7992	0.7998	0.7993	0.21749
	b2	100	100	100	100	100	100	100	100
	b3	0.23	0.25	0.3	0.18	0.24	0.16	0.16	0.44

In order to show the general behavior of the ASigmoid and Logistic curves when different coefficients are changed, a parametric analysis was done by changing one of the coefficients at a time. The results are shown in Figure 6-29 and Figure 6-30 for ASigmoid and Logistic curves, respectively. As shown in Figure 6-29, the b1 and b2 coefficients control the minimum and maximum values, b3 shifts the curve right or left, b4 shifts and rotates the curve, and b5 controls the asymmetry, especially the tail end of the curve. Figure 6-30 shows that b1 shifts the curve to left or right for the Logistic curve, b2 controls the minimum value (maximum is always 100), and b3 rotates and translates the curve.

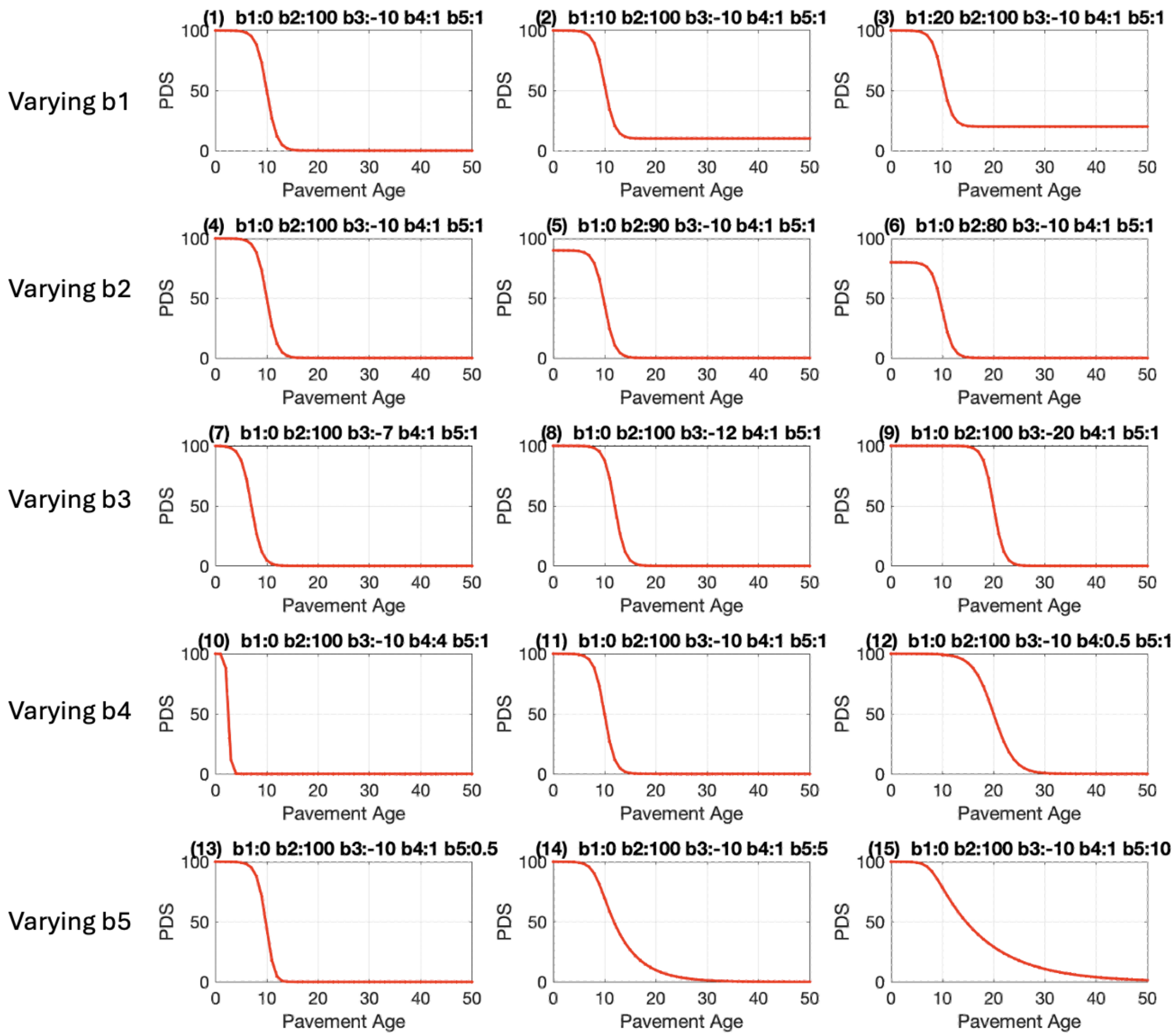


Figure 6-29 Parametric analysis of coefficients of Asymmetric Sigmoid (ASigmoid) curve

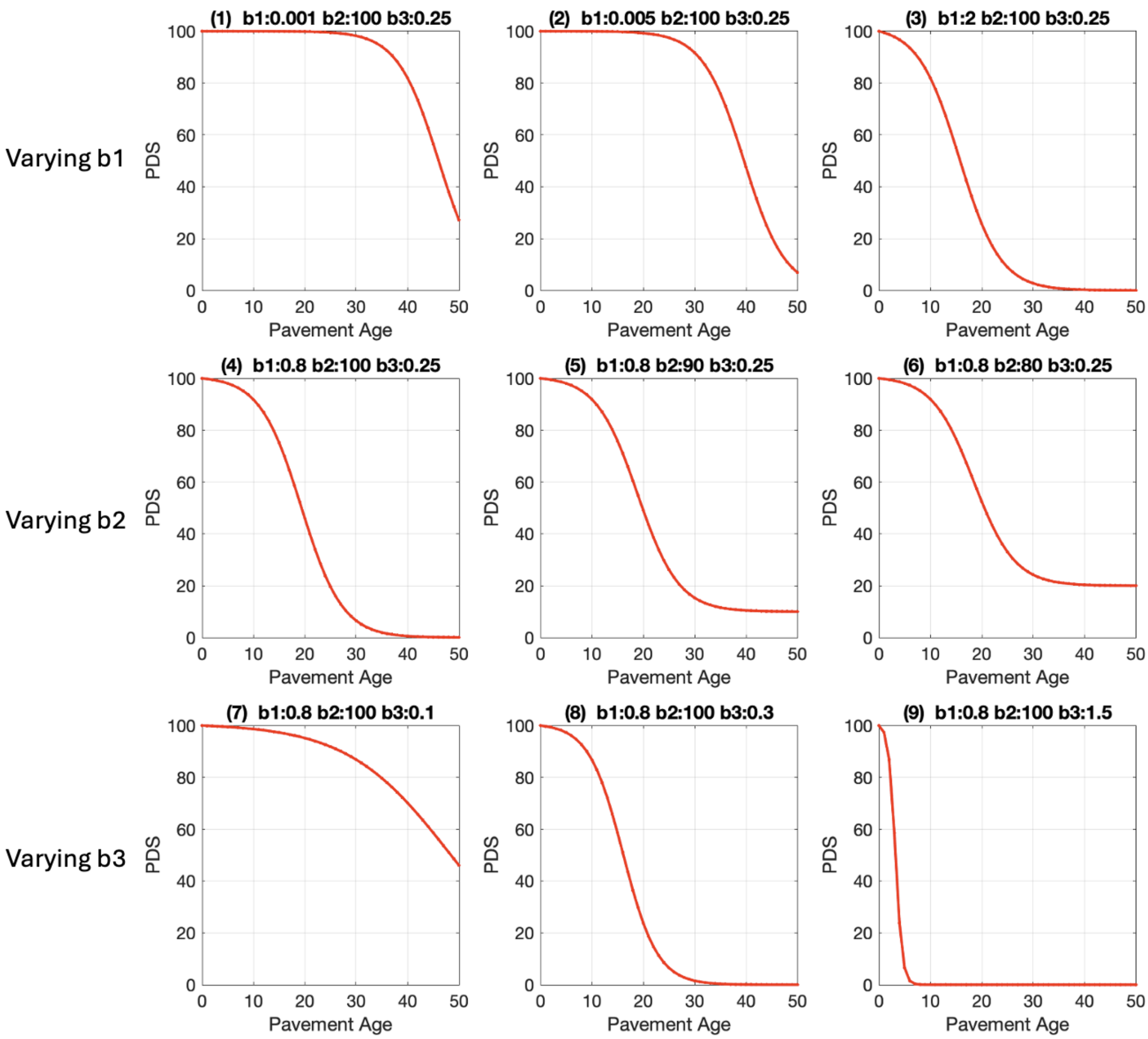


Figure 6-30 Parametric analysis of coefficients of Logistic curve

7 TASK5 REVIEW OF MDOT'S LCCA PROCESS AND RECOMMEND A METHOD FOR ESTABLISHING SERVICE LIVES

Life-cycle Cost Analysis (LCCA) is a critical tool highway officials use to compare different design alternatives and reach a suitable transportation investment decision. LCCA assists in determining the best, low-cost alternative to accomplish the project. It includes comparing the total cost of the competing alternatives, enabling the decision-makers to decide on implementing the appropriate transportation project. All of the relevant costs that occur throughout the life of an alternative, not simply the original expenditures, are included. These costs typically include maintenance, and related road user costs arising from traffic delays due to the initial construction and future maintenance costs (Walls and Smith 1998).

7.1 Existing Process to compute service lives based on DI

The Michigan Department of Transportation (MDOT) has been using LCCA since the mid-1980s to compare the costs of different pavement alternatives and to select the most cost-effective option (MDOT 2021). The LCCA incorporates costs incurred on initial construction, preventive maintenance, remaining life, and user costs resulting from each construction activity. MDOT's LCCA practice uses the department's pavement maintenance records and condition data to estimate a pavement's "Service Life," defined as the time (in years) before the pavement requires subsequent rehabilitation or reconstruction, including the increase in life due to maintenance (which distinguishes it from "fix life"). MDOT has also used the historical data to develop pavement preservation strategies (i.e., maintenance schedules) that reflect the average pavement performance and the associated average maintenance costs. This service life estimation uses a logistic growth equation to best fit a given fix type’s measured distress index (DI) data.

Table 7-1 summarizes MDOT's preventive maintenance (PM) strategies for new/reconstructed flexible pavements. During the service life estimation, the data in Table 7-1 account for 'drops' in DI values at the times of various PM treatments. Figure 7-1 shows an example logistic growth model used to forecast the progression of DI. As shown, the DI increases to approximately 9 at the age of 8 years (second row in Table 7-1). Then, due to the PM, the DI drops by 6 points to a value of 2. Then, between the ages of 8 and 13, the DI continues to grow, based on the logistic model, and again drops at the age of 13. This process is repeated four times (four PMs), after which the DI is allowed to continue to increase until it reaches the threshold of 50. The year at which the DI reaches 50 is considered the service life. As shown in Figure 7-1, the service life of a new or reconstructed HMA pavement is 37 years with four preventive maintenance (PM) treatments.

MDOT's pavement preservation strategies are based on the actual data and serve as input for developing the DI-based pavement deterioration curves. The age to apply a PM treatment and the related DI drops are average estimates from the MDOT's records.

7.2 Process to compute service lives based on PDS

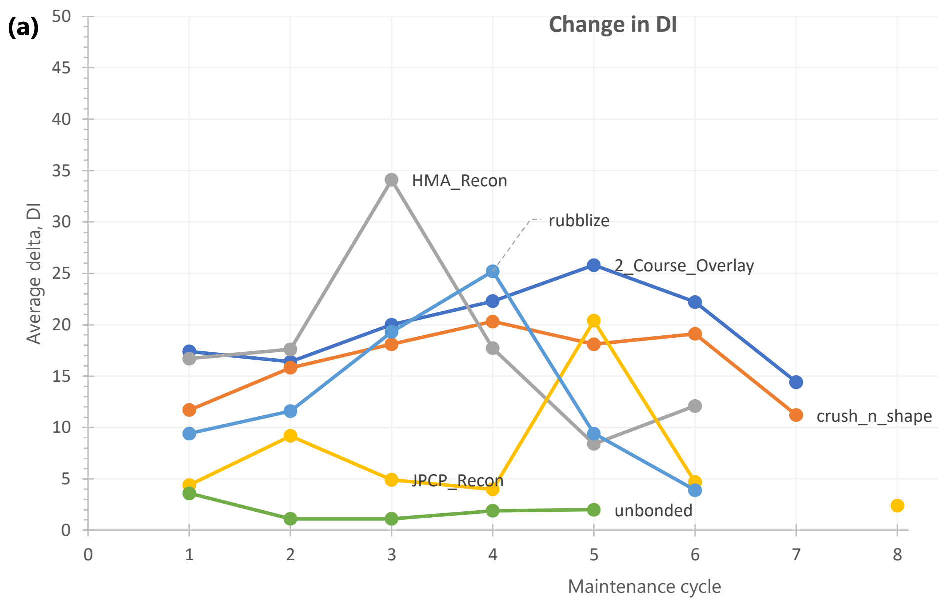
The magnitude and range of values of PDS are different than those of DI. Therefore, a thorough analysis of PDS data with past maintenance records was needed to determine the 'PDS before' and 'PDS after' each preventive maintenance to generate a table similar to the one in Table 7-1. A series of MATLAB codes were written to read, categorize, and organize the PM data provided by MDOT and link them with PDS values. The MATLAB codes were validated by computing the average delta DI values to replicate the data in Table 7-1. One additional benefit of doing this analysis for both DI and PDS was the creation of the curves shown in Figure 7-2. The figure shows the average change (improvement) in DI and PDS values at different maintenance cycles for different surface types. As shown, the change in the PDS and DI values for concrete pavements at each maintenance cycle is generally lower than those for flexible pavements.

Table 7-1 MDOT's HMA preventive maintenance data and their effect on New/Reconstructed HMA (MDOT 2021)

Activity	Approx. age	DI (before)	DI (after)	RSL (yrs) (before fix)	Life (yrs) (extension)	RSL (yrs) (after fix)	Cost/ lane-mile	Time to fix 1 lane-mile (days)
Initial const.	0		0			18	Computed	
PM*	8	9	2	10	5	15	$25,944**	0.48
PM	13	9	2	10	5	15	$38,209**	0.63
PM	17	7	1	11	5	16	$40,670**	0.65
PM	22	7	2	11	4	15	$29,955**	0.55
Rehab. or reconstruction	37							

* Preventive maintenance. ** Based on the actual average maintenance costs, in 2019-dollar values.

Figure 7-1 New/reconstructed HMA pavement service life deterioration curve



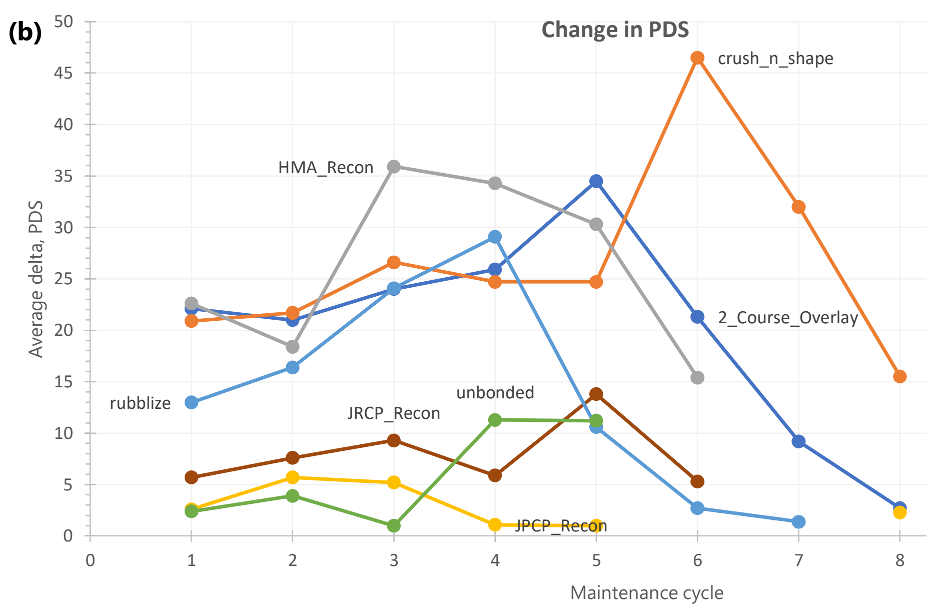


Figure 7-2 (a) Delta DI and (b) Delta PDS vs Maintenance cycles for all pavement treatments. The average per treatment is plotted to the right.

Table 7-2 summarizes the average changes in PDS values at each maintenance cycle. The table also shows the percent PDS increase at each maintenance cycle and is computed as follows:

$$\%PDS_{increase} = \frac{\Delta PDS}{100 - PDS_{before}} \cdot 100 \qquad 7.1$$

where $\%PDS_{increase}$ is the percent increase in PDS at a given maintenance cycle, PDS_{before} is the PDS value before the maintenance was done, ΔPDS is the change (increase) in PDS due to the maintenance activity, and PDS_{after} is the PDS value after the maintenance was done.

Table 7-2 MDOT's preventive maintenance data and their effect on PDS

Type	MC[(i)]	Age	ΔPDS	PDS_{before}	PDS_{after}	$\%PDS_{increase}$
HMA Reconstruction	1	8	23	72	95	82.6
HMA Reconstruction	2	12.7	18	76	95	78.2
HMA Reconstruction	3	17.1	36	57	93	83.8
HMA Reconstruction	4+	21.1	27	66	93	78.8
Concrete Reconstruction	1	12	6	89	94	51
Concrete Reconstruction	2	16.8	8	81	89	40.3
Concrete Reconstruction	3+	22.7	9	75	84	34.8
Concrete Overlay (Unbonded)	1	9.6	2	92	94	29
Concrete Overlay (Unbonded)	2	11.8	4	94	98	62.7
Concrete Overlay (Unbonded)	3	14.7	1	75	76	4
Concrete Overlay (Unbonded)	4+	17.2	11	68	79	34.9
HMA over Rubblized Concrete	1	6.9	13	84	97	81.1
HMA over Rubblized Concrete	2	11.1	16	79	95	76.6
HMA over Rubblized Concrete	3	14.9	24	73	97	90.4
HMA over Rubblized Concrete	4+	18	16	81	96	81.6
HMA over Crush & Shape HMA	1	8.7	21	74	95	82.3
HMA over Crush & Shape HMA	2	13.4	22	72	94	79.2
HMA over Crush & Shape HMA	3	18.6	26	67	93	79.7
HMA over Crush & Shape HMA	4+	22.5	29	65	94	81.9
Multi Course Overlay HMA	1	6.7	22	69	91	70.5
Multi Course Overlay HMA	2	11.5	21	70	92	71.1
Multi Course Overlay HMA	3	16	24	67	91	73.7
Multi Course Overlay HMA	4+	19.5	19	69	88	61.4
HMA over ASCRL	1	6.9	13	84	97	81.1
HMA over ASCRL	2	11.1	16	79	95	76.6
HMA over ASCRL	3	14.9	24	73	97	90.4
HMA over ASCRL	4+	18.0	16	81	96	81.6
Concrete_Thin	1	9.6	2	92	94	29.0
Concrete_Thin	2	11.8	4	94	98	62.7
Concrete_Thin	3	14.7	1	75	76	4.0
Concrete_Thin	4+	17.2	11	68	79	34.9
Note: (i) MC = Maintenance Cycle.						

In order to compute the service lives, first, the so-called 'sawtooth' curves need to be generated. To generate the sawtooth curves, the equivalent time that corresponds to the PDS value after the delta PDS is added. Then, the curve starting from this equivalent year forward is used after the maintenance. It is noted that MDOT currently uses this approach in the sawtooth graph shown in Figure 7-1.

7.3 Service life curves based on MDOT families

Figure 7-3 and Figure 7-4 show the sawtooth graphs based on Logistic composite curves for flexible and rigid pavements, respectively. The service lives range from 36 to 44 years, depending on the surface type. Similar graphs were developed based on the ASigmoid model and shown in Figure 7-5 and Figure 7-6 for flexible and rigid pavements, respectively.

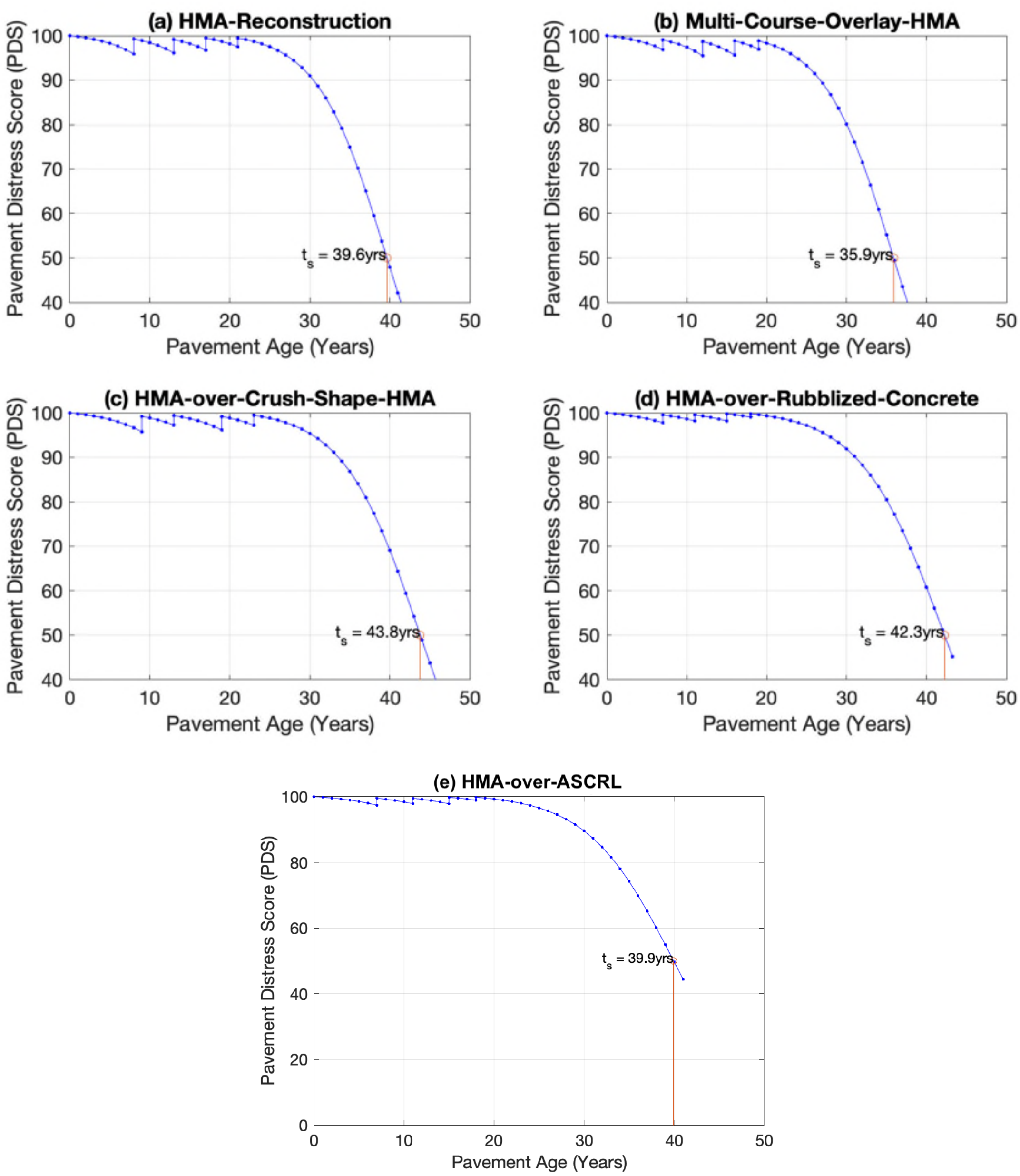


Figure 7-3 Sawtooth graphs for <u>HMA</u> surfaces based on the <u>Logistic</u> model (composite curve is based on MDOT Families).

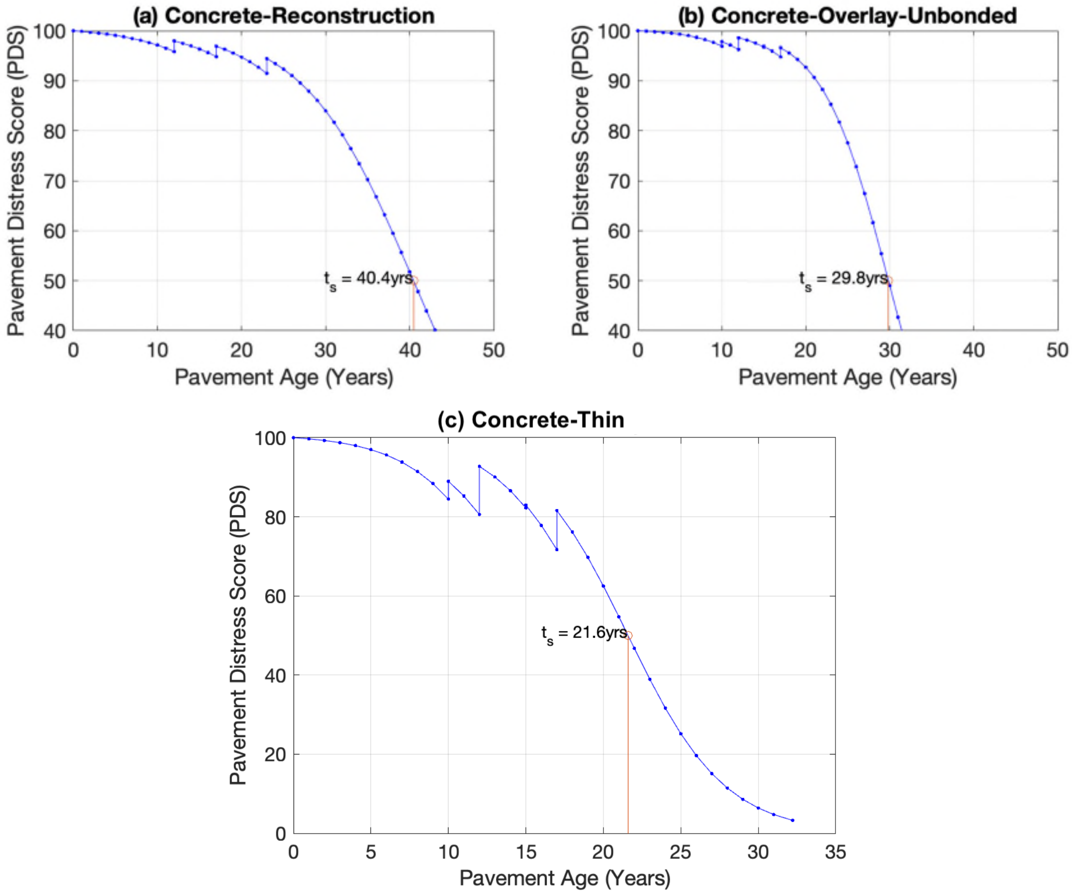


Figure 7-4 Sawtooth graphs for <u>Concrete</u> surfaces based on the <u>Logistic</u> model (composite curve is based on MDOT Families).

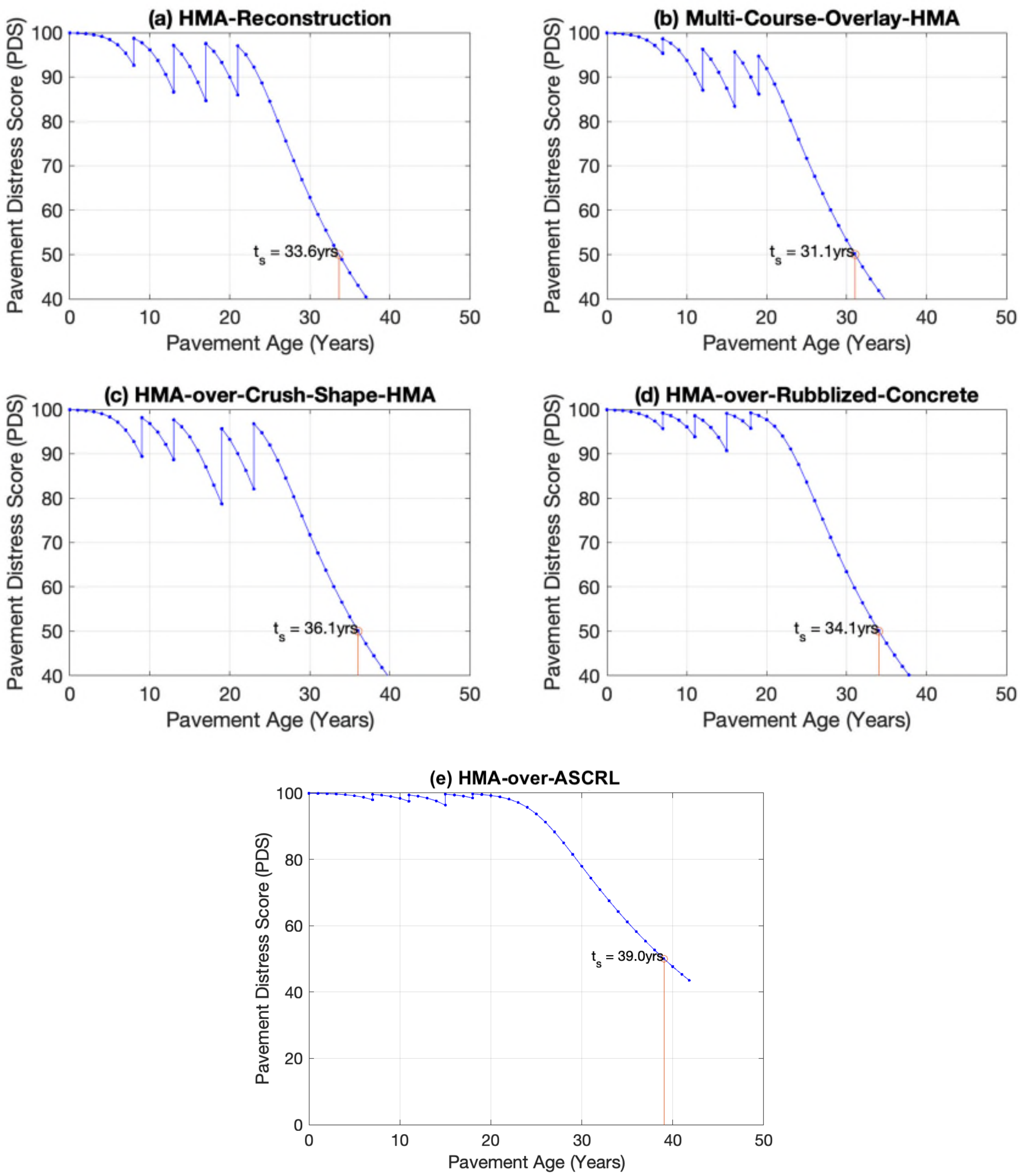


Figure 7-5 Sawtooth graphs for HMA surfaces based on the ASigmoid model (composite curve is based on MDOT Families).

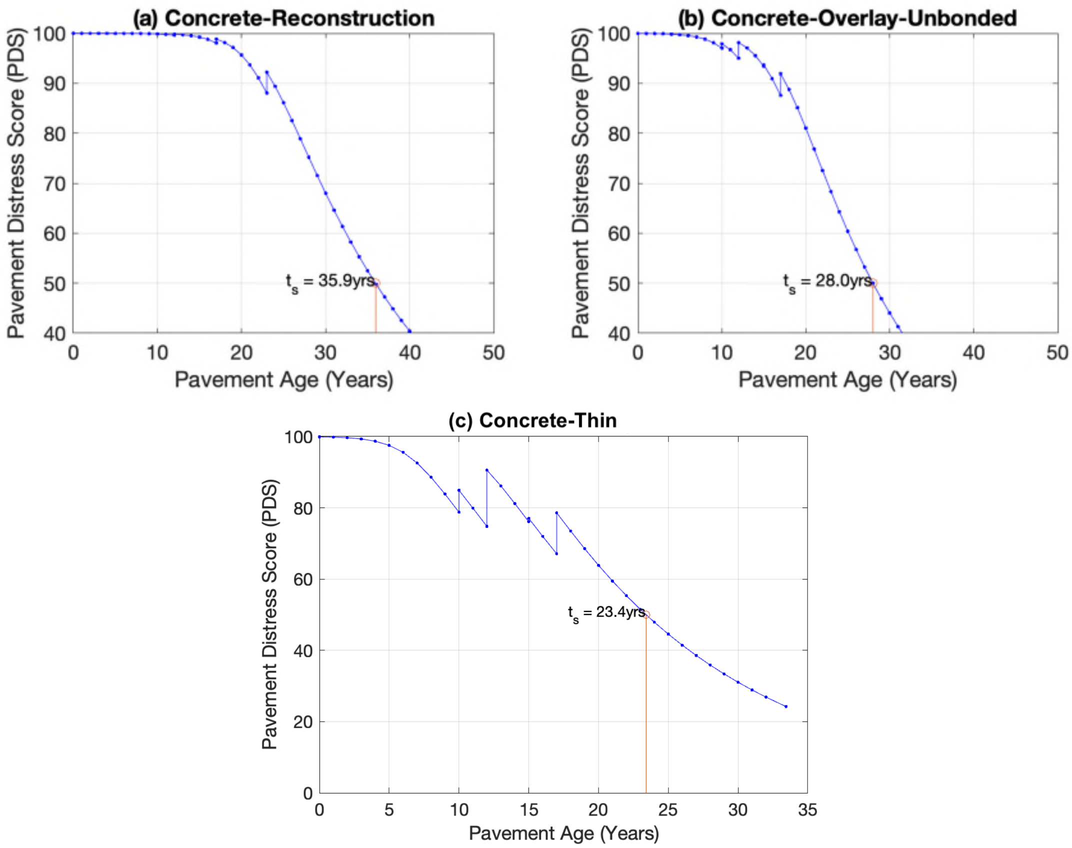


Figure 7-6 Sawtooth graphs for <u>Concrete</u> surfaces based on the <u>ASigmoid</u> model (composite curve is based on MDOT Families).

Table 7-3 summarizes service lives based on ASigmoid and Logistic curves for different pavement surface types.

Table 7-3 PDS-based service lives computed using MDOT families

Surface Types	Models		MDOT[1]
	ASigmoid	Logistic	
HMA Reconstruction	34	40	36
Multi Course Overlay HMA	31	36	38
HMA over Crush & Shape HMA	36	44	39
HMA over Rubblized Concrete	34	42	32
HMA over ASCRL	39	40	40
Concrete Reconstruction	36	40	36
Concrete Overlay (Unbonded)	28	30	23
Thin Concrete Overlay	23	22	21

Note: (1) This column shows MDOT's existing service lives based on DI.

7.4 Service life curves based on new modeling approach

The service lives were also computed using the composite curves based on the new modeling approach (see section 6.2), where ASigmoid and Logistic curves fit the PDS of individual pavement segments and a weighted average PDS curve was developed based on each segment's length. Figure 7-7 and Figure 7-8 show the new service life curves for HMA and Concrete surfaces, respectively, using the Logistic model. On the other hand, Figure 7-9 and Figure 7-10 show the service life curves based on the ASigmoid curve for HMA and Concrete surfaces.

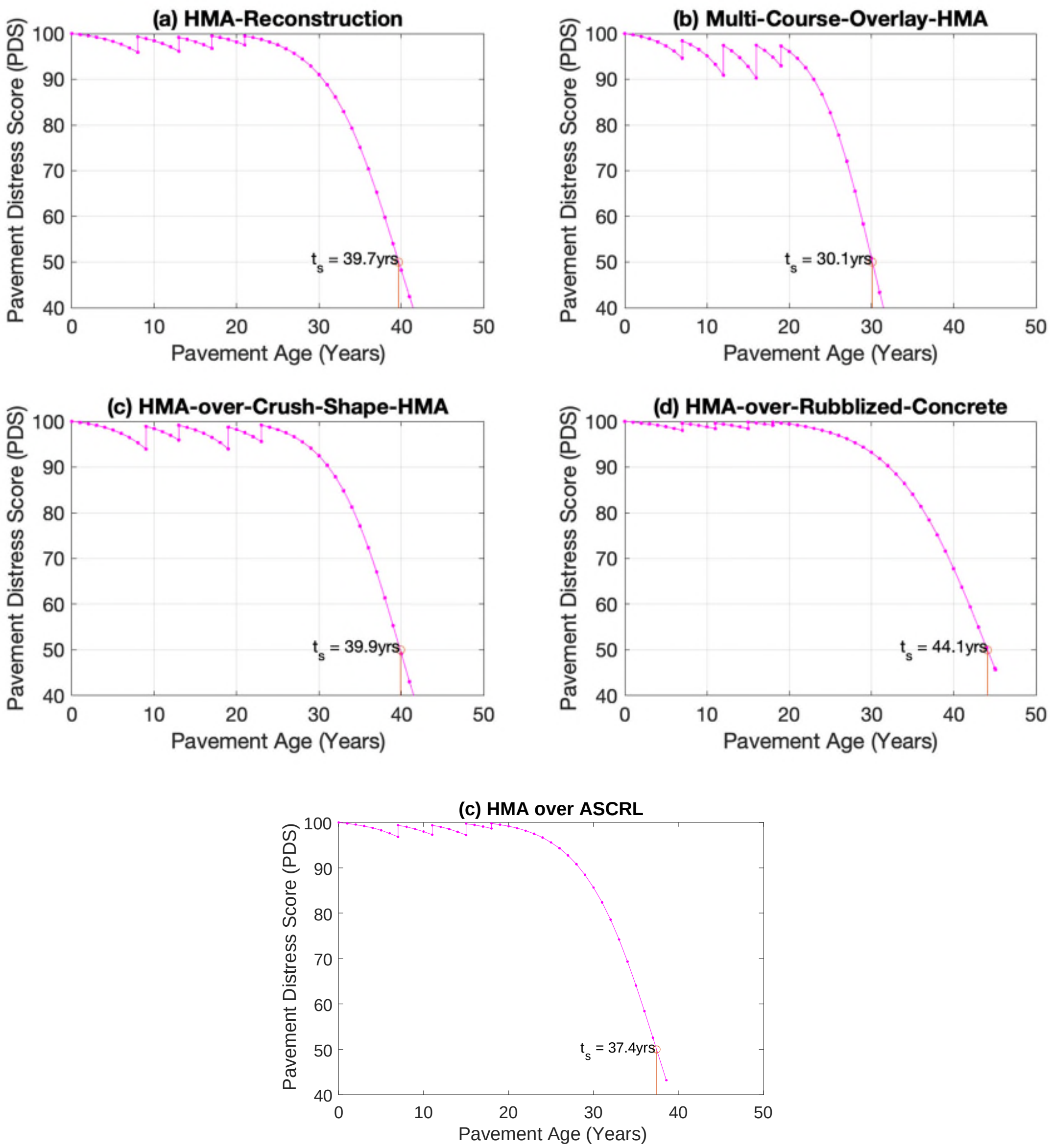


Figure 7-7 Sawtooth graphs for <u>HMA</u> surfaces based on the <u>Logistic</u> model (new modeling approach).

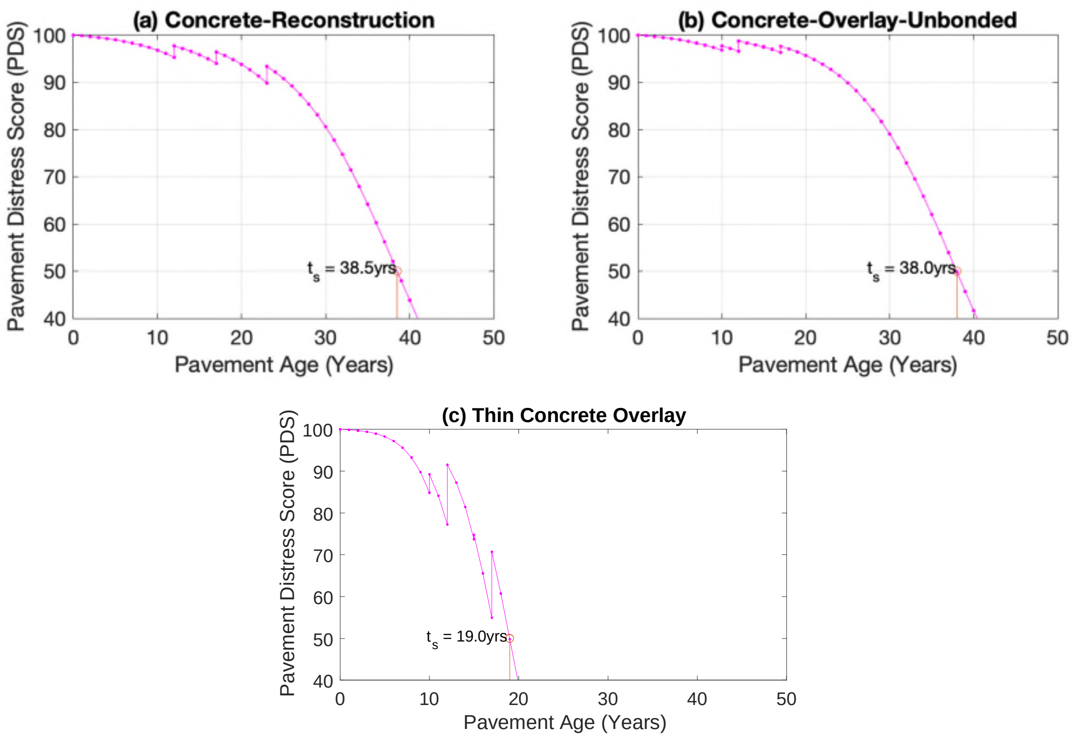


Figure 7-8 Sawtooth graphs for <u>Concrete</u> surfaces based on the <u>Logistic</u> model (new modeling approach).

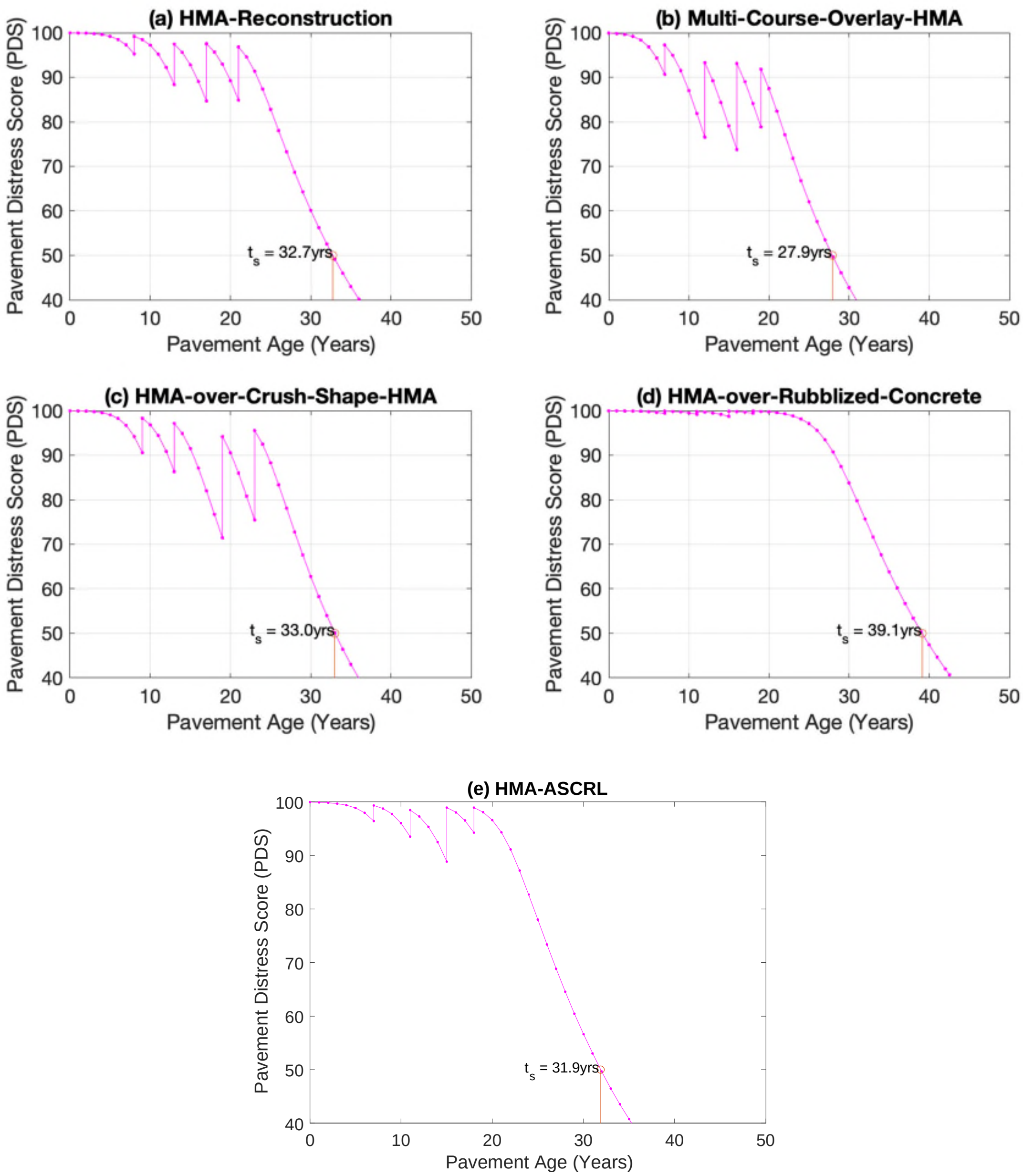


Figure 7-9 Sawtooth graphs for HMA surfaces based on the ASigmoid model (new modeling approach).

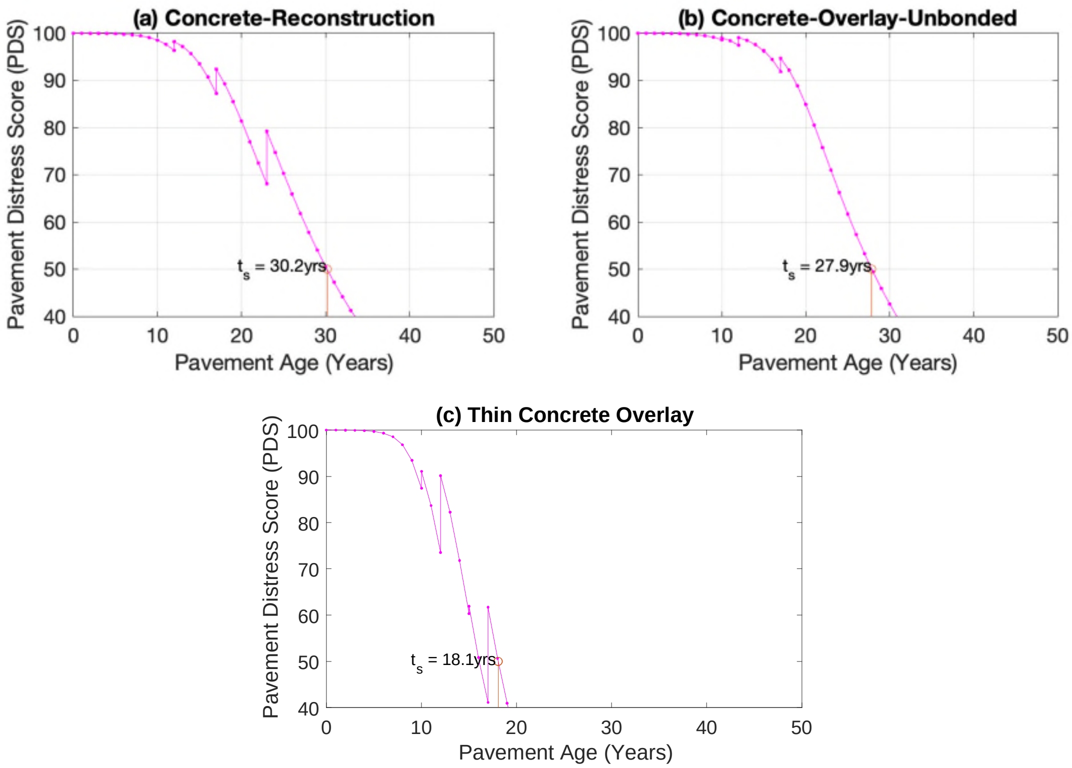


Figure 7-10 Sawtooth graphs for <u>Concrete</u> surfaces based on the <u>ASigmoid</u> model (new modeling approach).

Table 7-4 shows the summary of service lives based on ASigmoid and Logistic curves for different pavement surface types based on the new modeling approach.

Table 7-4 PDS-based service lives computed using the new modeling approach and those based on the MDOT families (which are the same values shown in Table 7-3).

Surface Types	New modeling (fit each curve)		Modeling based on MDOT families		MDOT(1)
	Based on Asigmoid model	Based on Logistic model	Based on Asigmoid model	Based on Logistic model	
HMA Reconstruction	33	40	34	40	36
Multi Course Overlay HMA	28	30	31	36	38
HMA over Crush & Shape HMA	33	40	36	44	39
HMA over Rubblized Concrete	39	44	34	42	32
HMA over ASCRL	32	37	39	40	40
Concrete Reconstruction	30	39	36	40	36
Concrete Overlay (Unbonded)	28	38	28	30	23

Surface Types	New modeling (fit each curve)		Modeling based on MDOT families		MDOT[1)]
	Based on Asigmoid model	Based on Logistic model	Based on Asigmoid model	Based on Logistic model	
Thin Concrete Overlay	18	19	23	22	21

Note: (1) This column shows MDOT's existing service lives based on DI.

8 TASK 6: ALGORITHMS FOR DETERMINING SERVICE LIVES BASED ON THE PAVEMENT DISTRESS SCORE (PDS) AND IRI

This chapter includes descriptions of the algorithms written in MATLAB programming language to perform 'modeling' of PDS and IRI. The modeling algorithms for PDS will be discussed first, then the efforts for IRI modeling will be described next. Formulations and other technical details of the PDS models were provided in Chapters 6 and 7. This chapter only includes the algorithm descriptions.

8.1 Modeling PDS algorithms

The outputs of the PDS 'modeling' algorithms are the following:

- Coefficients of 'ASigmoid' and 'Logistic' models (see Chapter 6 for the details of these models) for each of the groups of pavements that correspond to a specific surface type as listed below:
    - HMA Reconstruction
    - Multi-Course Overlay HMA
    - HMA over Crush & Shape HMA
    - HMA over Rubblized Concrete
    - Concrete Reconstruction
    - Concrete Overlay Unbonded
- For each of the surface types above, several families of pavement segments (e.g., good, fair, and poor-performing pavements) exist. The coefficients of 'ASigmoid' and 'Logistic' models are generated for each of the families for each of the surface types listed above.
- Composite curve coefficients for 'ASigmoid' and 'Logistic' models and the fix lives that correspond to each surface type.
- Sawtooth graphs and service lives for each surface type.

A snapshot of the entry algorithm called 'batch_PDS_modeling.m' is shown in Figure 8-1. As shown, there are several inputs to this algorithm:

- The first input is an Excel sheet named 'PvmntPresrvStrategies.xlsx', which includes the typical maintenance years and increase in PDS values due to these treatments. A snapshot of this file is shown in Figure 8-2. The data in this table is identical to the data shown in Table 7-2. Details on how this table is generated is provided in section 7.2 of this report.
- The second input is the set of file names that correspond to specially formatted CSV files for each surface type. An example CSV input file is shown in Figure 8-3 for the surface

type 'HMA over Rubblized Concrete'. These files contain section-level data for various pavement family groups, including attributes such as pavement age, and corresponding DI and PDS values.

- Initial values, lower and upper bounds of the coefficients of each of the 'ASigmoid' and 'Logistic' models. These are entered manually within the entry script.
- Lengths of the pavements within each family of segments, for each surface type.

The 'batch_PDS_modeling.m' algorithm includes two nested loops. The first one goes through the model types, in this case; two models 'ASigmoid' and 'Logistic'. The second one goes through the pavement surface types. For each model and pavement surface combination, a function named 'main_PDS_modeling.m' is called. The 'main_PDS_modeling.m' function is the main function that computes the outputs listed above.

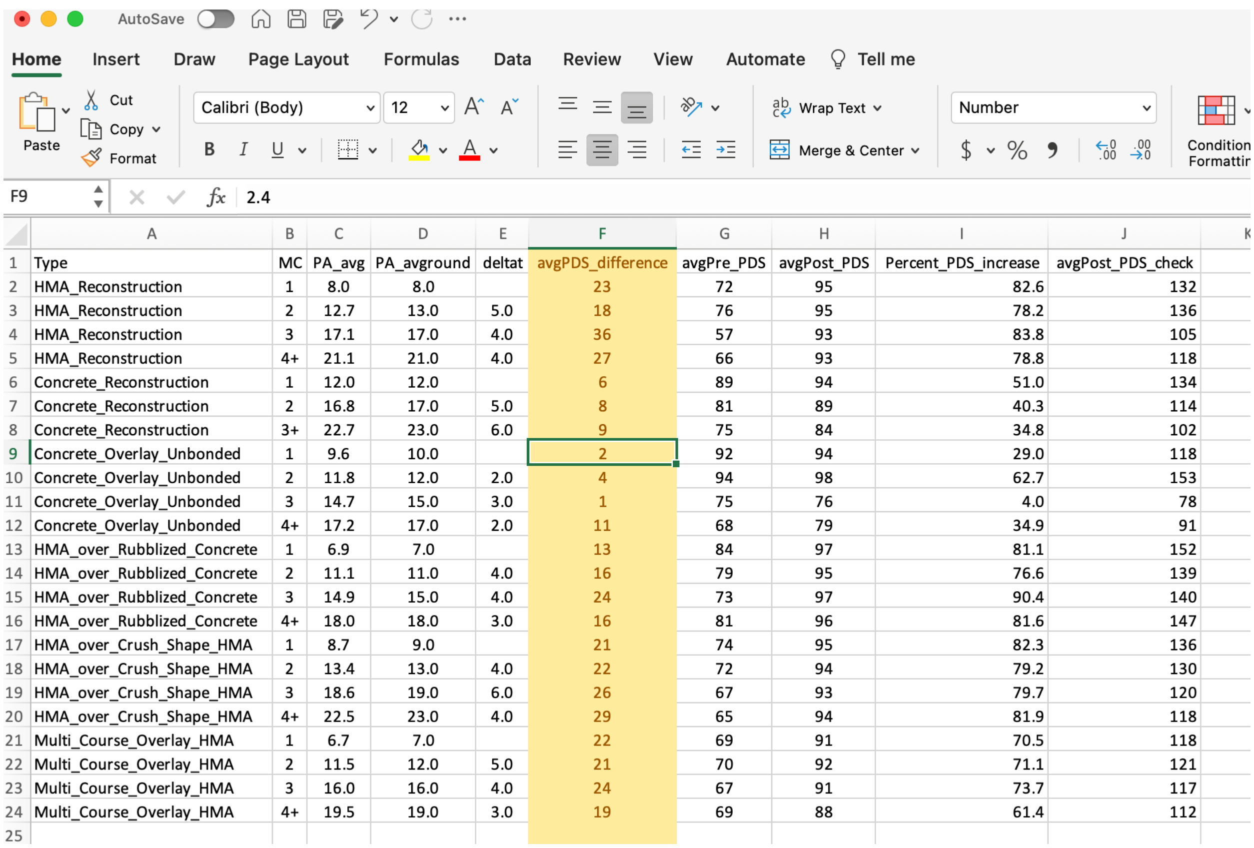
```
%% batch_PDS_modeling.m
% ----------------------------------------------------------------------
% Authors:
% M. Emin Kutay, Michigan State University
% Mumtahin Hasnat, Michigan State University
% James Bryce, West Virginia University
%
% Date: June 1, 2025
%
% Description:
% This script performs batch modeling of Pavement Distress Score (PDS)
% data for different surface types and pavement types (Flexible and Rigid).
% It:
%   1. Reads in pavement family data and preservation strategy parameters.
%   2. Fits PDS deterioration models (ASigmoid, Logistic) to each family.
%   3. Computes composite fix lives and service lives per surface type.
%   4. Saves model coefficients and results to Excel files in the Output folder.
%
% Dependencies:
% - main_PDS_modeling.m
% - f_coeff.m
% - f_get_compositefixlife.m
% - f_calc_service_lives.m
%
% Inputs:
% - Input CSVs and strategy Excel file under `[pwd]/InputData/`
%   * Pavement family data (e.g., 'All_Crush_n_Shape_Pavement_Family.csv')
%   * Preservation strategy file ('PvmntPresrvStrategies.xlsx')
%
% Outputs:
% - Excel tables written to `[pwd]/InputData/Output/`, including:
%   * Coefficients for each model and surface type
%   * Fix life and service life tables
%
% Notes:
% - The script loops over pavement types: 'FLX' (Flexible) and 'RIG' (Rigid).
% - Each surface type is modeled using both ASigmoid and Logistic models.
```

```
% - The Output folder is automatically created if it does not exist.
% - Make sure all necessary files exist under InputData before running.
%
% -----------------------------------------------------------------------
% Main inputs
clear
close all
parentfld          = [pwd,'/InputData/'];
PvmntPrsrvStrtgFile = 'PvmntPresrvStrategies.xlsx';
PDSthreshold       = 50;
plt                = false ;

...
```

Figure 8-1 A snapshot of the beginning of the algorithm called 'batch_PDS_modeling.m'.

In the end, the 'batch_PDS_modeling.m' algorithm creates a summary output file named 'FixLife_ServiceLifeTable_all_surfaces_ASigmoid.xlsx' or 'FixLife_ServiceLifeTable_all_surfaces_Logistic.xlsx', depending on the model chosen. A snapshot of 'FixLife_ServiceLifeTable_all_surfaces_ASigmoid.xlsx' output Excel sheet is shown in Figure 8-4. As shown, the rows of this Excel file correspond to each surface type and columns include the model type, fix life, coefficients of the model (for the composite curve), and the service life.

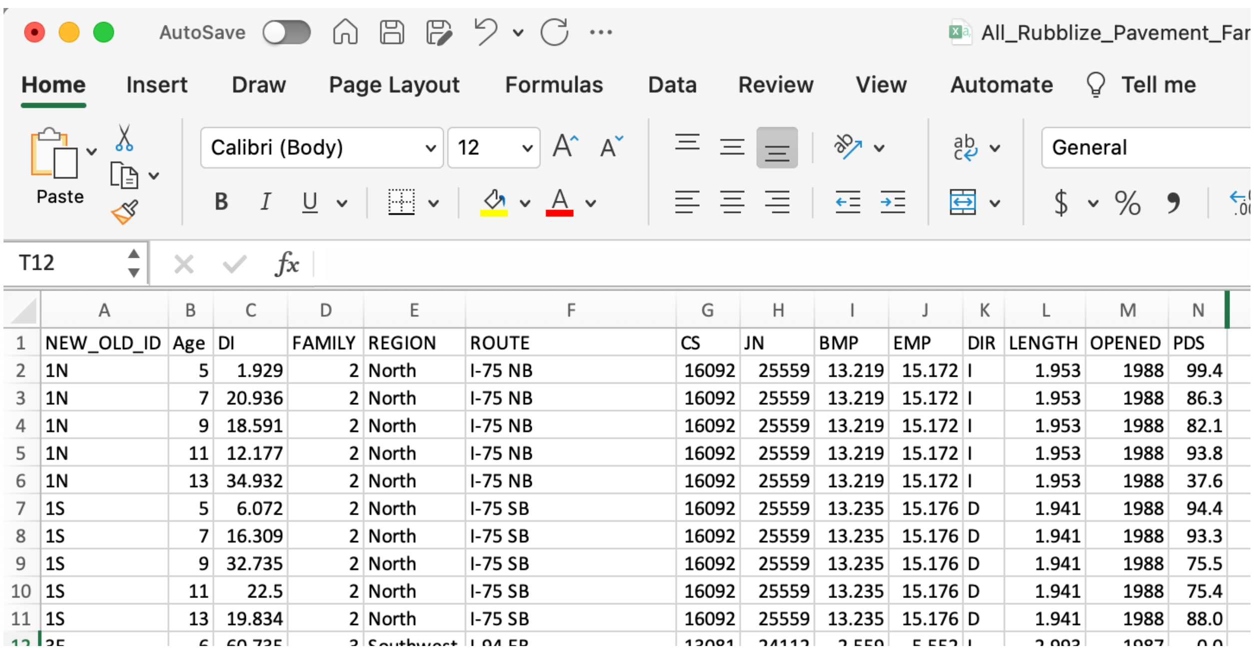


Type	MC	PA_avg	PA_avground	deltat	avgPDS_difference	avgPre_PDS	avgPost_PDS	Percent_PDS_increase	avgPost_PDS_check
HMA_Reconstruction	1	8.0	8.0		23	72	95	82.6	132
HMA_Reconstruction	2	12.7	13.0	5.0	18	76	95	78.2	136
HMA_Reconstruction	3	17.1	17.0	4.0	36	57	93	83.8	105
HMA_Reconstruction	4+	21.1	21.0	4.0	27	66	93	78.8	118
Concrete_Reconstruction	1	12.0	12.0		6	89	94	51.0	134
Concrete_Reconstruction	2	16.8	17.0	5.0	8	81	89	40.3	114
Concrete_Reconstruction	3+	22.7	23.0	6.0	9	75	84	34.8	102
Concrete_Overlay_Unbonded	1	9.6	10.0		2	92	94	29.0	118
Concrete_Overlay_Unbonded	2	11.8	12.0	2.0	4	94	98	62.7	153
Concrete_Overlay_Unbonded	3	14.7	15.0	3.0	1	75	76	4.0	78
Concrete_Overlay_Unbonded	4+	17.2	17.0	2.0	11	68	79	34.9	91
HMA_over_Rubblized_Concrete	1	6.9	7.0		13	84	97	81.1	152
HMA_over_Rubblized_Concrete	2	11.1	11.0	4.0	16	79	95	76.6	139
HMA_over_Rubblized_Concrete	3	14.9	15.0	4.0	24	73	97	90.4	140
HMA_over_Rubblized_Concrete	4+	18.0	18.0	3.0	16	81	96	81.6	147
HMA_over_Crush_Shape_HMA	1	8.7	9.0		21	74	95	82.3	136
HMA_over_Crush_Shape_HMA	2	13.4	13.0	4.0	22	72	94	79.2	130
HMA_over_Crush_Shape_HMA	3	18.6	19.0	6.0	26	67	93	79.7	120
HMA_over_Crush_Shape_HMA	4+	22.5	23.0	4.0	29	65	94	81.9	118
Multi_Course_Overlay_HMA	1	6.7	7.0		22	69	91	70.5	118
Multi_Course_Overlay_HMA	2	11.5	12.0	5.0	21	70	92	71.1	121
Multi_Course_Overlay_HMA	3	16.0	16.0	4.0	24	67	91	73.7	117
Multi_Course_Overlay_HMA	4+	19.5	19.0	3.0	19	69	88	61.4	112

Figure 8-2 A snapshot of the input file named 'PvmntPresrvStrategies.xlsx'

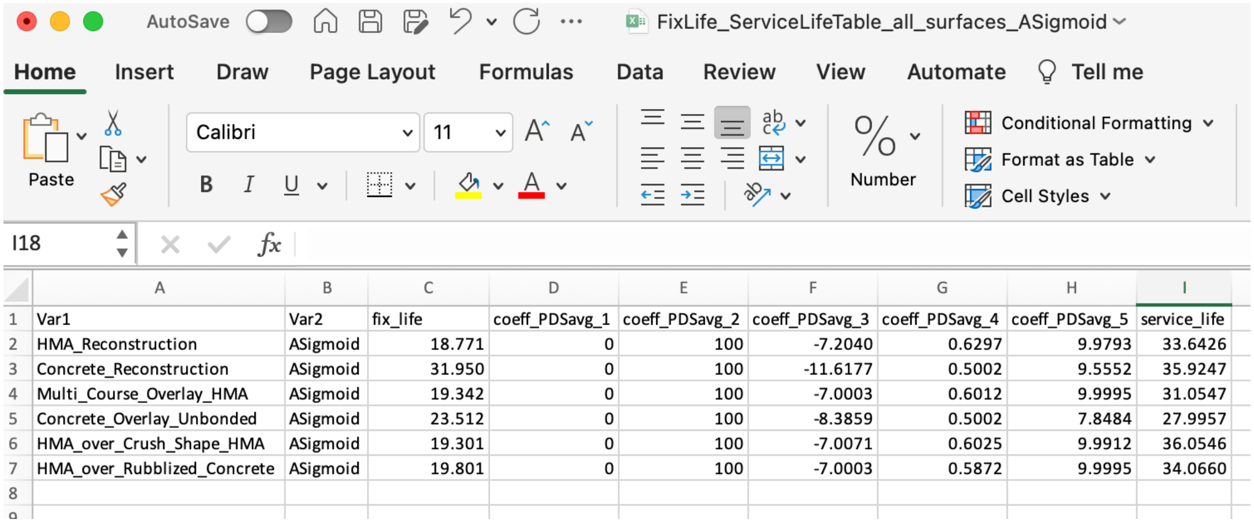
A snapshot of the main algorithm called 'main_PDS_modeling.m' is shown in Figure 8-5. There are four main steps in this algorithm:

- The first step includes reading the CSV file corresponding to a given surface type, and the 'PvmntPresrvStrategies.xlsx' file.
- The second step is fitting the given model to each of the families using the f_coeff.m function. The f_coeff.m algorithm is provided in Appendix A. There are loops and sub-functions within f_coeff.m algorithm that goes through each family of curves and fits the given equation (for example the 'ASigmoid' equation). After fitting, the algorithm computes the fix-life based on the pre-selected threshold for PDS, which is an input shown in the top portion of the 'batch_PDS_modeling.m' code (see the line that includes 'PDSthreshold = 50;').
- The third step involves computation of composite modeling curves based on the modeling curves for each of the families. The 'f_get_compositefixlife.m' function performs this step and this algorithm is provided in Appendix A.
- The fourth step is the computation of service life (sawtooth) curves and this step is performed using the 'f_calc_service_lives.m' function, which is also provided in Appendix A.



NEW_OLD_ID	Age	DI	FAMILY	REGION	ROUTE	CS	JN	BMP	EMP	DIR	LENGTH	OPENED	PDS
1N	5	1.929	2	North	I-75 NB	16092	25559	13.219	15.172	I	1.953	1988	99.4
1N	7	20.936	2	North	I-75 NB	16092	25559	13.219	15.172	I	1.953	1988	86.3
1N	9	18.591	2	North	I-75 NB	16092	25559	13.219	15.172	I	1.953	1988	82.1
1N	11	12.177	2	North	I-75 NB	16092	25559	13.219	15.172	I	1.953	1988	93.8
1N	13	34.932	2	North	I-75 NB	16092	25559	13.219	15.172	I	1.953	1988	37.6
1S	5	6.072	2	North	I-75 SB	16092	25559	13.235	15.176	D	1.941	1988	94.4
1S	7	16.309	2	North	I-75 SB	16092	25559	13.235	15.176	D	1.941	1988	93.3
1S	9	32.735	2	North	I-75 SB	16092	25559	13.235	15.176	D	1.941	1988	75.5
1S	11	22.5	2	North	I-75 SB	16092	25559	13.235	15.176	D	1.941	1988	75.4
1S	13	19.834	2	North	I-75 SB	16092	25559	13.235	15.176	D	1.941	1988	88.0

Figure 8-3 An example input CSV file for the surface type 'HMA over Rubblized Concrete'.



	A	B	C	D	E	F	G	H	I
1	Var1	Var2	fix_life	coeff_PDSavg_1	coeff_PDSavg_2	coeff_PDSavg_3	coeff_PDSavg_4	coeff_PDSavg_5	service_life
2	HMA_Reconstruction	ASigmoid	18.771	0	100	-7.2040	0.6297	9.9793	33.6426
3	Concrete_Reconstruction	ASigmoid	31.950	0	100	-11.6177	0.5002	9.5552	35.9247
4	Multi_Course_Overlay_HMA	ASigmoid	19.342	0	100	-7.0003	0.6012	9.9995	31.0547
5	Concrete_Overlay_Unbonded	ASigmoid	23.512	0	100	-8.3859	0.5002	7.8484	27.9957
6	HMA_over_Crush_Shape_HMA	ASigmoid	19.301	0	100	-7.0071	0.6025	9.9912	36.0546
7	HMA_over_Rubblized_Concrete	ASigmoid	19.801	0	100	-7.0003	0.5872	9.9995	34.0660
8									

Figure 8-4 A snapshot of the output excel sheet: 'FixLife_ServiceLifeTable_all_surfaces_ASigmoid.xlsx'

```
function [fix_life, coeff_PDSavg, service_life, PDSsawtooth, time_yrs_sawtooth, coeff_tbl_each_family,
PDS_measured_tbl_each_family] = main_PDS_modeling(varargin)
% main_PDS_modeling - Main wrapper function for PDS modeling workflow.
% INPUTS:
%   parentfld - Folder path containing input files
%   csvfilename - Pavement family CSV file
%   surf_typelbl - Surface type label (e.g., 'HMA_ASCRL')
%   model - Model name (e.g., 'ASigmoid')
%   binit, bmin, bmax - Model parameter bounds
%   PDSthreshold - PDS threshold for fix life
%   lngth_each_fmly - Lane lengths for weighting
%   PvmntPrsrvStrtgFile - Excel file for preservation strategies
%   doType - Pavement type ('FLX' or 'RIG')
%   outputFolder - Folder to store result files
% OUTPUTS:
%   fix_life - Composite fix life
%   coeff_PDSavg - Average model coefficients
%   service_life - Calculated service life
%   PDSsawtooth, time_yrs_sawtooth - Sawtooth response
%   coeff_tbl_each_family, PDS_measured_tbl_each_family - Per-family fit results

if nargin == 0
    clear
    close all
    %  <------------- Inputs ------------->
    parentfld           = [pwd,'/InputData/'];
    csvfilename         = 'All_Crush_n_Shape_Pavement_Family.csv';
    surf_typelbl        = 'HMA_over_Crush_Shape_HMA';
    model               = 'ASigmoid';
    binit               = [0, 100, -10, 1, 1];
    bmin                = [0, 100, -20, 0.5, 0.5];
    bmax                = [0, 100, -7, 4, 10];
```

```
    PDSthreshold       = 50;
    lngth_each_fmly    = [723.3, 568.0, 252.1, 245.7]; % miles
    PvmntPrsrvStrtgFile = 'PvmntPresrvStrategies.xlsx';
    plt                = true ;
else
    close all
    % <------------- Inputs ------------->
    parentfld          = varargin{1};
    csvfilename        = varargin{2};
    surf_typelbl       = varargin{3};
    model              = varargin{4};
    binit              = varargin{5};
    bmin               = varargin{6};
    bmax               = varargin{7};
    PDSthreshold       = varargin{8};
    lngth_each_fmly    = varargin{9};
    PvmntPrsrvStrtgFile = varargin{10};
    plt                = varargin{11};
    doType             = varargin{12};
    outputFolder       = varargin{13};

end

…
```

Figure 8-5 A snapshot of the beginning of the algorithm called 'main_PDS_modeling.m'.

There are several intermediate outputs of the algorithms. A snapshot of the folders where the intermediate outputs of the algorithms are located is shown in Figure 8-6. These intermediate outputs include:

- A CSV file for each surface type that includes the coefficients of a chosen model (e.g., ASigmoid or Logistic) used to fit each family of curves (see Figure 8-7).
- A folder (labeled 'pngs') that includes several kinds of graphs:
    - Example Graph 1: "HMA_over_Rubblized_Concrete-ASigmoid_fit_families.png" (see Figure 8-8)
    - Example Graph 2: "HMA_over_Rubblized_Concrete-ASigmoid_composite_families.png" (see Figure 8-9)
    - Example Graph 3: " HMA_over_Rubblized_Concrete-ASigmoid_sawtooth.png " (see Figure 8-10)

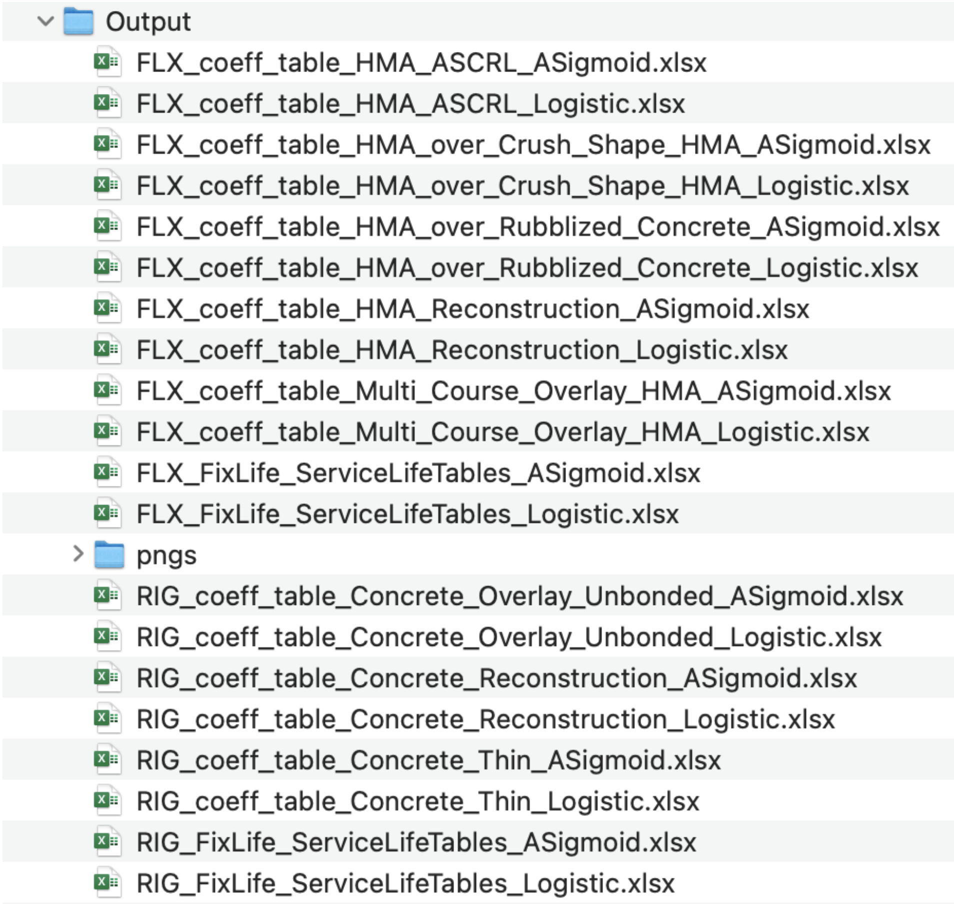
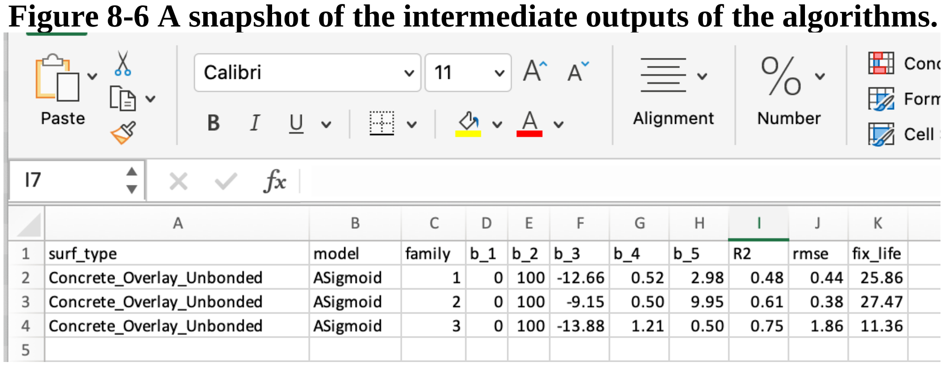


Figure 8-6 A snapshot of the intermediate outputs of the algorithms.



	A	B	C	D	E	F	G	H	I	J	K
1	surf_type	model	family	b_1	b_2	b_3	b_4	b_5	R2	rmse	fix_life
2	Concrete_Overlay_Unbonded	ASigmoid	1	0	100	-12.66	0.52	2.98	0.48	0.44	25.86
3	Concrete_Overlay_Unbonded	ASigmoid	2	0	100	-9.15	0.50	9.95	0.61	0.38	27.47
4	Concrete_Overlay_Unbonded	ASigmoid	3	0	100	-13.88	1.21	0.50	0.75	1.86	11.36
5											

Figure 8-7 A snapshot of the CSV file that includes the coefficients of the models for each family of curves.

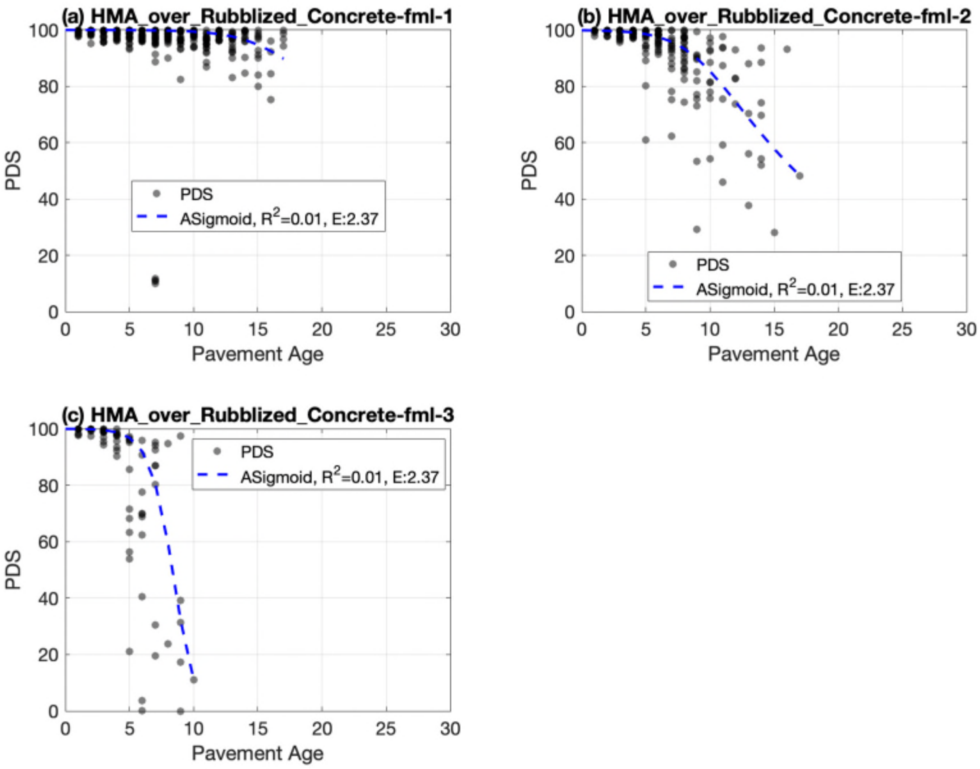


Figure 8-8 A snapshot of the "HMA_over_Rubblized_Concrete-ASigmoid_fit_families.png" file.

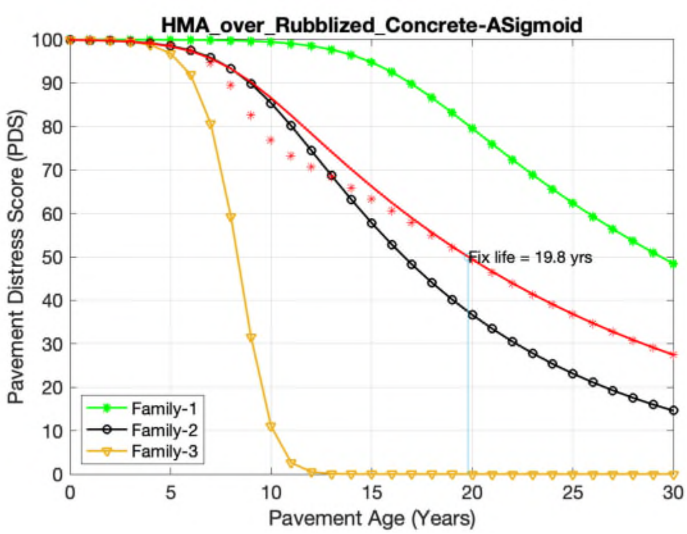


Figure 8-9 A snapshot of the "HMA_over_Rubblized_Concrete-ASigmoid_composite_families.png" file.

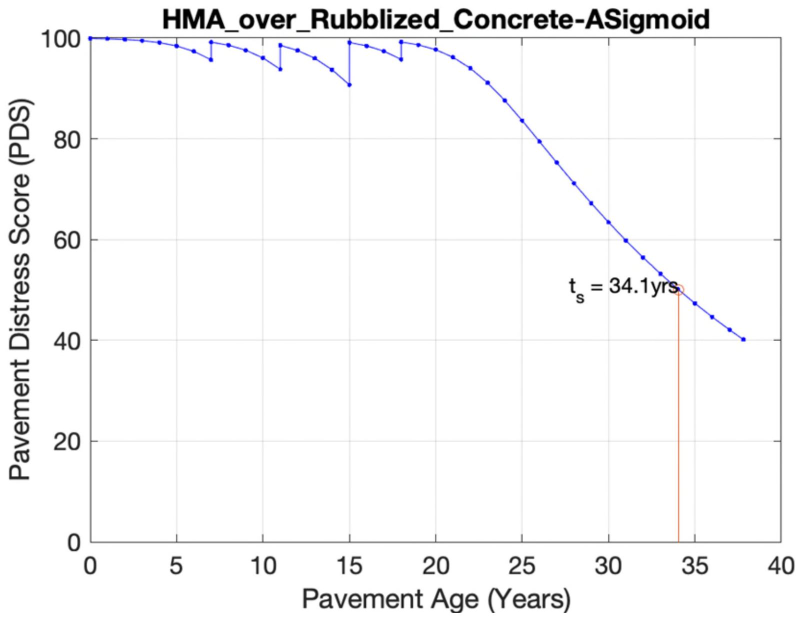


Figure 8-10 A snapshot of the "HMA_over_Rubblized_Concrete-ASigmoid_sawtooth.png" file.

8.2 IRI Modeling - service life curves for IRI

One objective of the analysis in this chapter was to evaluate whether IRI should be used to inform the lifecycle modeling. In order to evaluate what impact IRI may have on the lifecycle modeling results, service lives were calculated based on IRI instead of PDS. Only reconstruction of HMA and Concrete pavements were considered in the first iteration of this analysis, with acknowledgement that the remainder of the fix types would be evaluated if the results from the reconstruction analysis were promising.

The first consideration is that the IRI data do not completely coincide with DI data. For example, Table 8-1 shows the first 10 years of data for a pavement segment, and ages one, seven and nine show examples where either IRI or DI data exists, but not both. The consequence of this is that different data are available to calculate the ages for different maintenance cycles when calculated with IRI as compared to the DI (or PDS). This does not mean that different maintenance actions occur for a given segment, only that the sample of data used to calculate the age for different maintenance cycles is different. Therefore, it was determined that two sets of analyses should be performed. The first calculates the change in IRI and age for each maintenance cycle using the same approach as was used with PDS, meaning that the ages at the maintenance cycles will be different. The second approach assumes that the ages at each maintenance cycle calculated for the PDS is the correct age to consider, and the changes in IRI from the first approach were applied with the PDS ages.

Table 8-1 Subset from table matching IRI and DI (PDS) data.

ID	Pavement Age	IRI	Rut	DI	Year	Location or Remark or Fix
41W	NaN	NaN	NaN	NaN	1998	'US-12 WB'
	1	NaN	NaN	0	1999	'<undefined>'
	3	83.4	0.24	0.8	2001	'<undefined>'
	5	77.7	0.09	2.3	2003	'<undefined>'
	6	NaN	NaN	NaN	2004	'OCF/CM(1.5"-3")&R(1.5"-3")'
	7	84.4	0.11	NaN	2005	'segments'
	9	76.5	0.25	NaN	2007	'<undefined>'
	10	NaN	NaN	NaN	2008	'CM(1.5")&R(1.5")'

For the first analysis, the ages at each maintenance cycle and changes in IRI were calculated using the same approach as was used with the PDS. Table 8-2 shows the ages at the four maintenance categories along with the respective change in IRI for HMA Reconstruct, both freeway and non-freeway. Table 8-3 shows the results for concrete reconstruction. Next, an exponential curve was fitted to the IRI growth using a generalized linear model assuming a lognormal distribution in the data. Bryce (2023) details why this is a good modeling approach for IRI data. Figure 8-11 shows the service life curve for asphalt reconstruction, and the service life is 47 years when assuming that 170 inches/mile is failure. Similarly, Figure 8-12 shows the service life curve for concrete reconstruction, and the service life is 44 years when assuming that 170 inches/mile is failure. Both of those values are many years higher than when calculated using PDS based service life estimates.

Table 8-2. Age at maintenance categories and change in IRI for HMA reconstruct.

Type	MC	Age	ΔIRI (inch/mile)
HMA Reconstruction (F & NF)	1	7.2	4.2
HMA Reconstruction (F & NF)	2	11	10.8
HMA Reconstruction (F & NF)	3	12.8	8.8
HMA Reconstruction (F & NF)	4+	18.4	7.2

Table 8-3. Age at maintenance categories and change in IRI for concrete reconstruct.

Type	MC	Age	ΔIRI (inch/mile)
Concrete Reconstruction	1	8.9	3.7
Concrete Reconstruction	2	14.1	11.5
Concrete Reconstruction	3+	18	7.9

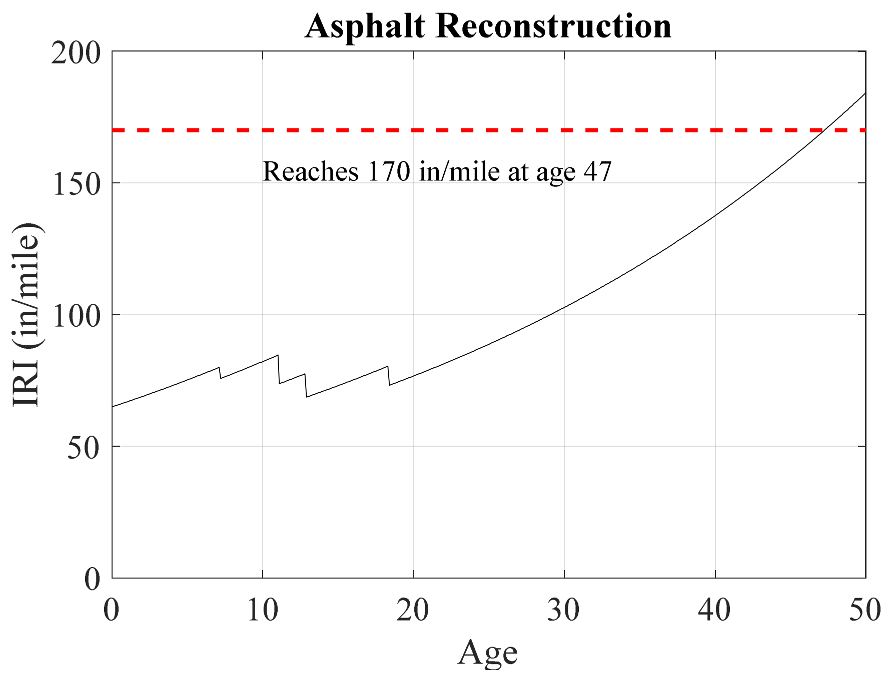


Figure 8-11. Service life curve for asphalt reconstruction assuming the IRI based maintenance cycle ages.

It is not reasonable to have different ages for the same maintenance category depending on whether IRI or PDS is considered, so the next analysis considered the maintenance category ages from the PDS analysis along with the change in IRI from Table 8-2 and Table 8-3. Figure 8-13 shows the service life curve for HMA reconstruct when using the PDS maintenance category ages, and the estimated service life is 46 years. Similarly, Figure 8-14 shows the service life curve for concrete reconstruct when using the PDS maintenance category ages, and the estimated service life is 43 years.

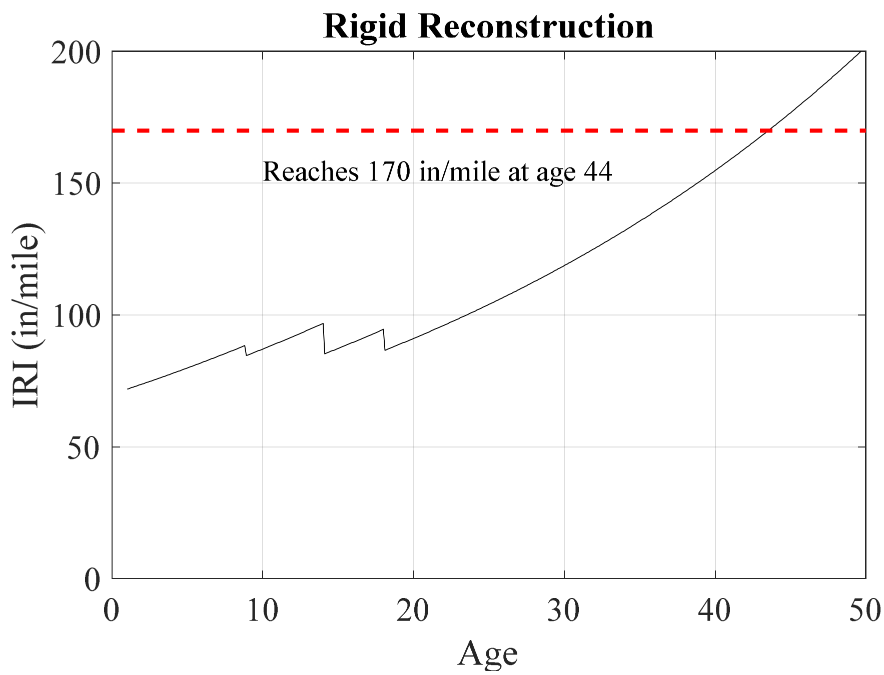


Figure 8-12. Service life curve for concrete reconstruction assuming the IRI based maintenance cycle ages

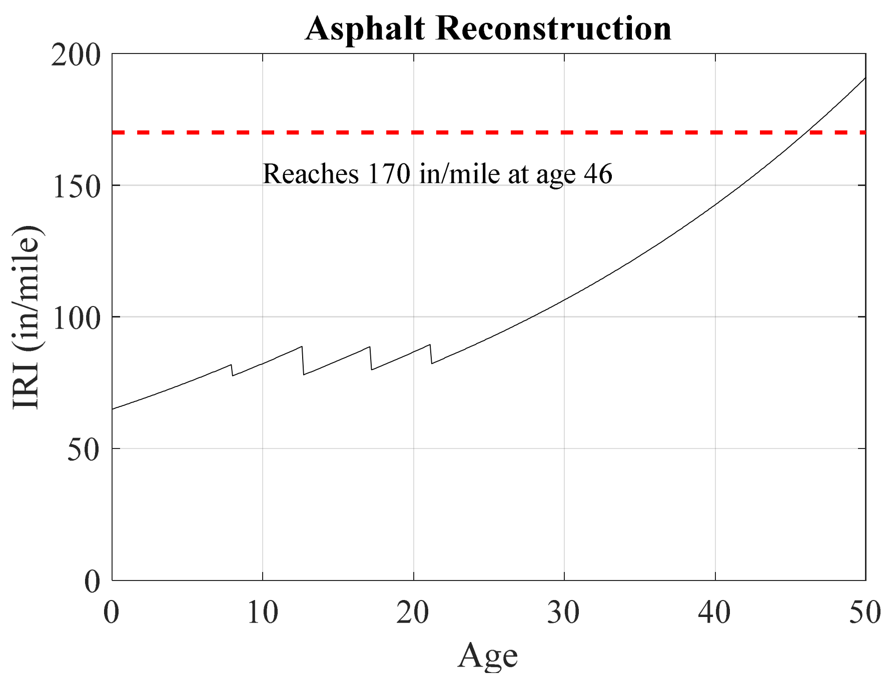


Figure 8-13. Service life curve for asphalt reconstruction assuming the PDS based maintenance cycle ages

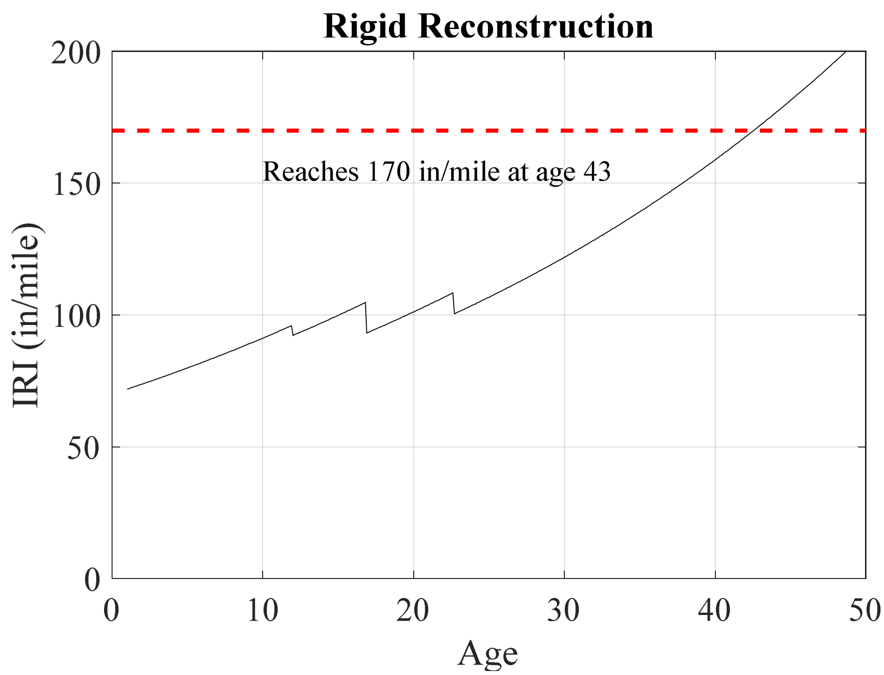


Figure 8-14. Service life curve for concrete reconstruction assuming the PDS based maintenance cycle ages

In both analyses performed to evaluate the service life curves for IRI, the estimated service life values were larger for IRI than for PDS. In the case of asphalt reconstruction, the IRI based service life was 46 years, compared to 36 years when using the PDS. For concrete reconstruction, the IRI based service life was 43 years, compared to 36 years when using the PDS.

9 TASK 7: EVALUATE AND RECOMMEND NETWORK-LEVEL MODELING METHODS FOR IRI, CRACKING, RUTTING AND FAULTING

9.1 INTRODUCTION

Since the implementation of the national pavement performance management rules detailed in 23 CFR Part 490, there has been significant interest in modeling IRI, HPMS (Highway Performance Monitoring System) percent cracking, rutting, and faulting at the network-level. The objective of this task was to propose methodologies for MDOT to model network level IRI, HPMS cracking, faulting, and rutting. The methodologies will allow for MDOT to set target network pavement conditions goals to meet the related requirements within the federal pavement performance rule. The National Cooperative Highway Research Program (NCHRP) Report 1035 presented a comprehensive guide for setting performance targets (Grant, et al. 2023). As part of the NCHRP Report 1035 effort, a broad review of target setting practices was conducted, and the findings were distilled into five different approaches:

1. *Target Change in Condition*: This approach does not require analysis, but instead relies on consensus of a group of experts. First, a long-term (e.g., 10-year) target is defined, and then a required change per year is established. This change per year value is then used to define the 2- and 4-year targets. This is useful if little or no historical data are available.

2. *Time Series Trend*: In this approach, the annual change in condition (e.g., change in percent poor) is plotted as a function of annual expenditures. A linear relationship is then developed, and that relationship is projected into the future.

3. *Time-Series Trend plus Future Funding*: Similar to previous approach, except a regression relationship is developed between change and performance and expenditures, then future expenditures are projected.

4. *Pavement Management System*: In this approach, the data and models within the pavement management system are used along with projected future expenditures and programmed work to develop trends.

5. *Scenario Analysis*: This approach uses the pavement management system and information on future programmed projects to perform many different scenario analyses based on varying levels of future funding.

A review of practices across multiple state DOTs was conducted to better understand options for MDOT implementation. For example, Missouri DOT develops a time series trend and, assuming the same level of funding in future years, projects the condition forward in time to develop a target (MoDOT 2019). Louisiana Department of Transportation and Development (DOTD) uses the first method in the above list due to a lack of historical measurements(Louisiana Department of Transportation and Development 2018) (LaDOTD 2018). The West Virginia Division of Highways (DOH) uses scenario analyses (approach 5) to develop targets (WV DOH 2019).

MDOT has significant historical condition data that can be used in the target setting process, so only the two approaches that rely on historical condition were further considered. The first approach involved developing performance models based on historical data, which could then be integrated into the pavement management system to support scenario analyses. The pavement management system is necessary in this case because the scenario analysis includes treatment selection for specific projects based on optimization across the pavement network. The second approach considered the development of Markovian Transition Probability Matrices (TPMs), in which scenario analyses could be conducted without using the pavement management system. Given that historical condition data could be used without the need of the pavement management system, the approach for using TPMs was further investigated.

9.2 DEVELOPMENT OF THE MARKOVIAN TRANSITION PROBABILITY MATRICES

Markovian Transition Probability Matrices (TPMs) are developed as a component for projecting the estimated evolution of various condition metrics across the network over time. Such condition metrics may include IRI (International Roughness Index), CRK (HPMS cracking), RUT (Rutting), and FLT (Faulting). The projections made with transition matrices account for both (1) natural pavement deterioration and (2) the expected effect of planned pavement treatments (or "fixes") over the network. Projections are conducted starting from an initial condition ("starting point"), representing the overall status of the network in a specific year. To generate these projections, an appropriate set of transition matrices for the selected condition metric is combined and weighted according to the anticipated fixes (categorized as either CPM-Capital Preventive Maintenance, RCN-Reconstruction, or RHB-Rehabilitation). Figure 9-1 presents an overview of the general steps of the process, which are explained next.

The input data that was used to build the transition matrices included two types of files:

- ***"GroupRecord"* files.** These files contain road network data including ID, Linear Referencing System information (PR/BMP/EMP), number of lanes, and TAMP Tier. A road section is generally defined by the limits of the original rehabilitation or reconstruction job. Additionally, these files include a detailed record of the maintenance (fix type, cycle, maintenance BMP/EMP) performed on the road sections. They are an output report from MDOT's *Pavement Analysis, Valuation, Examination, and Tracking* (PAVETrack) application. Each rehabilitation or reconstruction fix type has a separate file. Depending on the material type on the surface of the pavement surface, the files are divided into two groups: flexible or rigid.
- **"HPMS-formatted" files:** These files contain yearly 0.1-mile measurements of the condition metrics (IRI, CRK, RUT, FLT) for a significant portion of the network. On average, these files record measurements over nearly 7,000 (route) miles yearly. Figure 9-2 illustrates the extent of miles measured each year contained in these files. These are files of MDOT's data collection that are for submittal to FHWA for HPMS requirements.

When building the transition matrices, only the data from road segments with a known maintenance record may be used.

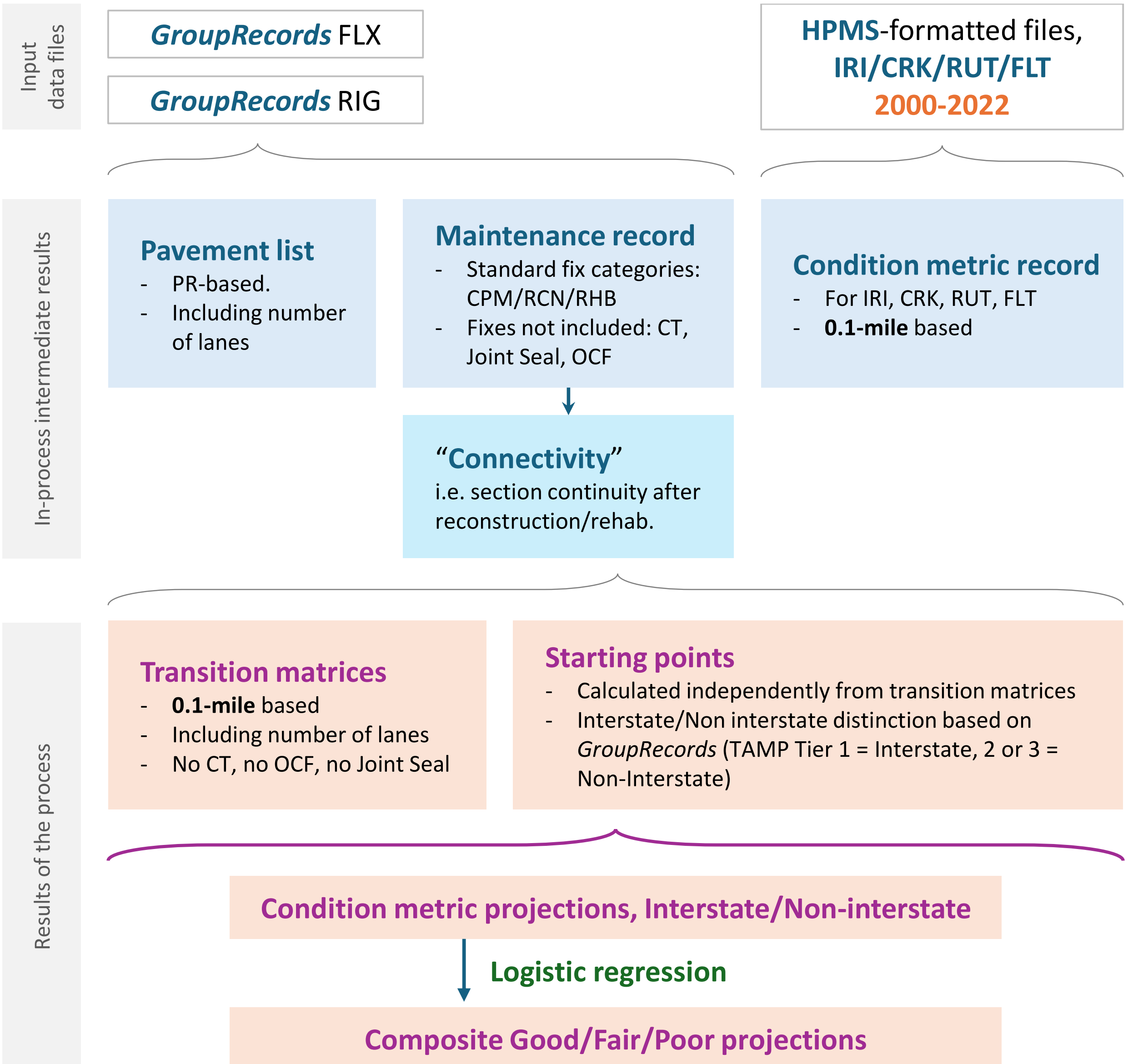


Figure 9-1. Chart describing the steps of the process: building transition matrices, performing projections of the condition metrics, and using a calibrated logistic regression to produce composite projections.

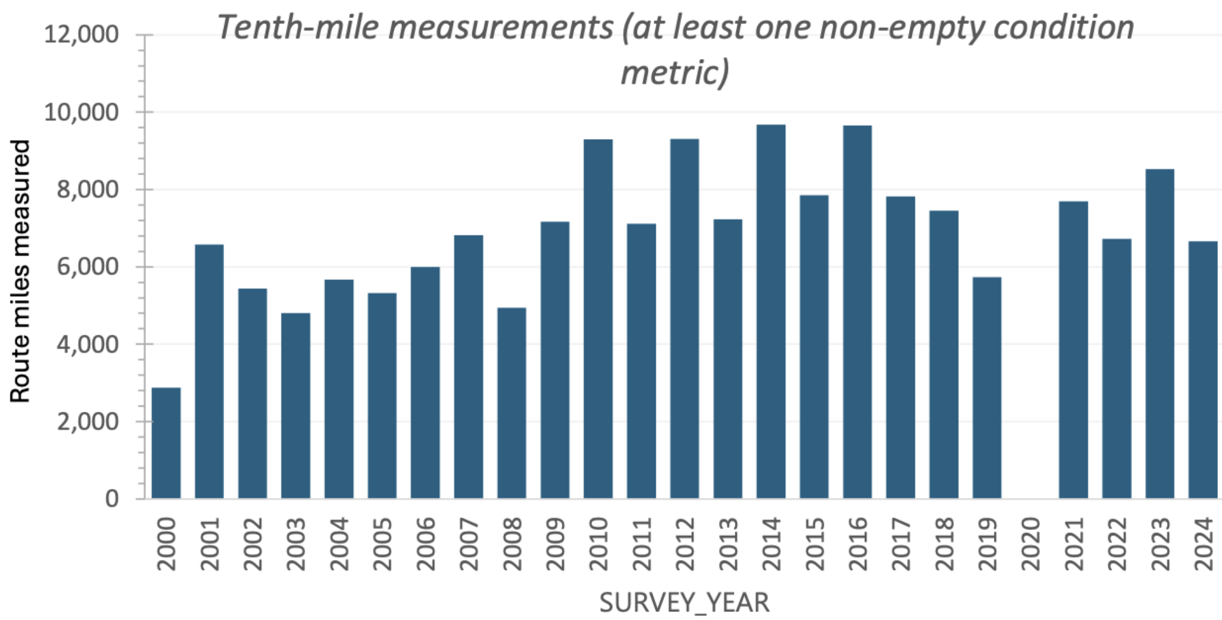


Figure 9-2. Total route miles surveyed (measured) each year, from the HPMS-formatted data files. The measurements are taken every tenth-mile.

A set of transition matrices was developed for each condition metric, consisting of six matrices: three representing deterioration (one each for CPM, RCN, and RHB) and three representing improvement (again, one each for CPM, RCN, and RHB), as detailed later. Each condition metric is associated with either flexible or rigid pavement types, as follows: IRI FLX, IRI RIG, CRK FLX, CRK RIG, RUT (flexible only), and FLT (rigid only).

The process of building the transition matrices is divided into steps:

- *Step 1.* Create a pavement list based on the *GroupRecords* files “stacked” together, i.e. each fix type file appended at the end of the other to produce a single file.
- *Step 2.* Compile the maintenance record of the sections, using data from the *GroupRecords* files.
- *Step 3.* Compile the history of the condition metrics (IRI, CRK, RUT, FLT) for the road sections, i.e. a set of BMP, EMP, and tenth-mile condition measurements over time.
- *Step 4.* Combine the information from the maintenance record (Step 2) and the condition history (Step 3) to build the transition matrices.

A set of MATLAB scripts were developed to perform the steps. This code is included as a digital appendix to the report. The considerations for each of the steps are described below.

9.3 STEP 1. PAVEMENT LIST CREATION, INCLUDING SECTION CONNECTIVITY

The pavement list is a file that summarizes the road network data of the sections. This information includes the section ID, its PR (BMP/EMP), number of lanes, and TAMP tier classification. To build the pavement list:

- First, identify the “Parent” fix of each of the *GroupRecords* files, to characterize the individual files as either Flexible (Multi-Course HMA, Crush & Shape, HMA Reconstruction, Rubblize, ASCRL-Asphalt Stabilized Crack Relief Layer) or Rigid (JRCP Reconstruction, JPCP Reconstruction, Concrete Overlay (Unbonded), Thin Concrete Overlay). The individual files are “stacked” together into one file.
- The rows of this file where the field CYCLE is “Parent” correspond to the start of the life of the road sections. These rows are extracted to a separate file that becomes the basis of the pavement list.
- Two additional fields (two additional columns to the Excel sheet) are added to the pavement list: Each section’s opening and ending year, if applicable.

An additional element is the “connectivity” of the sections. Connectivity means that if a section has reached its end of life, the pavement list includes the ID of the section(s) that were built in its place (i.e. same PR, similar BMP/EMP range, opened at the same year the previous section ended). At the same time, if a section is a reconstruction, the pavement list includes the ID of the section(s) that preceded it. Connectivity is established using an analysis of the PR BMP/EMP ranges of the sections, together with their ending and opening years. Additionally, the pavement list includes the surface type (flexible or rigid) of the preceding and following sections.

The pavement list contains information on 2,008 *active* FLX sections (2,408 including end-of-life) and 630 *active* RIG sections (790 including end-of-life). The active sections have an extent of 13,405 flexible lane miles (75%) and 4,477 rigid lane miles (25%). A partial screenshot of the pavement list is shown in Figure 9-3.

	A	B	C	D	E	F	G	H	I	J	K
1	ID	FLX_RIG	PARENT_FIX	ROUTE	DIR	REGION	TIER	YEAR_OPEN	YEAR_END	LIFE	PR
2	7	FLX	MULTI-CSE HMA	M-85	NB	Metro	3	2005	2011	6	4700047
3	9	RIG	RECON JRCP	M-59	WB	Metro	3	1995	2018	23	807801
4	10	RIG	RECON JRCP	M-59	EB	Metro	3	1995	2018	23	820202
5	15	FLX	MULTI-CSE HMA	I-94	EB	Metro	1	2002	2013	11	798501
6	16	FLX	MULTI-CSE HMA	I-94	WB	Metro	1	2002	2020	18	1588802
7	17	FLX	MULTI-CSE HMA	I-94	EB	Metro	1	2002	2020	18	1576405
8	18	FLX	MULTI-CSE HMA	I-94	WB	Metro	1	2002	2013	11	798502
9	31	FLX	MULTI-CSE HMA	I-94	EB	Metro	1	2002	2020	18	1576405
10	32	FLX	MULTI-CSE HMA	I-94	WB	Metro	1	2002	2020	18	1588802
11	39	RIG	RECON JRCP	I-96	EB	Metro	1	1977	2004	27	1606201
12	40	RIG	RECON JRCP	I-96	WB	Metro	1	1977	2004	27	1606503
13	41	FLX	C&S	M-72	2 Way	North	3	1984	2019	35	535803
14	45	FLX	MULTI-CSE HMA	I-96	WB	University	1	1989	2019	30	337310
15	46	FLX	MULTI-CSE HMA	I-96	EB	University	1	1989	2019	30	337304
16	48	FLX	MULTI-CSE HMA	US-31	NB	Grand	2	2001			1906409
17	49	FLX	MULTI-CSE HMA	US-31	SB	Grand	2	2001			1906610
18	57	RIG	RECON JRCP	M-14	EB	Metro	2	1979	2007	28	1606205
19	58	RIG	RECON JRCP	M-14	WB	Metro	2	1979	2007	28	1606204
20	66	FLX	MULTI-CSE HMA	M-139	2 Way	Southwest	3	1983	1994	11	3111292

Figure 9-3. Screenshot of the pavement list (partial view). Each row contains data for one section.

9.4 STEP 2. MAINTENANCE RECORD

Before building the transition matrices, it is necessary to compile a detailed record of the maintenance (fix) activities that were performed throughout the life of each road section. The transition matrices will use this data to capture and reflect two key aspects: (1) how the sections deteriorate after a fix, and (2) the impact and effectiveness of the fixes.

The information related to maintenance events is also contained in the *GroupRecords* files. Besides the section identification information, these files contain a list of the maintenance activities performed on the sections over the years, as well as the maintenance BMP-EMP range, and job number. Each fix-event is identified with a label. There were 32 unique fix types reported in the maintenance record of the sections. To facilitate the creation of the transition matrices, the fix types were sorted into three categories: (i) “CPM”: Capital Preventive Maintenance, (ii) “RCN”: reconstruction, and (iii) “RHB”: rehabilitation. Once categorized, there were 1,547 individual CPM fixes, 673 reconstructions, and 1,035 rehabilitations in the record. The unique fix types are presented in Table 9-1 along with the number of times each of the fixes took place. The count considers the fact that a unique job number may refer to several fix locations in the same year. The maintenance record is summarized as a spreadsheet. A partial screenshot of the maintenance record is provided in Figure 9-4. The maintenance record includes the fix type (after categorization), maintenance cycle, the PR and BMP/EMP range of each maintenance, as well as information on Job number and the number of lanes that were intervened. This data enables the calculation of lane-miles receiving each type of fix annually, according to the record. Figure 9-5 presents a summary of this data.

	B	C	D	E	F	G	H	I	J	K	L	M
1	FLX_RIG	PARENT_FIX	ROUTE	DIR	REGION	TIER	DATE	YEAR	AGE	FIX_TYPE	CYCLE	PR
2	FLX	MULTI-CSE HMA	M-85	NB	Metro	3	10/31/05 0:00	2005	0	RHB	Parent	4700047
3	FLX	MULTI-CSE HMA	M-85	NB	Metro	3	10/31/11 0:00	2011	6	RCN	End	4700047
4	RIG	RECON JRCP	M-59	WB	Metro	3	10/31/95 0:00	1995	0	RCN	Parent	807801
5	RIG	RECON JRCP	M-59	WB	Metro	3	10/31/05 0:00	2005	10	CPM	1	807801
6	RIG	RECON JRCP	M-59	WB	Metro	3	10/31/07 0:00	2007	12	CPM	2	807801
7	RIG	RECON JRCP	M-59	WB	Metro	3	10/31/10 0:00	2010	15	CPM	3	807801
8	RIG	RECON JRCP	M-59	WB	Metro	3	10/31/18 0:00	2018	23	RCN	End	807801
9	RIG	RECON JRCP	M-59	EB	Metro	3	10/31/95 0:00	1995	0	RCN	Parent	820202
10	RIG	RECON JRCP	M-59	EB	Metro	3	10/31/05 0:00	2005	10	CPM	1	820202
11	RIG	RECON JRCP	M-59	EB	Metro	3	10/31/07 0:00	2007	12	CPM	2	820202
12	RIG	RECON JRCP	M-59	EB	Metro	3	10/31/10 0:00	2010	15	CPM	3	820202
13	RIG	RECON JRCP	M-59	EB	Metro	3	10/31/18 0:00	2018	23	RCN	End	820202
14	FLX	MULTI-CSE HMA	I-94	EB	Metro	1	10/31/02 0:00	2002	0	RHB	Parent	798501
15	FLX	MULTI-CSE HMA	I-94	EB	Metro	1	10/31/10 0:00	2010	8	CPM	N/A	798501
16	FLX	MULTI-CSE HMA	I-94	EB	Metro	1	10/31/13 0:00	2013	11	RHB	End	798501
17	FLX	MULTI-CSE HMA	I-94	WB	Metro	1	10/31/02 0:00	2002	0	RHB	Parent	1588802
18	FLX	MULTI-CSE HMA	I-94	WB	Metro	1	10/31/11 0:00	2011	9	CPM	2	1588802
19	FLX	MULTI-CSE HMA	I-94	WB	Metro	1	10/31/20 0:00	2020	18	RHB	End	1588802
20	FLX	MULTI-CSE HMA	I-94	EB	Metro	1	10/31/02 0:00	2002	0	RHB	Parent	1576405

Figure 9-4. Screenshot of the maintenance record (partial view). The first row of data of each section is shaded: darker for a flexible section, lighter for a rigid section.

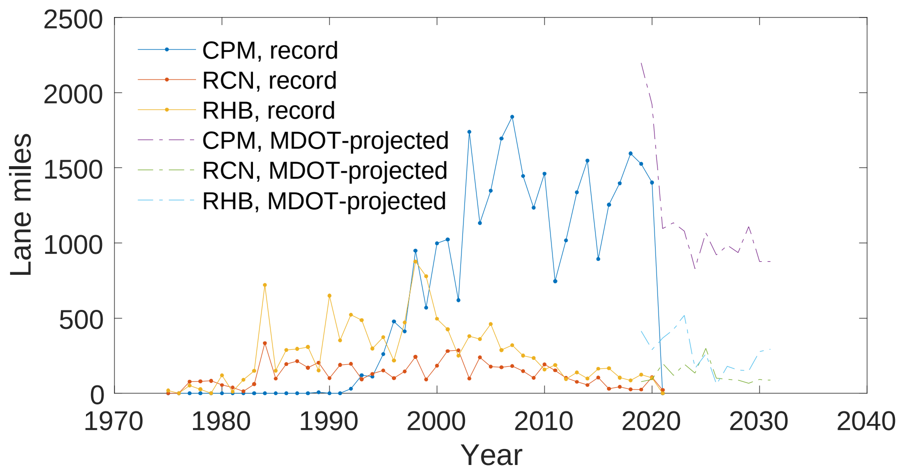


Figure 9-5. Number of lane-miles undergoing CPM, reconstruction (RCN), and rehabilitation (RHB) over the years, according to the maintenance record. The dotted lines to the right are the planned values provided by MDOT for the years after 2020.

Table 9-1. Fix types and count, based on the maintenance record. Rehabilitations (RHB) are shaded, reconstructions (RCN) are framed in a box. All other fixes are categorized as Capital Preventive Maintenance (CPM)*.

Fix type	Number of occurrences	Fix type	Number of occurrences
ASCRL (Asphalt Stabilized Crack Relief Layer)	37	Hot Mastic	4
C&S (Crush and Shape)	297	Joint Seal †	44
CPR (Concrete Pavement Repairs)	108	Micro Double	85
CT (Crack Treatment) †	346	Micro Single	151
Cape Seal	22	Multi-Cse HMA	622
Chip Double	58	OCF (Overband Crack Fill) †	133
Chip Single	120	PPSS (Paver Placed Surface Seal)	31
Conc FDRs	137	Recon HMA	346
Conc Overlay	32	Recon JPCP	161
Conc Overlay Thin	3	Recon JRCP	136
DBR (Dowel Bar Retrofit)	2	Rubblize	79
DG (Diamond Grinding)	10	Skip Patching	9
ET(Emerging Technology)	13	Slab Stabilization	3
FiberMat	4	Slurry Seal	1
HMA Ovly Single	176	Texas Underseal	6
HMA Ovly Single & Mill	617	UT HMA (ultra-thin HMA overlay)	60

† Note: When building the transition matrices, the following fixes are not considered: CT (Crack Treatment), Joint Seal, and OCF (Overband Crack Fill).

An additional set of factors (or "fractions") can be calculated based on the maintenance record, related to the yearly fraction of intervened miles that are FLX or RIG, and Interstate or Non-Interstate, depending on the fix. For example, it was possible to estimate that on average, from the CPM-fix lane miles intervened in a year, approximately 15% are Interstate/Flexible, 19.4%

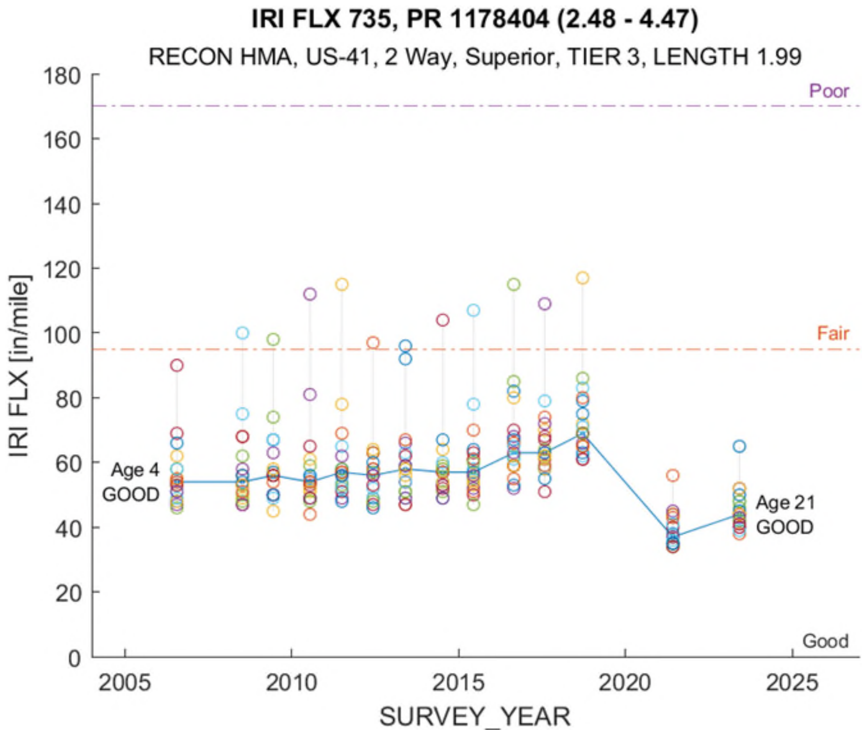
are Interstate/Rigid, 30% are Non-Interstate/Flexible, and 7.3% are Non-Interstate/Rigid; the remaining percent are Tier 4 miles. This data represents the surface type after the fixes take place. The factors are of importance when producing projections, since these are calculated independently for four fractions of the network (Interstate/Flexible, Interstate/Rigid, Non-Interstate/Flexible, and Non-Interstate/Rigid).

9.5 STEP 3. HISTORY OF THE CONDITION METRICS

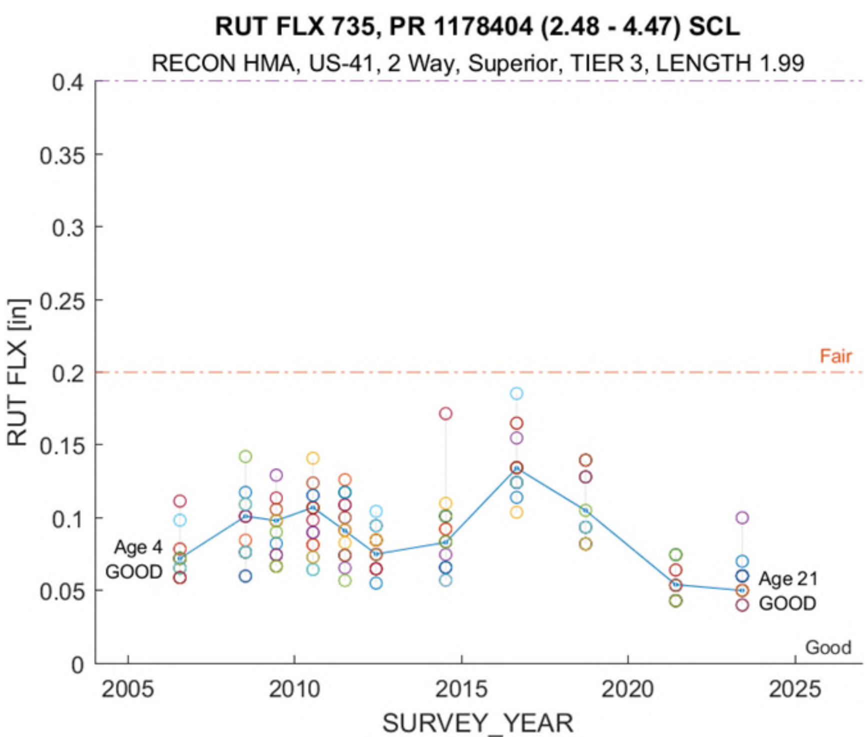
The record of the condition metrics of the sections was built from HPMS-formatted files, which contain thousands of 0.1-mile measurements of parameters (IRI, CRK, RUT, FLT) collected across the MDOT pavement network. While data collection is conducted annually at the network level, individual road segments are generally surveyed biennially, with the exception of one direction of the Interstate where annual measurements are available. To compile the condition metric record for a section, the HPMS-formatted files are accessed to get a set of coincident BMP, EMP and tenth-mile measurements for each section. The record was compiled for all sections listed in the pavement list which had data recorded in the HPMS-formatted files. This process resulted in five separate condition metric records (spreadsheets): IRI, CRK FLX, CRK RIG, RUT, and FLT. Figure 9-6 shows a partial screenshot of the IRI record, while Figure 9-7 displays plots of two condition metric records over time (IRI and RUT) for a flexible section with ID 735. The maintenance record of this section lists the following fix-events: HMA reconstruction opening in 2002, HMA overlay single in 2009 and again in 2020. The figure also highlights the Good/Fair and Fair/Poor thresholds (IRI: 95-170 in/miles, RUT: 0.20-0.40 in) and shows the impact of homogenization (which is described in a later subsection) on the RUT record, which was previously much closer to the "Fair" range before 2015.

ID	FLX_RIG	SURVEY_YEAR	AGE	IRI_DATE	IRI_MDN	IRI_AVG	IRI_STDV	MILES_G	MILES_F	MILES_P	GFP_YEAR	GFP_AGE	TNTH_MLS_MSRD	BMP_EMP_IRI
7	FLX	2006	1	5 10 2006 00:00	133	158.9	80.6	0.1	0.7	0.2	FAIR	POOR	1	[0 0.1 140;0.1 0.2 122;0.2 0.3 1
7	FLX	2007	2	1 07 2007 00:00	123	152.9	83.1	0.1	0.7	0.2	FAIR	POOR	1	[0 0.1 105;0.1 0.2 121;0.2 0.3 1
7	FLX	2009	4	16 05 2009 00:00	125.5	169.1	109.4	0.2	0.6	0.2	FAIR	POOR	1	[0 0.1 99;0.1 0.2 126;0.2 0.3 12
7	FLX	2010	5	16 06 2010 00:00	105.5	161.3	128.2	0.4	0.4	0.2	FAIR	FAIR	1	[0 0.1 141;0.1 0.2 145;0.2 0.3 4
9	RIG	2007	12	26 06 2007 00:00	112	120.3	37.3	0.1	1.1	0.1	FAIR	FAIR	1.3	[4.5 4.6 89;4.6 4.7 96;4.7 4.8 10
9	RIG	2009	14	29 04 2009 00:00	146	210	190.9	0	1.1	0.2	FAIR	FAIR	1.3	[4.5 4.6 109;4.6 4.7 120;4.7 4.8
9	RIG	2011	16	17 05 2011 00:00	184	182.1	32.3	0	0.4	0.9	POOR	POOR	1.3	[4.5 4.6 164;4.6 4.7 145;4.7 4.8
9	RIG	2013	18	1 05 2013 00:00	185	178.4	23.2	0	0.5	0.8	POOR	POOR	1.3	[4.5 4.6 159;4.6 4.7 152;4.7 4.8
9	RIG	2015	20	9 05 2015 00:00	235	230.9	42	0	0.1	1.2	POOR	POOR	1.3	[4.5 4.6 216;4.6 4.7 199;4.7 4.8
9	RIG	2017	22	31 05 2017 00:00	206	185.5	45	0	0.5	0.8	POOR	POOR	1.3	[4.5 4.6 152;4.6 4.7 165;4.7 4.8
10	RIG	2007	12	26 06 2007 00:00	117	116.5	18.5	0.2	1.1	0	FAIR	FAIR	1.3	[1.5 1.6 103;1.6 1.7 108;1.7 1.8
10	RIG	2009	14	29 04 2009 00:00	137	145.3	34.9	0	1.1	0.2	FAIR	FAIR	1.3	[1.5 1.6 116;1.6 1.7 116;1.7 1.8
10	RIG	2010	15	15 05 2010 00:00	142	146.5	15.6	0	1.2	0.1	FAIR	FAIR	1.3	[1.5 1.6 149;1.6 1.7 129;1.7 1.8
10	RIG	2011	16	17 05 2011 00:00	147	151.1	26.9	0	1.1	0.2	FAIR	FAIR	1.3	[1.5 1.6 147;1.6 1.7 147;1.7 1.8
10	RIG	2012	17	2 05 2012 00:00	147	145.8	16.5	0	1.3	0	FAIR	FAIR	1.3	[1.5 1.6 147;1.6 1.7 135;1.7 1.8
10	RIG	2013	18	1 05 2013 00:00	160	159.1	11.8	0	1	0.3	FAIR	FAIR	1.3	[1.5 1.6 158;1.6 1.7 158;1.7 1.8
10	RIG	2014	19	4 05 2014 00:00	192	189.9	22	0	0.3	1	POOR	POOR	1.3	[1.5 1.6 173;1.6 1.7 167;1.7 1.8
10	RIG	2015	20	9 05 2015 00:00	196	199.5	15	0	0	1.3	POOR	POOR	1.3	[1.5 1.6 190;1.6 1.7 189;1.7 1.8
10	RIG	2016	21	25 06 2016 00:00	234	238.3	31.7	0	0	1.3	POOR	POOR	1.3	[1.5 1.6 202;1.6 1.7 198;1.7 1.8
10	RIG	2017	22	31 05 2017 00:00	207	200.5	29.7	0	0.3	1	POOR	POOR	1.3	[1.5 1.6 144;1.6 1.7 165;1.7 1.8

Figure 9-6. Condition metric record for IRI (partial screenshot). Shading has been added to identify rows corresponding to the same road section. The record for the first seven sections is visible. Notice the BMP-EMP-IRI (tenth-mile) column to the right. Additional spreadsheets contain the records for CRK, RUT and FLT.



(a) IRI FLX record. Section 735



(b) RUT record, after homogenization. Section 735

Figure 9-7. Examples of condition metric records of IRI and RUT for a flexible section. Each circular marker is a tenth-mile measurement. The continuous line is the median of the yearly measurements.

9.5.1 Considerations related to Dates (date format in the CSV files)

The HPMS-formatted files include an exact date (year, month, day) for the measurements. This information is relevant when building the transition matrices, because it enables setting an exact time step for the matrices. When reading the measurement date data, however, some considerations were needed. Three different date formats have been in use in the HPMS files over the years. Before 2018, a date can be recorded as “6 07 2017”; between 2018 – 2021 the format can be “11/3/2018 11:17:27 AM”. After 2021 (and also in 2002), the files use Excel formatting for the dates. In some cases, different formats are combined in the same file. It was necessary to consider these disparities when using the code to read these files.

9.5.2 Considerations for RUT and FLT – Homogenization of RUT data

After the condition records were built, it was possible to access the summarized data in spreadsheet form for analyses. This data was used to determine the lane-miles and percentages classified as Good, Fair, and Poor for each condition metric over the years. For example, Figure 9-8 and Figure 9-9 present the percentage of lane miles classified as Good, Fair, and Poor (“GFP”) for the Interstate fraction of the network. Notice that this data includes only Interstate sections that are listed in the Pavement list, i.e., only the sections which are included in the *GroupRecords* files.

The fluctuation of some of the Good/Fair/Poor (GFP) records over time is mostly explained by two facts:

- The nature of the data collection *frequency*, which is performed every two years for non-Interstate roads, and every year for one direction of Interstate roads since circa 2017.
- The fact that the segments measured in consecutive years, for the most part, are not the same (except for more recent years where one direction of Interstate roads have been measured annually).

Additionally, it is also the case that apparent discontinuities or “spikes” may appear on years with limited data collection. For example, the CRK RIG record (Interstate) shows a pronounced spike in 2016. Only 6.5 lane miles (in Good condition) were measured on that year; for reference, other years have measurements between 1,300 and 2,800 lane-miles. The effect of the number of lane miles with data is particularly visible for CRK FLX (Interstate), which alternated between around 2,100 down to 55 lane-miles in consecutive years between 2005 and 2017.

The GFP records for IRI and CRK generally exhibit continuity over time. On the other hand, significant discontinuities are evident in the RUT and FLT records, which are not explained by the number of lane-miles with data. After discussions with MDOT, it is considered that discontinuities in the records likely stem from changes in vendors or data acquisition techniques. These changes are characterized by abrupt shifts in the measured data range, which become evident when examining the "tails" of the data distribution. For instance, every year between 2007 and 2011, less than 1.5% of the lane-miles with RUT data (all network) reported values below 0.10 inches. In contrast, from 2012 to 2019, this same range of RUT values was observed in over 30% of the lane-miles yearly.

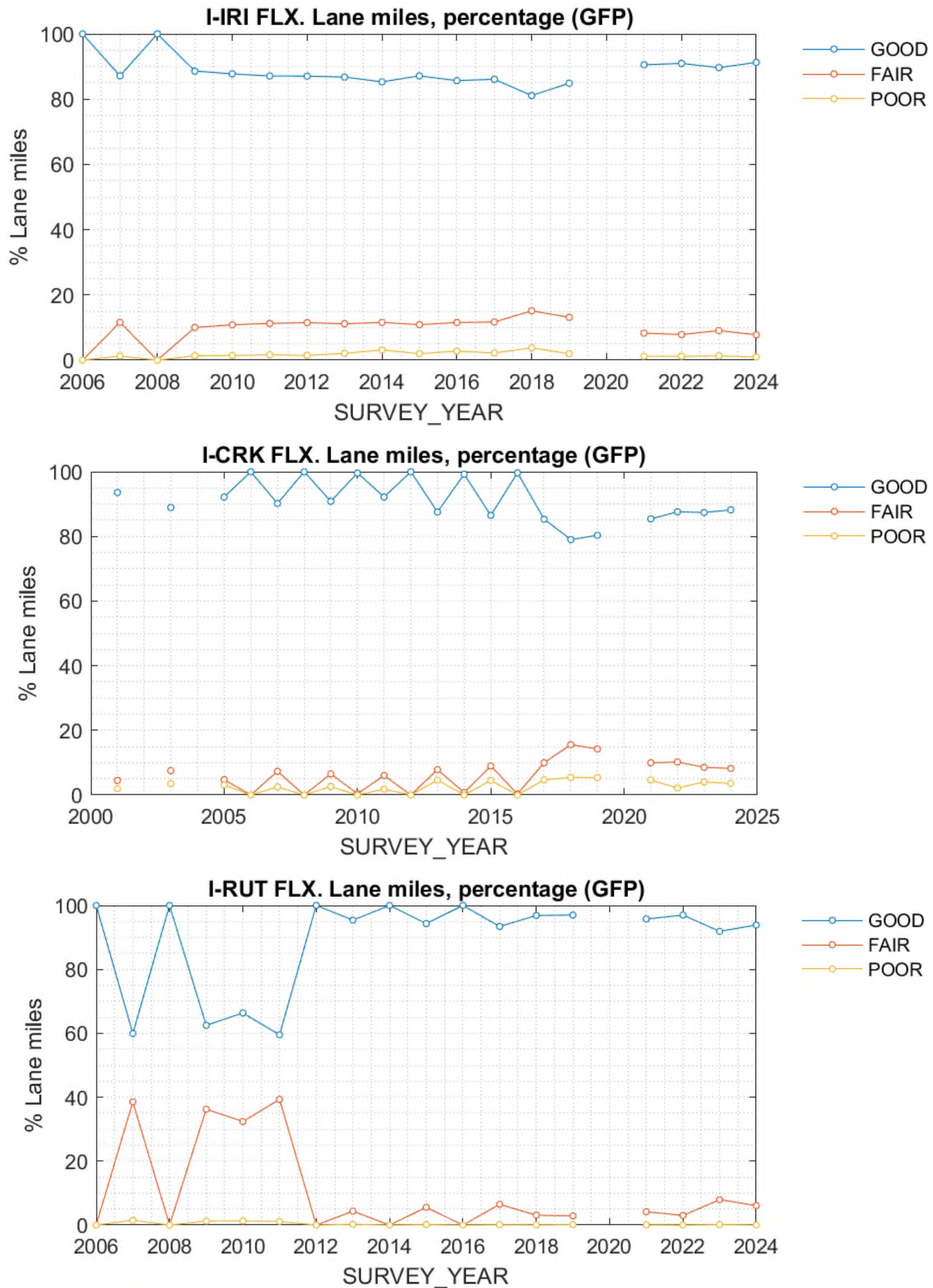


Figure 9-8. Flexible pavement Good/Fair/Poor ("GFP") lane-mile percentages for the condition metrics of Interstate fraction of the network over the years: (a) IRI FLX, Interstate, (b) CRK FLX, Interstate, (c) RUT (FLX), Interstate before homogenization

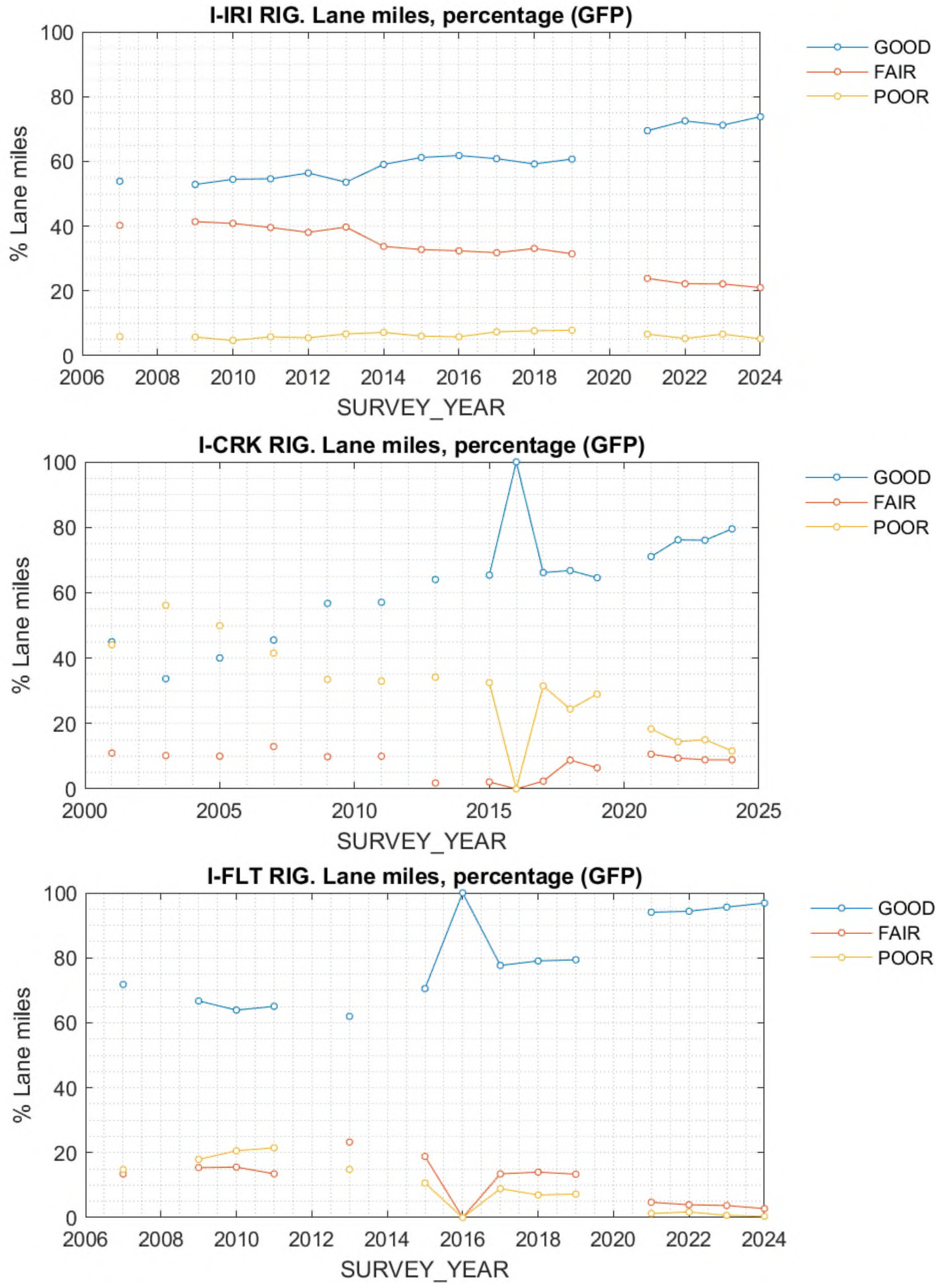


Figure 9-9. Rigid pavement Good/Fair/Poor ("GFP") lane-mile percentages for the condition metrics of Interstate fraction of the network over the years: (a) IRI RIG, Interstate, (b) CRK RIG, Interstate, (c) FLT (RIG), Interstate

The continuity reflected in the GFP records is relevant when developing transition matrices, which rely on contiguous data intervals over time. Thus, the irregularities in the RUT and FLT data presented a significant challenge, necessitating adjustments to minimize year-to-year discrepancies. To address these discontinuities, a scaling process called homogenization was applied to the RUT data. The process of homogenization involves shifting and scaling the tenth-mile data from each year to equalize the average and dispersion across years. For RUT, the targets were based on the years 2022 to 2024, which were deemed more reliable, characterized by lower variability, and a continuous, consistent, and representative GFP record.

In the case of FLT, only the data measured after 2020 was used to build the transition matrices. The statistical distribution of FLT data measured before 2020 was considerably different from that of post-2020 measurements, much more different among years than was the case for RUT (i.e. in FLT data, year-to-year data distributions were considerably different). For these reasons, scaling/homogenization did not produce satisfactory results for FLT.

The homogenization approach was developed after extensive testing, which began with a partial scaling of only the most clearly "offset" years, followed by an all-year scaling, and finally, the full homogenization process. It was observed that equalizing the data's dispersion (standard deviation) caused only slight changes to the yearly median, with minimal impact on projections. The most significant improvement came from the initial application of scaling, with subsequent adjustments—moving to all-year scaling and homogenization—resulting in only minor changes. This process resulted in making the RUT data suitable for building transition matrices. Figure 9-10 presents the GFP record for the RUT data after the homogenization process. After homogenization, the discontinuity has been addressed, as can be seen when comparing this figure with the previous one.

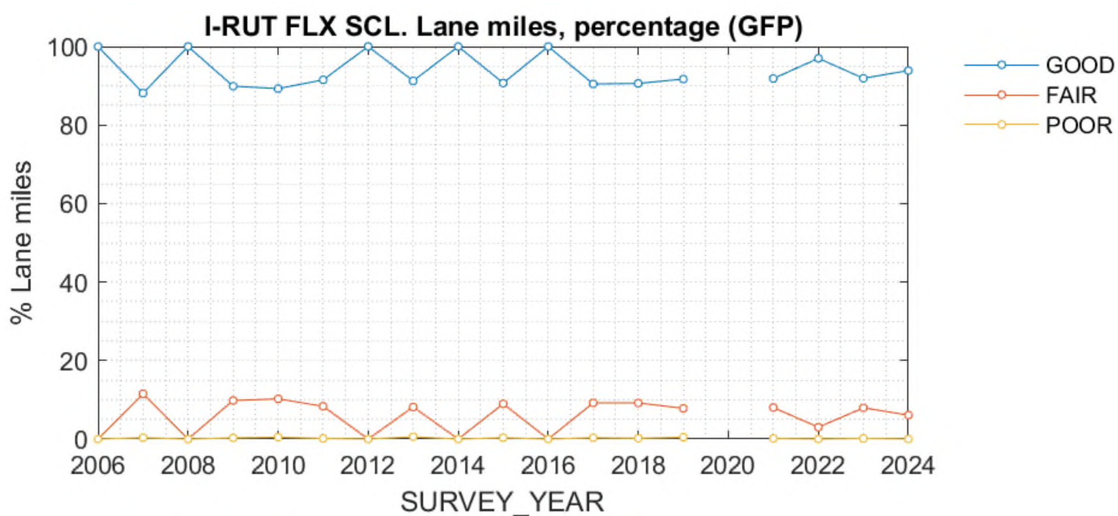


Figure 9-10. GFP record for the RUT (FLX) data after homogenization. Interstate fraction of the network.

As mentioned before, it is important to note that the total number of lane-miles with data fluctuates yearly. Figure 9-11 illustrates the number of lane-miles accumulated in bins for IRI FLX over the years. This figure offers an appreciation of the fact that the available data changes over time, but at least in the case of IRI FLX, the bin characterization keeps consistent in terms of percentages. This stability is helpful for the transition matrices. Using equally sized bins provides several advantages:

- The bins discretize the range of condition metric values, offering an improved resolution for the projections (i.e. when compared to the broader Good/Fair/Poor ranges).
- They are designed so that their boundaries align with the Good/Fair and Fair/Poor thresholds, so regrouping the data for interpretation in terms of Good/Fair/Poor is straightforward.

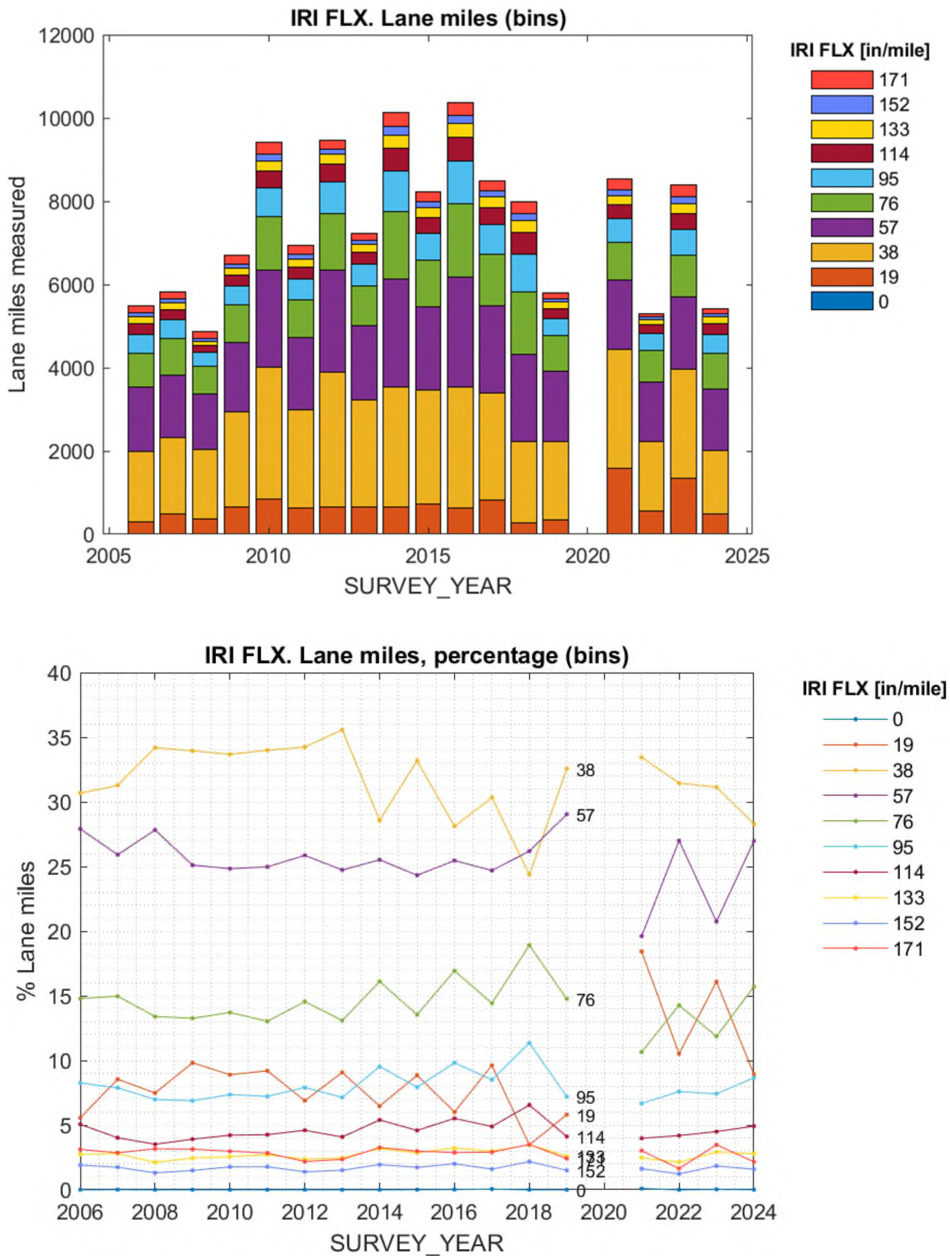


Figure 9-11. IRI FLX, yearly number of lane-miles measured (i.e. with condition metric data), and percentage, discretized into bins. Data from all sections in the Pavement list (i.e. *GroupRecords* data). The numbers in the legend indicate the lower end of the bin.

9.6 STEP 4. DEVELOPING TRANSITION MATRICES

The maintenance record (Figure 9-4) and the condition metric history of the sections (Figure 9-6, Figure 9-7) provide the necessary information for building the transition matrices. A transition matrix can be used to project the evolution of the number of lane miles (in bin ranges) for a given condition metric over time. To build transition matrices for a condition metric, the condition metric history of the sections needs to be paired with their maintenance record, as described next.

9.6.1 Precursor matrices and transition matrices

The history of the condition metrics for each section (see Figure 9-7, for example) is divided into "date intervals", or pairs of consecutive sets of data points. Each interval is composed of two sets, *present* and a *future*, of tenth-mile condition metric measurements for the section. At the same time, one dimension of a matrix is assigned to the *present* set of measurements and the other to the *future* set of measurements. Both dimensions of the matrix are segmented into bins, discretizing the range of condition metric measurements. Then, each pair of tenth-mile condition metric data of the interval is sorted into its corresponding *present* and *future* bin. BMP/EMP data is used to ensure that the present and future measurements correspond to the same tenth-mile location.

For each *present/future* tenth-mile data pair, the following value is added to the appropriate *present/future* bin in the matrix: the length of each tenth-mile (most of the time, but not always, 0.1 mile) multiplied by the number of lanes of the segment. In this way, a preliminary or "precursor" matrix is built. This precursor matrix is populated with *lane miles*. In other words, the precursor ("miles") matrix consolidates all the measured tenth-mile/lane-miles of road as they transition between condition metric bins.

An example of a precursor ("miles") matrix is presented in Figure 9-12(a). To understand the meaning of such a matrix, it is useful to observe a single row. For example, the second row of the matrix summarizes all the *future* states of lane miles that at some point had a *present* IRI of 19-38 in/mile. In this case, most of those miles (3,297 miles, about 66% of the row) kept in the same bin in the future, while a fraction (1,636 miles, about 33% of the row) increased IRI towards the next bin, 38-57 in/mile. This particular matrix describes the deterioration after a fix was applied (more on this is presented later).

The second row of the matrix contains about 5,000 lane miles in total. Notice that the number of lane miles in each bin can be converted into a percentage (i.e. percentage of total lane miles in the row), thus generalizing the meaning of the row. To turn a precursor matrix into a *transition matrix*, the precursor matrix is normalized across its rows. Now, for any given "present" condition metric value (bin) in the vertical dimension, each row represents *the probability of transitioning* to a "future" value (bin). Figure 9-12(b) illustrates the corresponding transition matrix for the precursor matrix in Figure 9-12(a).

(a)

(b)

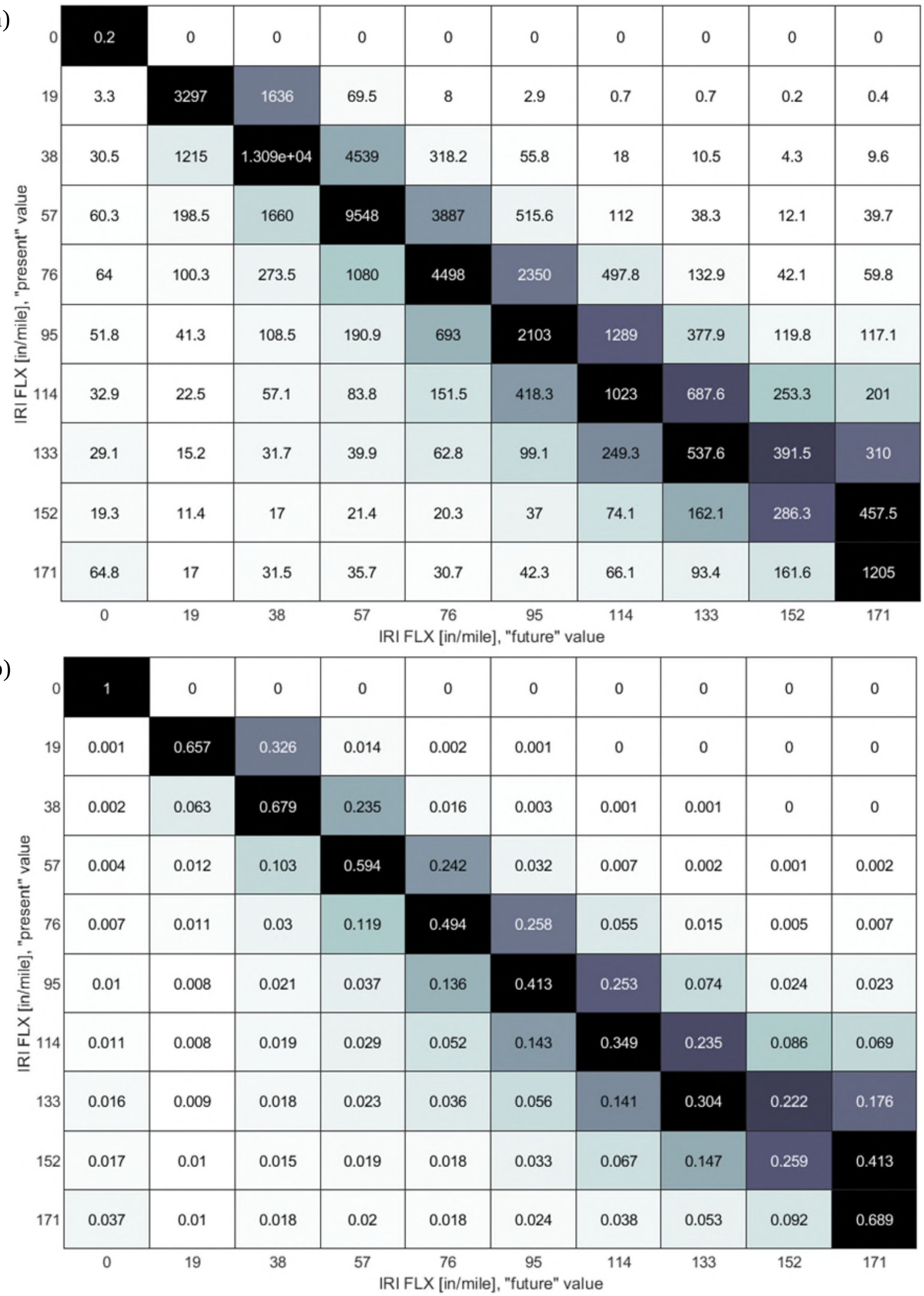


Figure 9-12. (a) An example of a precursor ("miles") matrix, and (b) its associated transition matrix. Data for condition metric IRI FLX. All the data intervals added to this matrix followed a CPM fix event.

9.6.2 Improvement matrices and Deterioration matrices

Each interval in the condition metric history of a section is classified as either an *improvement interval*—when a fix event such as CPM, RCN, or RHB occurs—or a *deterioration interval*, when no maintenance takes place and the section continues to deteriorate naturally.. To better illustrate the difference between improvement and deterioration intervals, Figure 9-13 shows the condition metric history of a section paired with its maintenance record.

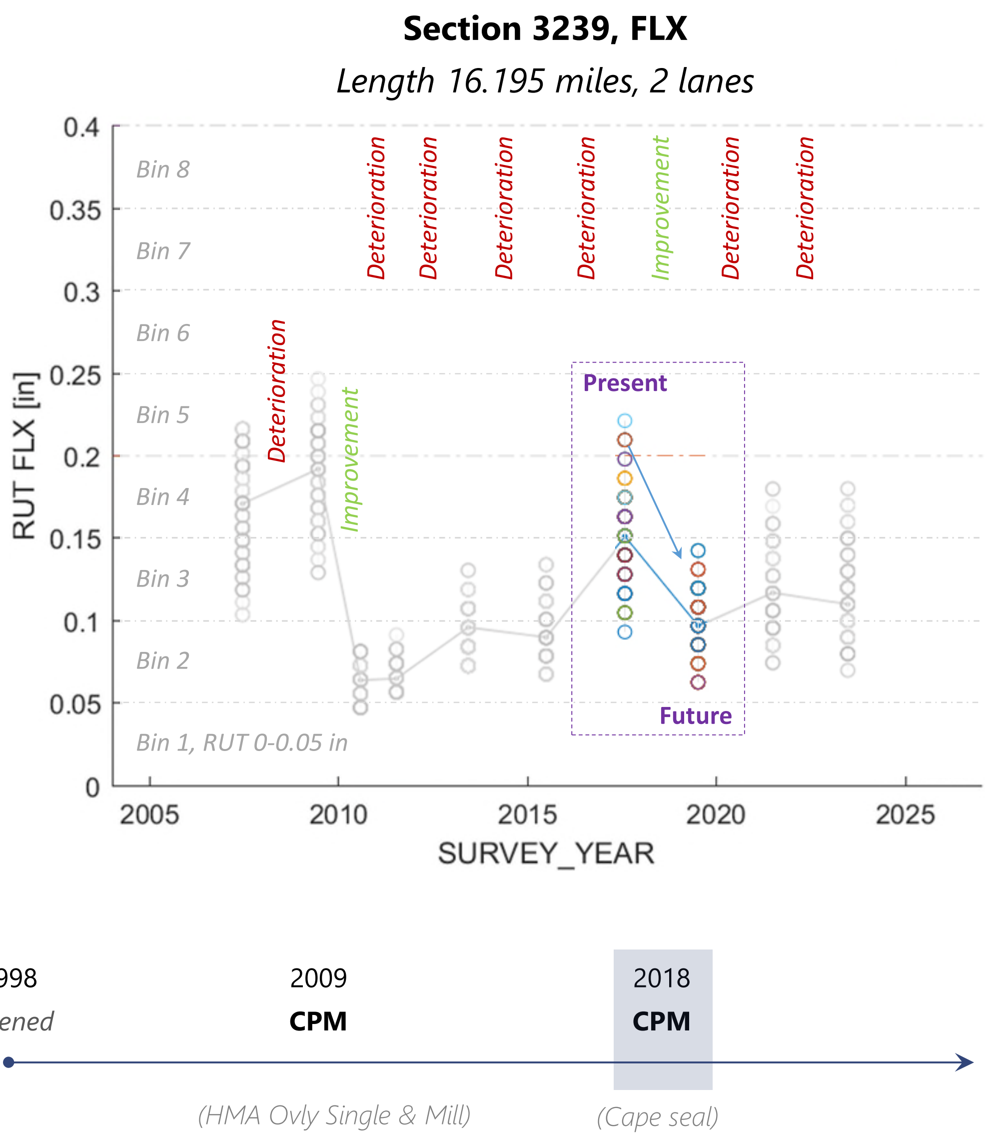


Figure 9-13. Section 3239: Condition metric history and maintenance record of the section. The condition metric is RUT (FLX). Each interval is identified as either a deterioration or an improvement interval. A CPM improvement interval is highlighted. Bin ranges are presented as well.

The transition matrices can reflect the **aftermath** (deterioration) of the fix activities explicitly. For example, the matrix shown in Figure 9-12 was constructed using only *deterioration* intervals where the last known fix was CPM. Likewise, transition matrices can reflect the **impact** (improvement) of a given fix, by accumulating only intervals where a CPM, a RCN or a RHB happened.

Accordingly, two groups of matrices were prepared for each condition metric, to separately account for the effects of fixes and deterioration. Each group consists of three matrices, corresponding to the three fix categories of CPM, RCN, and RHB. The groups are described as follows:

- The first group consists of *deterioration* matrices. They include only intervals representing the deterioration of a section. Since the rate of deterioration may differ after a CPM, RCN, or RHB fix, three separate deterioration matrices are created.
- The second group consists of *improvement* matrices. They include only intervals that coincide with fix events. For instance, all intervals involving reconstructions are added to a specific improvement matrix for reconstructions (RCN). Given the three types of maintenance (CPM, RCN, and RHB), there are three corresponding improvement matrices as well.

This approach enables to capture separately (a) the *deterioration* of the condition metrics following each type of fix and (b) the immediate impact of each fix on the condition metrics. Once built, the transition matrices can be used to project the evolution of a set of lane-miles sorted into bins. As an example, Figure 9-14 and Figure 9-15 illustrate, respectively, the deterioration and improvement transition matrices for one condition metric: IRI FLX where the parent fix is RHB. Noticeable differences can be observed between *deterioration* and *improvement* matrices shown in Figure 9-14 and Figure 9-15. For example, deterioration matrices are stronger along their diagonals. This indicates that “present” data is likely to remain unchanged, and to evolve relatively slowly over time. In contrast, improvement matrices tend to have higher values in the left-most columns. This means that when a fix is applied, “future” values are more likely to shift towards a low (improved) range, regardless of the “present” value of the condition metric. This behavior aligns well with the expected effect of a fix, which is to restore the condition metric to a “Good” range.

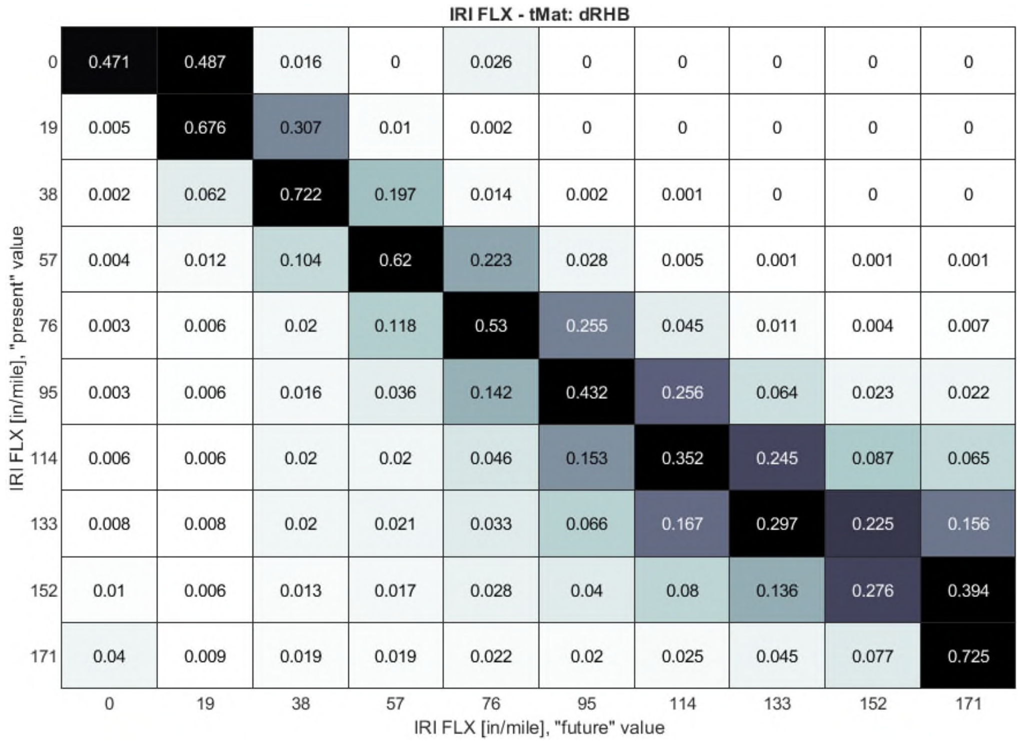


Figure 9-14. An example 0.1-mile-based deterioration matrix for the condition metric IRI FLX where the parent fix is RHB.

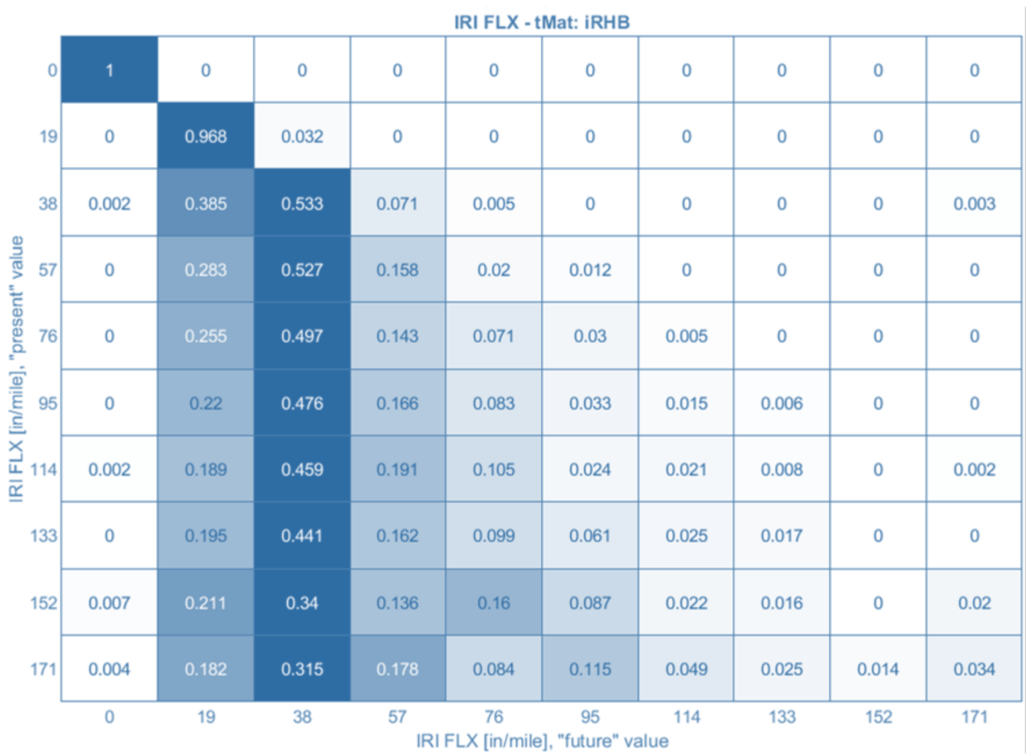


Figure 9-15. An example 0.1-mile-based improvement matrix for the condition metric IRI FLX after application of a RHB fix.

9.6.3 Special Considerations

Several considerations were incorporated during the development of the transition matrices to enhance their accuracy and reliability, as detailed in the subsections below.

9.6.3.1 Data range used in transition matrix development

The transition matrix development has been revised to include only data from the past 10 years (since 2015). This modification addresses an issue identified in the original analysis where transition matrices for certain parameters, such as I-IRI RIG and I-CRK RIG, were producing unrealistic future predictions that systematically declined regardless of the starting GFP percentages.

The problem manifested as a contradiction between observed historical trends and projected future conditions. While historical data demonstrated that percent good was increasing for parameters like I-IRI RIG and I-CRK RIG, the transition matrix predictions showed an abrupt and sharp decrease in future projections. This inconsistency was traced to an artifact in the transition matrix methodology.

The root cause was identified as the inclusion of much older historical data from periods when percent good was characteristically low. The early historical data contained predominantly low values for the 'good' category across multiple parameters. Consequently, the transition matrices incorporated these historical patterns and inappropriately weighted the predictions toward these earlier poor conditions, effectively suppressing future percentage projections despite observable recent improving trends.

By restricting the analysis to data collected after 2015, the transition matrices now capture more recent infrastructure management practices, updated maintenance strategies, and current material technologies. This temporal constraint ensures that the transition behavior reflects contemporary pavement condition evolution patterns, resulting in more realistic and representative projections that align with current infrastructure management effectiveness and observed performance trends.

9.6.3.2 Interval length associated with the transition matrices

The time between each pair of measurements in the condition metric record of a section is known. When building deterioration matrices, this makes it possible to “set” the time step associated to the matrix to an exact value. When adding a *deterioration*-type interval, it is possible to (linearly) interpolate or extrapolate the “future” value to the expected deterioration after a fixed amount of time. This interval length was set constant at 1 year for all matrices. Intervals with gaps longer than 4 years were not added to the matrices.

9.6.3.3 Completion of matrix rows with no data

When building a miles/transition matrix, it is sometimes the case that no lane miles in the dataset transition from one condition bin to another. This results in a 0 value in the matrix. While a few zeros are expected, in some cases, an entire row of the matrix may remain empty even after processing all available data for a given condition metric. This typically occurs at the extreme ends of the metric range—such as the lowest bin of IRI (0 to 19 in/mile), which is rarely or never observed—or when limited data are available for certain metrics (e.g., CRK, RIG, or especially FLT). This is a normal occurrence and reflects the actual range of condition metrics observed in the field. However, for the transition matrix to be used effectively in the projection process, it cannot contain empty rows. To address this, a row-completion procedure was implemented:

- For deterioration or CPM improvement matrices, a value of “1” is inserted at the diagonal position of the empty row.
- For RCN or RHB improvement matrices, a value of “1” is inserted in the first column of the empty row.

This completion process is not expected to impact the projection outcomes. For instance, since no lane miles typically exhibit a present IRI of 0 in/mile, that row will not be used during projections. Similarly, in improvement matrices, placing a “1” in the first column mirrors the behavior observed in adjacent rows. This logic accounts for the “1” value seen in the top-left corner of the improvement matrix shown in Figure 9-15.

9.6.3.4 Handling road sections ending with a reconstruction/rehabilitation (“connectivity”)

According to the maintenance record, there are 400 flexible sections and 160 rigid sections that reached their end of life. Road segments can “end” with a reconstruction or rehabilitation, when a new segment is built in their place: same PR, and similar BMP-EMP range. As mentioned earlier, the segments that end were identified and paired with new segments that opened in the same year and PR, over the same or similar EMP/BMP values. This information is stored in the pavement list as “followers” and “precedents” of the sections (more information on connectivity was provided in Step 1).

When building a matrix, not all the sections that appear in the pavement list will have their condition metric record added. First, a filter is applied to keep the sections whose flexible or rigid type matches that of the condition metric whose matrix is being constructed (for example, for IRI FLX, only flexible sections are considered). Additionally, the connectivity between sections that ended and reconstructed sections is implemented as follows:

- If a section has no precedents, it is the start of a condition metric record.
- If a section ended, and it has reconstructions in place (“followers”), the condition metric and maintenance records of the followers (of the same type, FLX/RIG) is appended to its own, to create a continuous record.
- If a section has precedents (meaning it is a reconstruction itself), it may still be added to the matrix under some conditions. For example, when building the matrix for IRI RIG, and rigid section with flexible precedents will still get added.

Sometimes a reconstruction or rehabilitation changes a FLX section into RIG, or vice versa. In this case, only the first set of measurements of the reconstructed section is appended to the continuous record. In this way, the effect of the fix can still be reflected in the matrix. This connectivity was implemented for IRI and CRK, which are defined for both FLX and RIG sections.

In some cases, several sections may "converge" to the same follower. For example, two shorter, contiguous sections may have been superseded by one reconstructed section that covers both their spans. The record of both shorter sections should be added to the matrices, as well as the effect of the reconstruction at their ends, but the reconstructed segment should be added only once. To prevent duplications, all segments that are appended to the record are "marked" to make sure that the data of each segment is added only once to the matrices.

9.6.3.5 Special case, CRK RIG: Allowing "CPR" and "Conc FDRs" (CPMs) to only improve

In general, the transition matrices performed well when producing projections of the condition metrics, as presented in the next section. However, the projections for CRK RIG remained challenging even after several calibration attempts, particularly for the Interstate fraction of the network. Contrary to the other condition metrics, the effect of fixes (improvements) on CRK RIG was not apparent.

After some analysis, it was found that the CPM improvement matrix for CRK RIG was in fact tending slightly *towards* deterioration. This fix (CPM) is always performed over a larger percentage of lane miles than the other fix categories, therefore it was effectively masking the effect of rehabilitations and reconstructions. This behavior was explained by two causes:

- On one hand, few CPM fixes have a strong improving effect over CRK RIG, on average. Other condition metrics will usually have one or two CPM fixes that produce dramatic improvements.
- On the other hand, most of the lane miles added to the CPM improvement matrix (CRK RIG) came from only two fixes: *CPR* and *Conc FDRs*. On average, these two fixes induce no improvement on CRK RIG, but individual instances do contribute to deterioration, according to the data. Notice that many of the no-improvement situations may represent a "change" from 0% to 0% cracking.

For this particular case, it was decided to restrict the two CPM fixes (*CPR* and *Conc FDRs*) to only be able to improve CRK RIG. That is, only the instances where these fixes in fact reduced the percentage of cracking were added to the CPM improvement matrix (CRK RIG). This restriction was implemented **only** when building the CPM improvement matrix for CRK RIG.

9.7 PROJECTING FUTURE PAVEMENT NETWORK CONDITIONS

9.7.1 Overview of the projection methodology

At this stage, all the necessary components are in place to produce network-level projections of the condition metrics. The three main elements required for this task are:

- **Transition Matrices:** To recall, these matrices describe the probability of a nominal 1-lane 0.1-mile-long segment in a *present* state (that is, with condition metric values within a certain range or bin) transitioning into a *future* state over a time step. The time step associated with the matrix is 1 year. There are three deterioration matrices ($\mathbf{D_{CPM}}$, $\mathbf{D_{RCN}}$, $\mathbf{D_{RHB}}$) and three improvement matrices ($\mathbf{I_{CPM}}$, $\mathbf{I_{RCN}}$, $\mathbf{I_{RHB}}$) per condition metric, corresponding to each fix category: CPM, RCN, and RHB.

- **Starting Points for Projections:** The projection begins with the status of the network in a given year, detailing how many lane miles have condition metric values within each bin range.
- **Planned Fix Percentages:** These are the expected or planned percentages (lane miles) of network-wide CPM, RCN, and RHB fixes to be carried out in the coming years. Table 9-2 presents the MDOT-provided current values used for projections, covering the years 2023 to 2029.

Table 9-2. Expected or planned percentages of the network (lane miles) to be fixed with CPM, RCN, or RHB.

Year	Capital Preventive Maintenance, CPM [%]	Reconstruction, RCN [%]	Rehabilitation, RHB [%]
2023	3.62	0.65	1.74
2024	2.78	0.45	0.56
2025	3.58	1	0.88
2026	3.09	0.34	0.2
2027	3.3	0.31	0.6
2028	3.14	0.29	0.52
2029	3.72	0.22	0.5

The projections are performed in terms of lane miles sorted into condition metric bins. The projection is carried out as follows:

- **Step 1:** Retrieve the starting point data, i.e., a vector of lane miles sorted into condition metric bins for the year of interest. These lane miles are stored in vector *A*. Projection testing in this project started from the years 2023 and 2024.
- **Step 2:** Perform the projection for the next time step (1 years into the future) by multiplying vector *A* by a *combined deterioration* matrix (D_{cmb}), then by a *combined improvement* matrix (I_{cmb}). The combined matrices are weighted blends of the deterioration and improvement matrices of the condition metric. The weighting values are described next, and the calculation of the combined matrices is presented afterwards:
    - Weights of the *improvement* matrices (P_i): These are the fix percentages for the years within the time step (Table 9-2), noted as P_{CPM_i}, P_{RCN_i} and P_{RHB_i}. The percentages need to be adjusted for the fraction of the network being projected (Interstate FLX, Non-Interstate FLX, Interstate RIG, Non-Interstate RIG).
    - Weights of the *deterioration* matrices (P_d): These weights account for the evolution of the non-intervened portion of the network and are calculated separately for FLX and RIG based on the maintenance record. They represent the last known fix of the sections that are deteriorating. Herein they are noted as P_{CPM_d}, P_{RCN_d} and P_{RHB_d}.

The result of the vector-matrix multiplication represents the projected status of the miles one time step into the future (1 year). The multiplication is repeated multiple times depending on the length of the projection (i.e., how many years in the future). One calculation step is described in the following equations.

$$A_{future} = A_{present} \cdot \mathrm{I_{cmb}} \cdot \mathrm{D_{cmb}} \quad (9.1)$$

$$\mathrm{I_{cmb}} = P_{CPM_i} \cdot \boldsymbol{I_{CPM}} + P_{RCN_i} \cdot \boldsymbol{I_{RCN}} + P_{RHB_i} \cdot \boldsymbol{I_{RHB}} + P_{no\ work} \cdot \boldsymbol{I_1} \quad (9.2)$$

$$\mathrm{D_{cmb}} = P_{CPM_d} \cdot \boldsymbol{D_{CPM}} + P_{RCN_d} \cdot \boldsymbol{D_{RCN}} + P_{RHB_d} \cdot \boldsymbol{D_{RHB}} \quad (9.3)$$

$$P_{no\ work} = 1 - (P_{CPM_i} + P_{RCN_i} + P_{RHB_i}) \quad (9.4)$$

where:

$A_{present}$	=	Starting point, i.e. vector of lane miles sorted into condition metric bins for the starting year
A_{future}	=	Projected lane miles after one time step: 1 year (IRI, RUT, FLT), 2 years (CRK)
$\mathrm{I_{cmb}}$	=	Combined improvement matrix
$\mathrm{D_{cmb}}$	=	Combined deterioration matrix
P_{CPM_i}	=	Percent of lane miles to be improved with CPM during the current time step (Table 9-2, adjusted)
P_{RCN_i}	=	Percent of lane miles to be improved with RCN during the current time step (Table 9-2, adjusted)
P_{RHB_i}	=	Percent of lane miles to be improved with RHB during the current time step (Table 9-2, adjusted)
$P_{no\ work}$	=	Percent of lane miles that are not intervened during the current time step
$\mathbf{I_{CPM}}$	=	Improvement transition matrix, CPM. Time step: 0 years
$\mathbf{I_{RCN}}$	=	Improvement transition matrix, RCN. Time step: 0 years
$\mathbf{I_{RHB}}$	=	Improvement transition matrix, RHB. Time step: 0 years
$\boldsymbol{I_1}$	=	Identity matrix.
$\mathbf{D_{CPM}}$	=	Deterioration transition matrix, after CPM. Time step: 1 year (IRI, RUT, FLT), 2 years (CRK)
$\mathbf{D_{RCN}}$	=	Deterioration transition matrix, after RCN. Time step: 1 year (IRI, RUT, FLT), 2 years (CRK)
$\mathbf{D_{RHB}}$	=	Deterioration transition matrix, after RHB. Time step: 1 year (IRI, RUT, FLT), 2 years (CRK)
P_{CPM_d}	=	Percent of lane-miles currently deteriorating after CPM
P_{RCN_d}	=	Percent of lane-miles currently deteriorating after RCN
P_{RHB_d}	=	Percent of lane-miles currently deteriorating after RHB

9.7.2 Additional considerations while performing projections

In addition to the core projection methodology, several key considerations were incorporated to enhance the accuracy and relevance of the results—particularly concerning the flexible (FLX) and rigid (RIG) lane-mile distribution within the network.

As previously described, projections are fundamentally carried out in terms of lane miles sorted into condition metric bins. This structure reflects how the transition matrices are constructed. However, for more intuitive communication of results, these binned outputs can be regrouped and normalized to present the projections in terms of **Good/Fair/Poor (GFP)** condition categories. This simplification involves aggregating lane miles from relevant condition bins based on defined thresholds and expressing them as percentages of the total.

Projections are also conducted separately for four roadway classifications (herein called subnetworks) to capture differences in pavement type and road function:

- **Interstate Flexible (I-FLX)**
- **Interstate Rigid (I-RIG)**
- **Non-Interstate Flexible (NI-FLX)**
- **Non-Interstate Rigid (NI-RIG)**

While the input fix percentages provided in Table 9-2 represent the entire network—including Tier 4 segments—these overall values (e.g., %CPM) must be ***disaggregated*** into category-specific equivalents for each subnetwork (e.g., CPM_I_FLX, CPM_I_RIG, etc.). This transformation was *guided by historical maintenance activity* records, which allowed for the calculation of the share of lane miles improved within each roadway category relative to the full network.

9.7.2.1 Computation of correction factors to disaggregate into subnetworks

Since the projections are done for each subnetwork, such as I-FLX, we need to go from **overall planned percentages** (shown in Table 9-2 where for example for 2023, CPM [%] = 3.62% means that 3.62% of *total* network lane-miles that will get CPM in 2023) to **subnetwork-specific percentages** (e.g., % of *Interstate-Flexible* miles that will get CPM this year).

First, we want to define the key quantities:

- N_{total}: total lane-miles in the network
- N_s: lane-miles in subnetwork s (for example, $s = I - FLX$).
- M_t: lane-miles treated with method $t$in a year (where $t \in$ {CPM, RCN, RHB}).
- $M_{t,s}$: lane-miles in subnetwork s treated with method t.

From these we can build three types of ratios:

- Ratio of subnetwork s.

$$\gamma_s = \frac{N_s}{N_{\text{total}}} \tag{9.5}$$

  For example, $\gamma_s =$ lane miles of I-FLX divided by total lane miles. This can be calculated from the *GroupRecords* files.

- Subnetwork s share within treatment t:

$$\beta_{t,s} = \frac{M_{t,s}}{M_t} \tag{9.6}$$

For example, $\beta_{t,s}$= ratio of lane miles of I-FLX treated with CPM divided by the total lane miles treated with CPM. This is unknown for the future predictions, but it can be calculated for past years from *GroupRecords* files.

- Overall plan percentage for treatment t (this is known and given in Table 9-2):

$$p_t = \frac{M_t}{N_{\text{total}}} \tag{9.7}$$

For example, $p_t =$ total lane miles treated with CPM divided total lane miles of the network. The p_t is decided/planned by MDOT for the future.

To build the improvement matrices, we need to compute the following ratio:

$$r_{t|s} = \frac{M_{t,s}}{N_s} \tag{9.8}$$

where $r_{t|s}$ = the fraction of subnetwork s's miles that get treatment t. For example, $r_{t|s}$= ratio of lane miles of I-FLX treated with CPM, divided by the lane miles of I-FLX. The $r_{t|s}$ values are equivalent to P_{CPM_i}, P_{RCN_i} and P_{RHB_i} shown in Equation 9.2 above.

Deriving the conversion from p_t to $r_{t|s}$:

- Start with $r_{t|s}$:

$$r_{t|s} = \frac{M_{t,s}}{N_s} \tag{9.9}$$

- Multiply and divide to introduce known terms:

$$r_{t|s} = \left(\frac{M_{t,s}}{M_t}\right)\left(\frac{M_t}{N_{\text{total}}}\right)\left(\frac{N_{\text{total}}}{N_s}\right) \tag{9.10}$$

- Substitute definitions:

$$r_{t|s} = \beta_{t,s} \cdot p_t \cdot \frac{1}{\gamma_s} \tag{9.11}$$

The correction factor is defined as:

$$f_t(s) = \frac{\beta_{t,s}}{\gamma_s} \quad 9.12$$

As a result, the adjusted percentage becomes:

$$r_{t|s} = p_t \cdot f_t(s) \quad 9.13$$

The physical meaning of the correction factors are listed below:

- $f_t(s) = 1$: Treatment applied proportionally to network size
- $f_t(s) > 1$: Treatment over-applied in this subnetwork
- $f_t(s) < 1$: Treatment under-applied in this subnetwork

In order to compute the correction factors ($f_t(s)$), first the gamma (γ_s) and beta ($\beta_{t,s}$) values needed to be computed from the historical data given in *GroupRecords* files. The gamma (γ_s) values computed for each year is shown in Table 9-3. The beta ($\beta_{t,s}$) are shown in Table 9-4, Table 9-5 and Table 9-6 for CPM, RHB and RCN, respectively. In these tables, T4 represents Tier-4.

Table 9-3. Gamma (γ_s) values computed for each year.

year	I_FLX	I_RIG	NI_FLX	NI_RIG	T4_FLX	T4_RIG	Total
2000	11.0%	12.0%	29.0%	1.7%	46.3%	0.000%	100%
2001	33.7%	22.3%	26.5%	4.0%	13.4%	0.066%	100%
2002	6.8%	2.8%	40.1%	0.5%	49.7%	0.048%	100%
2003	38.0%	27.2%	20.9%	3.8%	10.1%	0.024%	100%
2004	7.5%	6.1%	37.7%	1.2%	47.5%	0.055%	100%
2005	30.9%	27.8%	25.5%	3.9%	11.8%	0.046%	100%
2006	11.1%	7.2%	35.0%	2.0%	44.6%	0.084%	100%
2007	26.6%	27.0%	29.9%	4.0%	12.5%	0.080%	100%
2008	8.5%	9.1%	37.0%	2.2%	43.1%	0.035%	100%
2009	31.9%	28.4%	26.0%	3.3%	10.3%	0.041%	100%
2010	7.6%	10.3%	36.9%	3.9%	41.2%	0.084%	100%
2011	31.2%	30.2%	26.8%	3.9%	7.9%	0.057%	100%
2012	8.2%	10.2%	35.4%	2.1%	44.0%	0.161%	100%
2013	29.7%	32.7%	26.4%	3.7%	7.4%	0.030%	100%
2014	9.0%	8.5%	38.8%	2.6%	41.0%	0.127%	100%
2015	27.7%	34.9%	25.6%	4.2%	7.6%	0.000%	100%
2016	7.6%	8.4%	39.7%	2.0%	42.2%	0.157%	100%

year	I_FLX	I_RIG	NI_FLX	NI_RIG	T4_FLX	T4_RIG	Total
2017	27.2%	29.0%	28.6%	3.9%	11.1%	0.099%	100%
2018	10.7%	8.9%	39.9%	3.1%	37.3%	0.102%	100%
2019	18.8%	17.8%	34.7%	2.8%	25.9%	0.068%	100%
Average =	19.2%	18.0%	32.0%	2.9%	27.7%	0.1%	100.0%

Table 9-4. Beta ($\beta_{t,s}$) values for CPM

year	I_FLX	I_RIG	NI_FLX	NI_RIG	T4_FLX	T4_RIG	Total
2000	19.2%	28.0%	24.8%	5.1%	23.0%	0.0%	100.0%
2001	25.0%	29.5%	25.2%	0.0%	20.4%	0.0%	100.0%
2002	10.8%	1.8%	51.0%	0.0%	36.3%	0.0%	100.0%
2003	43.5%	27.4%	6.8%	0.7%	21.6%	0.0%	100.0%
2004	13.9%	9.4%	30.5%	3.5%	42.7%	0.0%	100.0%
2005	8.3%	28.1%	24.3%	5.8%	33.6%	0.0%	100.0%
2006	17.6%	21.3%	23.7%	1.4%	36.1%	0.0%	100.0%
2007	13.3%	19.5%	43.2%	4.4%	19.5%	0.0%	100.0%
2008	15.6%	35.1%	26.3%	2.1%	20.8%	0.0%	100.0%
2009	28.4%	20.4%	29.5%	0.0%	21.8%	0.0%	100.0%
2010	18.5%	18.9%	33.2%	10.5%	19.0%	0.0%	100.0%
2011	30.5%	10.1%	29.3%	0.6%	29.5%	0.0%	100.0%
2012	20.0%	51.0%	13.1%	0.2%	15.7%	0.0%	100.0%
2013	25.8%	39.9%	16.1%	1.3%	16.8%	0.0%	100.0%
2014	30.7%	28.7%	22.8%	3.0%	14.8%	0.0%	100.0%
2015	12.0%	29.2%	38.9%	4.7%	15.2%	0.0%	100.0%
2016	12.9%	31.0%	33.2%	0.0%	22.9%	0.0%	100.0%
2017	19.2%	23.9%	31.9%	3.6%	21.5%	0.0%	100.0%
2018	21.1%	26.5%	26.0%	1.2%	25.3%	0.0%	100.0%
2019	18.8%	10.8%	40.4%	2.3%	27.8%	0.0%	100.0%
Average =	20.3%	24.5%	28.5%	2.5%	24.2%	0.0%	100.0%

Table 9-5. Beta ($\beta_{t,s}$) values for RHB

year	I_FLX	I_RIG	NI_FLX	NI_RIG	T4_FLX	T4_RIG	Total
2000	23.8%	15.6%	40.6%	0.0%	19.9%	0.0%	100.0%
2001	29.8%	25.0%	29.6%	0.0%	15.6%	0.0%	100.0%
2002	46.6%	0.0%	35.1%	0.0%	18.3%	0.0%	100.0%
2003	27.8%	2.4%	37.5%	1.5%	30.8%	0.0%	100.0%
2004	29.0%	13.7%	39.6%	0.0%	17.6%	0.0%	100.0%
2005	28.9%	1.9%	61.6%	2.1%	5.5%	0.0%	100.0%
2006	24.6%	5.3%	40.1%	0.0%	29.9%	0.0%	100.0%
2007	29.0%	4.7%	31.1%	0.0%	35.2%	0.0%	100.0%
2008	17.9%	9.8%	37.3%	0.0%	35.1%	0.0%	100.0%

year	I_FLX	I_RIG	NI_FLX	NI_RIG	T4_FLX	T4_RIG	Total
2009	36.3%	15.1%	15.6%	0.0%	33.0%	0.0%	100.0%
2010	14.6%	5.3%	34.9%	2.9%	42.3%	0.0%	100.0%
2011	15.8%	16.4%	43.4%	0.0%	24.4%	0.0%	100.0%
2012	38.1%	17.0%	17.3%	0.0%	26.2%	1.4%	100.0%
2013	24.3%	6.9%	45.5%	0.0%	22.2%	1.0%	100.0%
2014	21.5%	7.5%	41.6%	0.0%	29.4%	0.0%	100.0%
2015	29.1%	0.0%	41.6%	0.0%	29.2%	0.0%	100.0%
2016	38.0%	0.0%	33.8%	0.0%	28.1%	0.0%	100.0%
2017	32.7%	16.1%	20.0%	0.0%	31.2%	0.0%	100.0%
2018	52.3%	3.4%	39.1%	0.0%	5.2%	0.0%	100.0%
2019	41.5%	15.7%	23.4%	0.0%	19.4%	0.0%	100.0%
Average =	30.1%	9.1%	35.4%	0.3%	24.9%	0.1%	100.0%

Table 9-6. Beta ($\beta_{t,s}$) values for RCN

year	I_FLX	I_RIG	NI_FLX	NI_RIG	T4_FLX	T4_RIG	Total
2000	9.0%	50.6%	15.0%	14.3%	11.0%	0.0%	100.0%
2001	11.9%	35.7%	28.6%	12.1%	10.2%	1.6%	100.0%
2002	25.4%	46.3%	14.0%	4.6%	9.7%	0.0%	100.0%
2003	20.8%	36.6%	33.1%	3.5%	6.0%	0.0%	100.0%
2004	1.0%	67.0%	13.7%	4.8%	13.0%	0.5%	100.0%
2005	7.3%	67.9%	15.1%	7.7%	0.6%	1.4%	100.0%
2006	6.0%	68.2%	15.9%	1.8%	7.4%	0.7%	100.0%
2007	18.4%	61.2%	18.2%	2.3%	0.0%	0.0%	100.0%
2008	23.2%	49.0%	20.4%	3.9%	3.5%	0.0%	100.0%
2009	8.7%	70.8%	9.9%	2.9%	7.7%	0.0%	100.0%
2010	1.7%	60.3%	5.3%	24.4%	8.0%	0.3%	100.0%
2011	4.7%	58.3%	17.9%	11.3%	6.5%	1.2%	100.0%
2012	0.0%	22.3%	47.1%	15.0%	13.6%	1.9%	100.0%
2013	21.1%	26.9%	27.0%	14.1%	9.6%	1.4%	100.0%
2014	36.8%	48.9%	11.2%	0.8%	2.3%	0.0%	100.0%
2015	1.0%	54.0%	21.1%	14.1%	9.9%	0.0%	100.0%
2016	14.9%	59.1%	18.5%	0.0%	7.5%	0.0%	100.0%
2017	36.9%	47.9%	4.3%	2.4%	8.5%	0.0%	100.0%
2018	0.6%	73.5%	8.7%	15.9%	1.3%	0.0%	100.0%
2019	15.4%	73.9%	10.6%	0.0%	0.0%	0.0%	100.0%
Average =	13.2%	53.9%	17.8%	7.8%	6.8%	0.4%	100.0%

The correction factors were computed for each year for each of the subnetworks and shown in Table 9-7 and Table 9-8.

Table 9-7. Correction factors ($f_t(s)$) for I-FLX and I-RIG subnetworks.

year	I-FLX				I-RIG		
	CPM	RHB	RCN		CPM	RHB	RCN
2000	1.75	2.17	0.82		2.34	1.30	4.22
2001	0.74	0.88	0.35		1.32	1.12	1.60
2002	1.59	6.85	3.73		0.66	0.00	16.78
2003	1.15	0.73	0.55		1.01	0.09	1.35
2004	1.86	3.88	0.13		1.55	2.26	11.03
2005	0.27	0.93	0.24		1.01	0.07	2.44
2006	1.59	2.23	0.54		2.96	0.74	9.47
2007	0.50	1.09	0.69		0.72	0.17	2.27
2008	1.83	2.09	2.71		3.86	1.07	5.39
2009	0.89	1.14	0.27		0.72	0.53	2.49
2010	2.42	1.90	0.22		1.83	0.51	5.85
2011	0.98	0.51	0.15		0.34	0.54	1.93
2012	2.44	4.64	0.00		5.01	1.67	2.19
2013	0.87	0.82	0.71		1.22	0.21	0.82
2014	3.40	2.39	4.08		3.38	0.88	5.76
2015	0.43	1.05	0.04		0.84	0.00	1.55
2016	1.71	5.03	1.96		3.68	0.00	7.01
2017	0.70	1.20	1.35		0.82	0.55	1.65
2018	1.97	4.89	0.06		2.97	0.38	8.25
2019	1.00	2.21	0.82		0.61	0.88	4.16
Average =	1.40	2.33	0.97		1.84	0.65	4.81

Table 9-8. Correction factors ($f_t(s)$) for NI-FLX and NI-RIG subnetworks.

year	NI-FLX				NI-RIG		
	CPM	RHB	RCN		CPM	RHB	RCN
2000	0.85	1.40	0.52		2.92	0.00	8.29
2001	0.95	1.12	1.08		0.00	0.00	3.01
2002	1.27	0.87	0.35		0.00	0.00	8.67
2003	0.32	1.79	1.58		0.19	0.40	0.93
2004	0.81	1.05	0.36		3.01	0.00	4.13
2005	0.95	2.42	0.59		1.46	0.53	1.95
2006	0.68	1.15	0.45		0.67	0.00	0.90
2007	1.45	1.04	0.61		1.11	0.00	0.57
2008	0.71	1.01	0.55		0.96	0.00	1.76
2009	1.13	0.60	0.38		0.00	0.00	0.86
2010	0.90	0.95	0.14		2.65	0.75	6.18
2011	1.09	1.62	0.67		0.16	0.00	2.90

year	NI-FLX				NI-RIG		
	CPM	RHB	RCN		CPM	RHB	RCN
2012	0.37	0.49	1.33		0.08	0.00	7.15
2013	0.61	1.72	1.02		0.36	0.00	3.77
2014	0.59	1.07	0.29		1.17	0.00	0.30
2015	1.52	1.62	0.82		1.12	0.00	3.38
2016	0.84	0.85	0.47		0.00	0.00	0.00
2017	1.12	0.70	0.15		0.91	0.00	0.61
2018	0.65	0.98	0.22		0.39	0.00	5.15
2019	1.16	0.67	0.31		0.83	0.00	0.00
Average =	0.90	1.16	0.59		0.90	0.08	3.03

Table 9-9 shows the overall average correction factors ($f_t(s)$) for each treatment/subnetwork combination. The Tier 4 subnetwork is not shown here for brevity.

Table 9-9. Overall average correction factors ($\boldsymbol{f_t(s)}$) for each treatment/subnetwork combination

Subnetwork	CPM	RHB	RCN
I_FLX	1.40	2.33	0.97
I_RIG	1.84	0.65	4.81
NI_FLX	0.90	1.16	0.59
NI_RIG	0.90	0.08	3.03

An example of the computation procedure for P_{CPM_i}, required in Equation 9.2 for the I-FLX subnetwork, is shown below:

$$r_{t|s} = p_t \cdot f_t(s) \quad \rightarrow \quad P_{CPM_i} = p_t \cdot f_{CPM}(I - FLX) \qquad 9.14$$

Table 9-10 shows example values of subnetwork fix percentages for year 2023. The first row shows the planned fix percentages given in Table 9-2 for the year 2023. The subsequent rows show the calculated percentages of planned fixes for each of the subnetworks. Those values are calculated by simply multiplying the values in Table 9-9 with the first row shown in Table 9-10 (also the same as first row in Table 9-2). In conclusion, while performing projections for I-FLX for year 2023 (for example), the P_{CPM_i}= 5.09%, $P_{RCN_i} = 1.52\%$ and $P_{RHB_i} = 1.69\%$ are used in Equation 9.2.

Table 9-10. Example values of planned subnetwork fix percentages

Year	Subnetwork	CPM [%]	RCN [%]	RHB [%]
2023	**ALL (User Input)**	**3.62**	**0.65**	**1.74**
	I_FLX	5.09	1.52	1.69
	I_RIG	6.67	0.42	8.37
	NI_FLX	3.25	0.75	1.03
	NI_RIG	3.26	0.05	5.26

Another important consideration involves the **weights used in the deterioration matrices—** specifically P_{CPM_d}, P_{RCN_d} and P_{RHB_d}. These weights describe the deterioration behavior of the portion of the network not receiving any intervention during the current projection cycle. In essence, they reflect the question: *What was the most recent fix applied to the currently non-intervened sections?* To estimate these values, historical averages of CPM-, RCN-, and RHB-treated lane miles were used, calculated separately for flexible and rigid pavements. The values are expressed as a percentage of total historically fixed lane miles by surface type:

For flexible sections:

- P_{CPM_d} = 69.6%
- P_{RCN_d} = 4.8%
- P_{RHB_d} = 25.6%

For rigid sections:

- P_{CPM_d}= 63.6%
- P_{RCN_d}= 30.2%
- P_{RHB_d}= 6.1%

These values ensure that the deterioration patterns in the projection model reflect realistic historical maintenance practices, even for network segments not actively scheduled for fixes in the current cycle.

9.7.3 Individual projection results

The projections for each condition metric were performed separately for Interstate/Non-Interstate roads. The starting years for the Interstate projections were 2023 and 2024, and for Non-Interstate, only 2023. The reason for this difference was that there were very few lane miles with measurements on the NI-fraction for the year 2024. For Interstate, because there are projections starting on 2023 and 2024, a unique weighted projection is produced per condition metric based on the number of lane miles with measurements each year.

The condition metric projections for ***Interstate*** and ***Non-Interstate*** pavements are presented in Figure 9-16 through Figure 9-27. The ‘gray’ lines in these figures visible after 2023 and 2024 represent the ‘no work’ scenario (i.e. only deterioration).

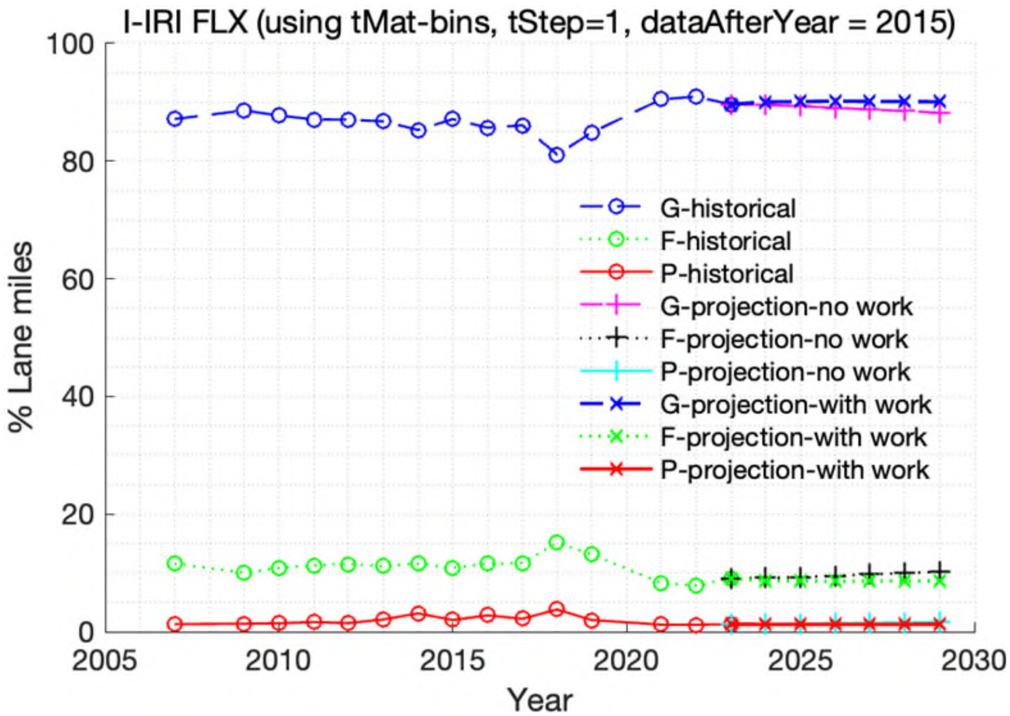


Figure 9-16. I-IRI FLX projections

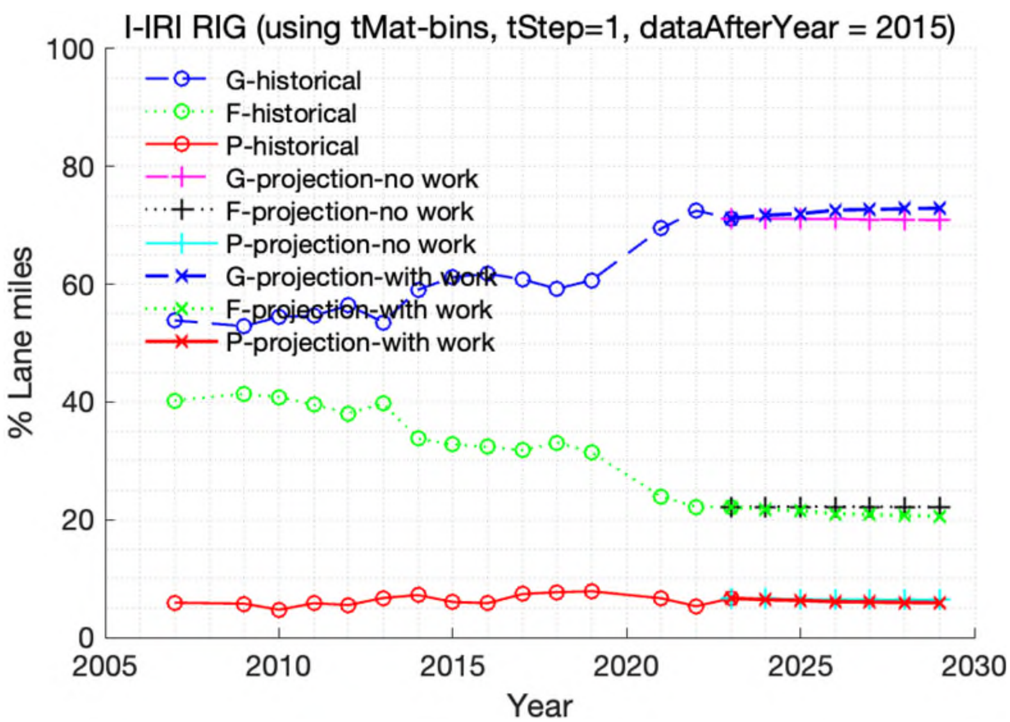


Figure 9-17. I-IRI RIG projections

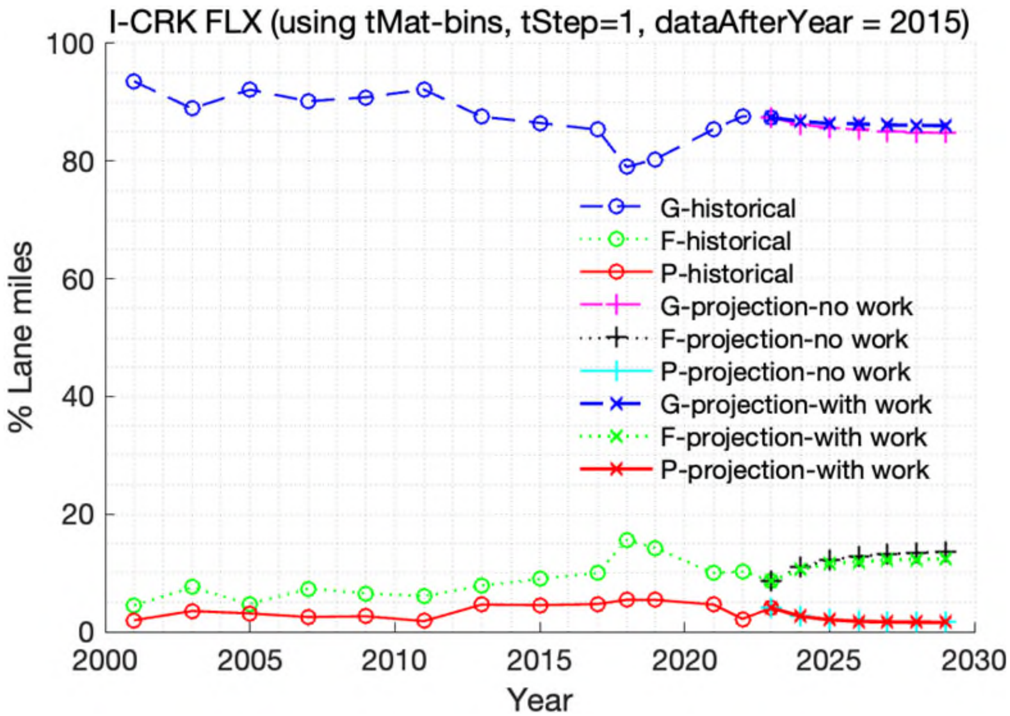


Figure 9-18. I-CRK FLX projections

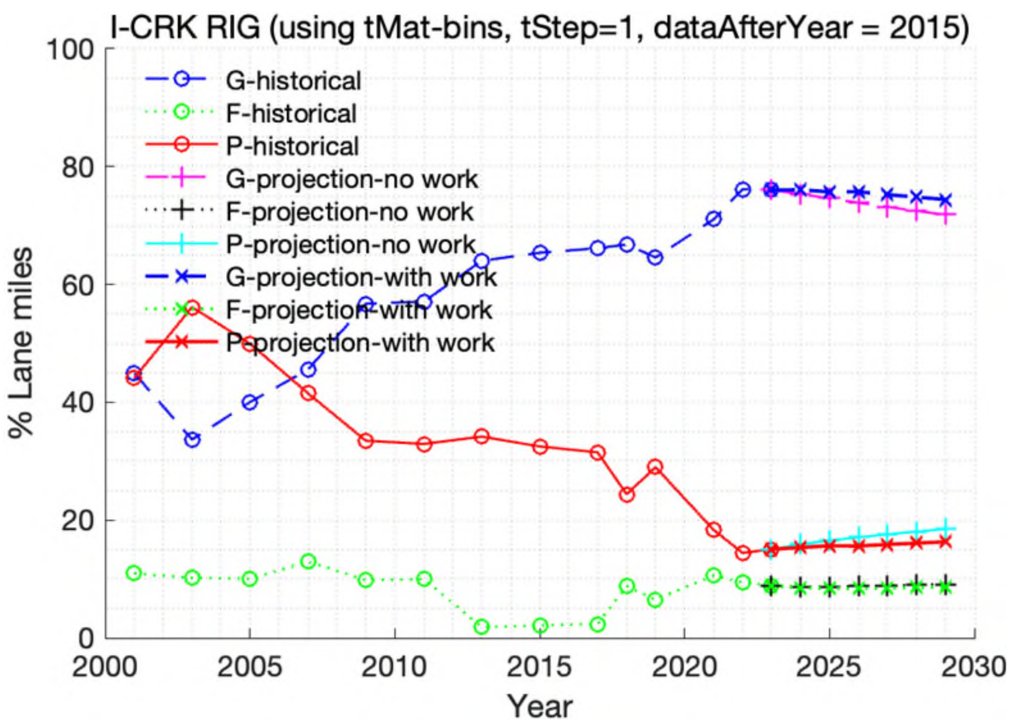


Figure 9-19. I-CRK RIG projections

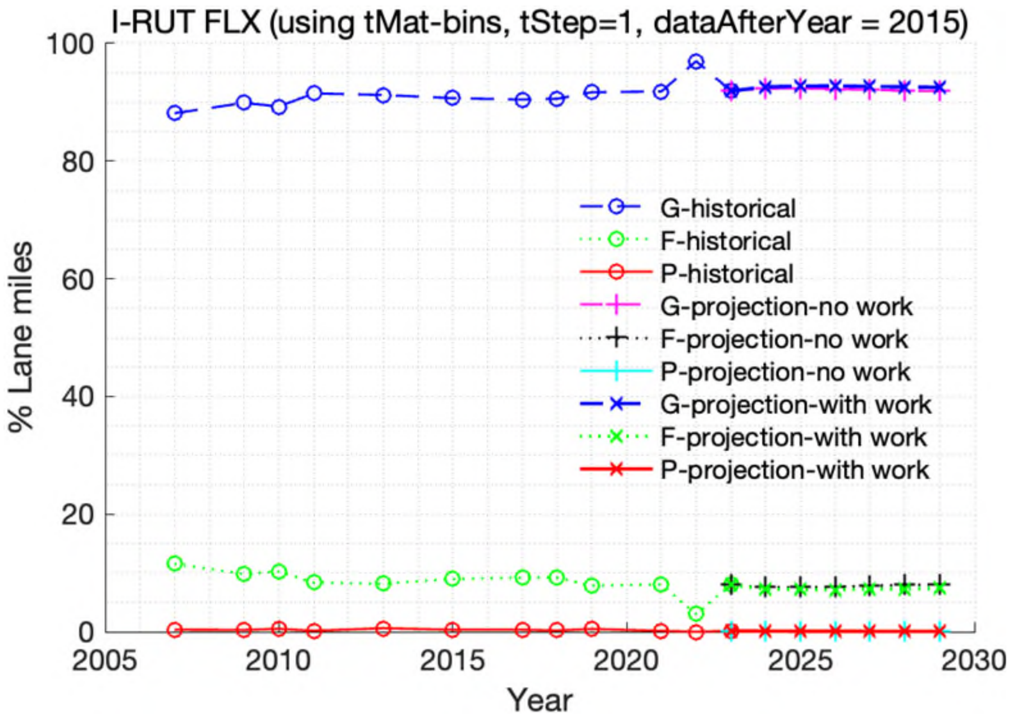


Figure 9-20. I-RUT FLX projections

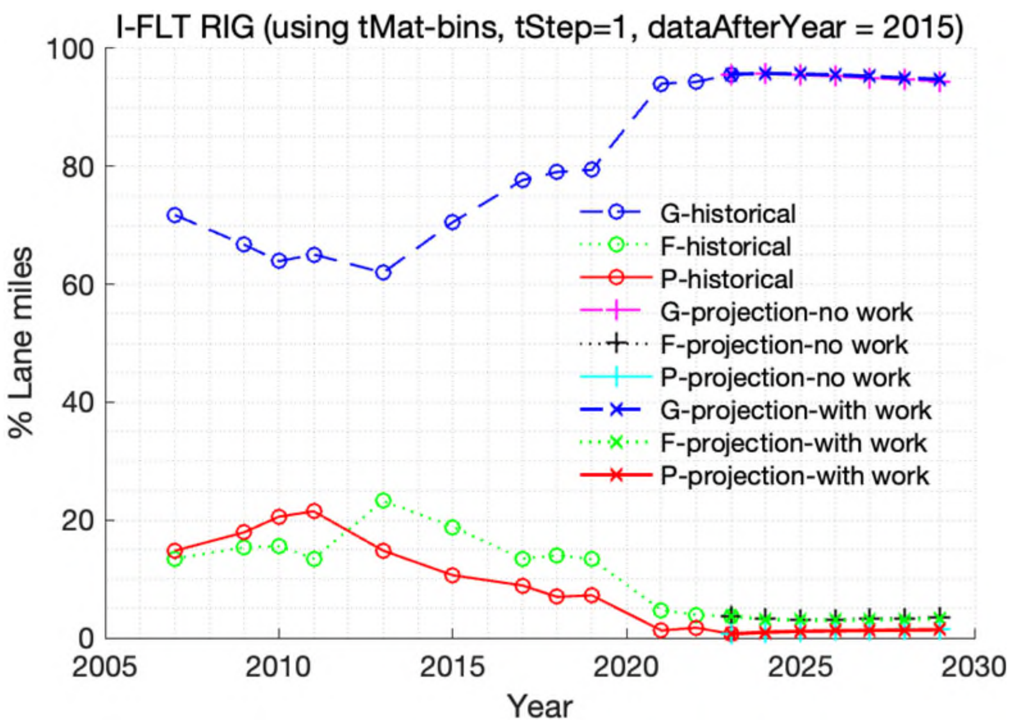


Figure 9-21. I-FLT RIG projections

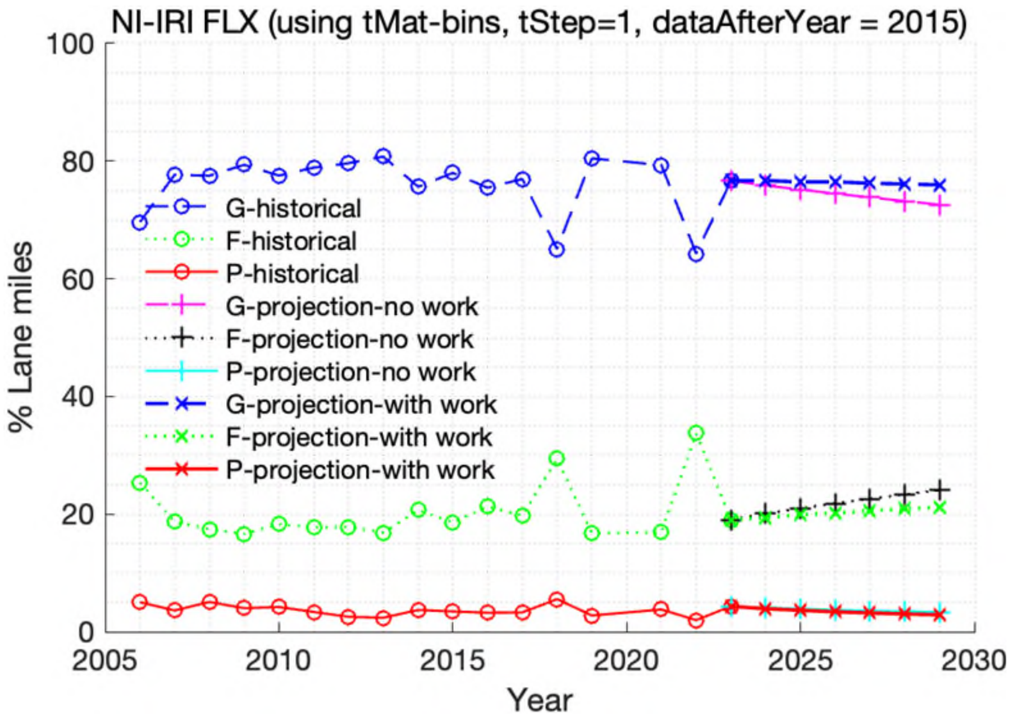


Figure 9-22. NI-IRI FLX projections

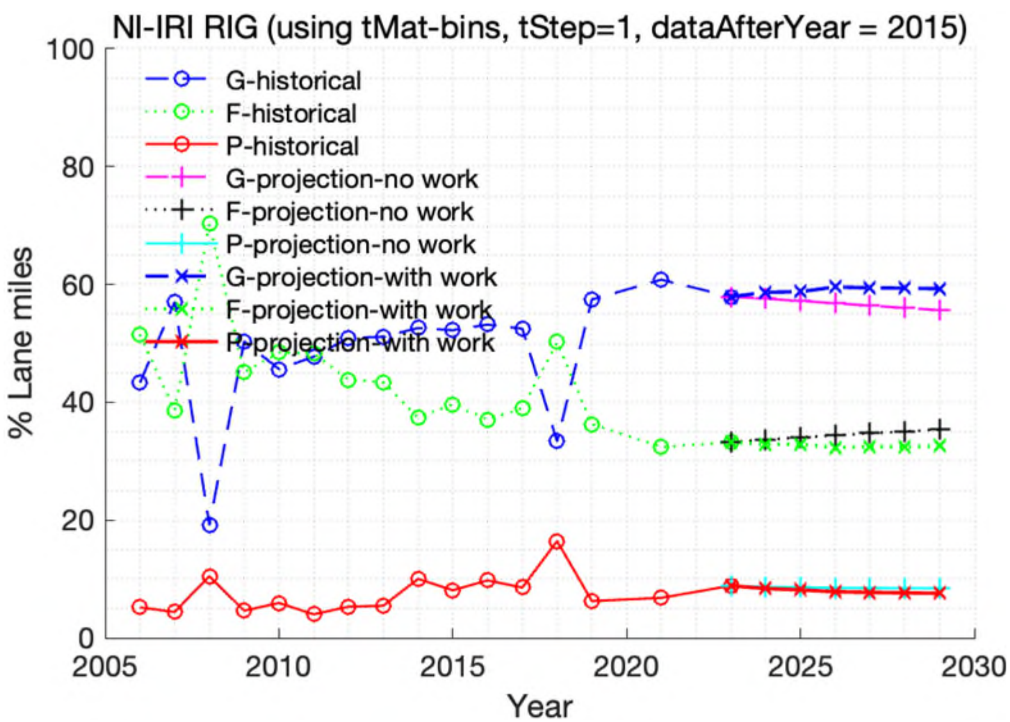


Figure 9-23. NI-IRI RIG projections

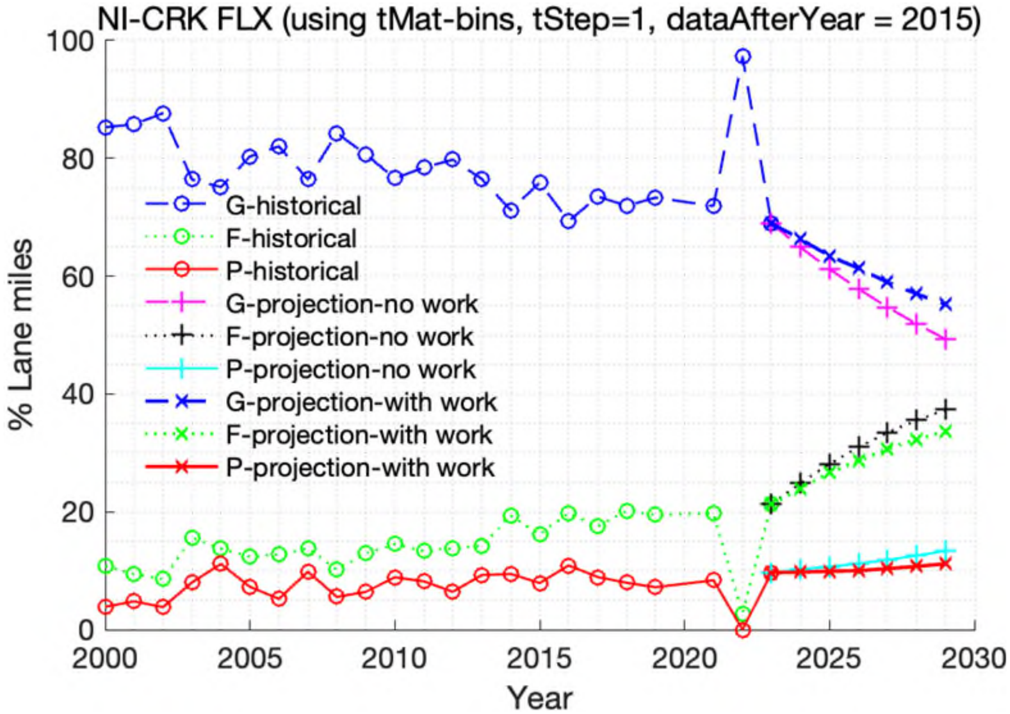


Figure 9-24. NI-CRK FLX projections

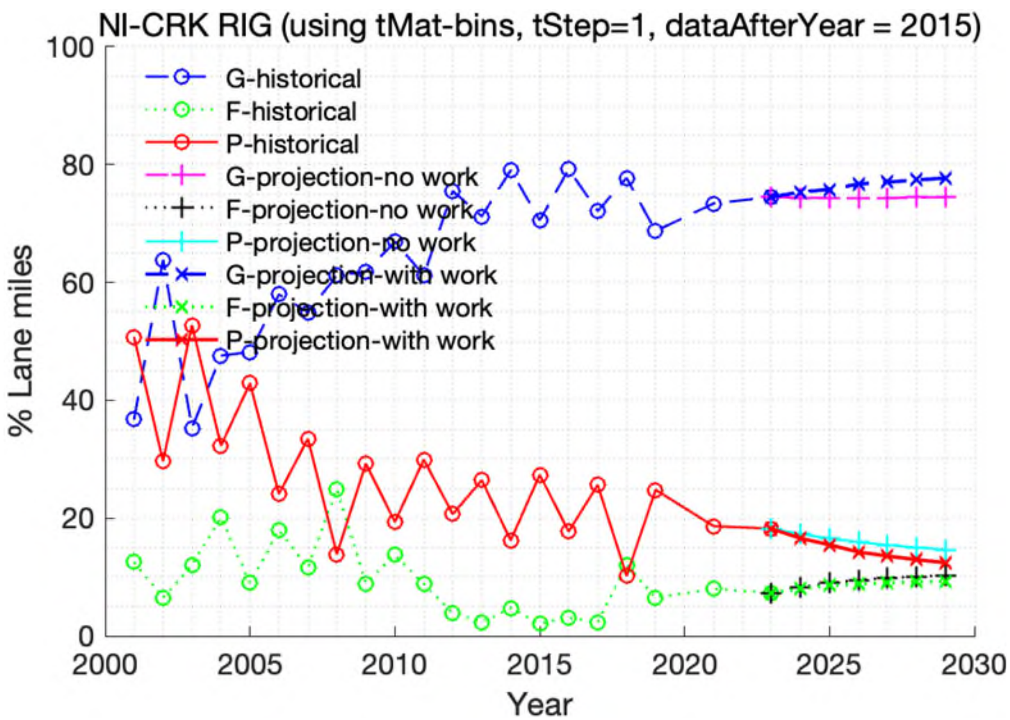


Figure 9-25. NI-CRK RIG projections

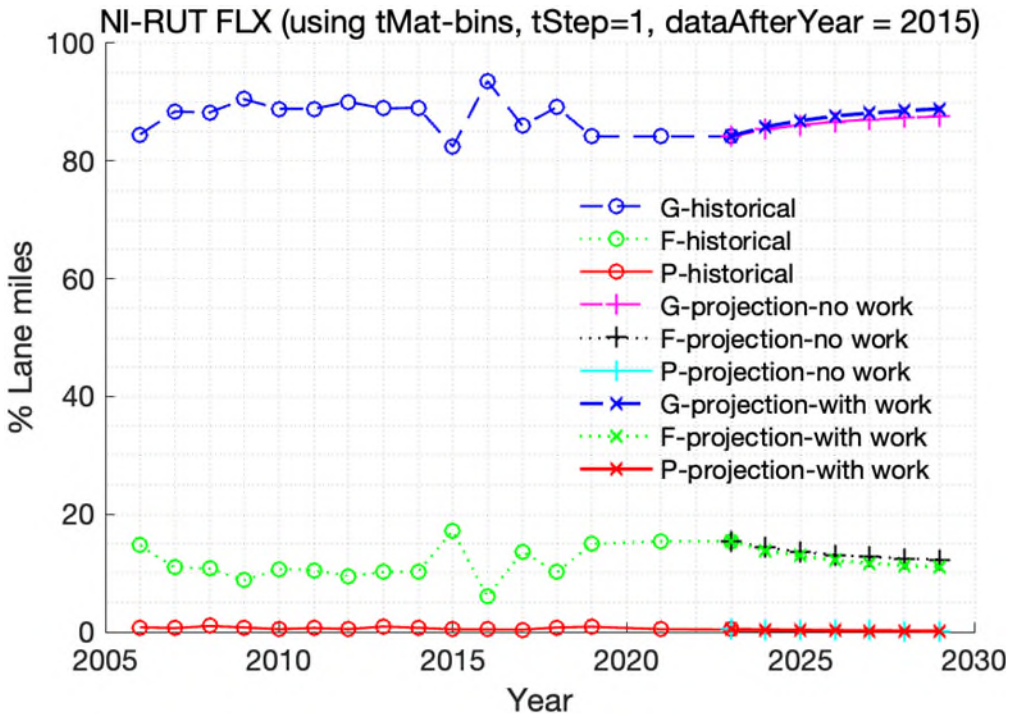


Figure 9-26. NI-RUT FLX projections

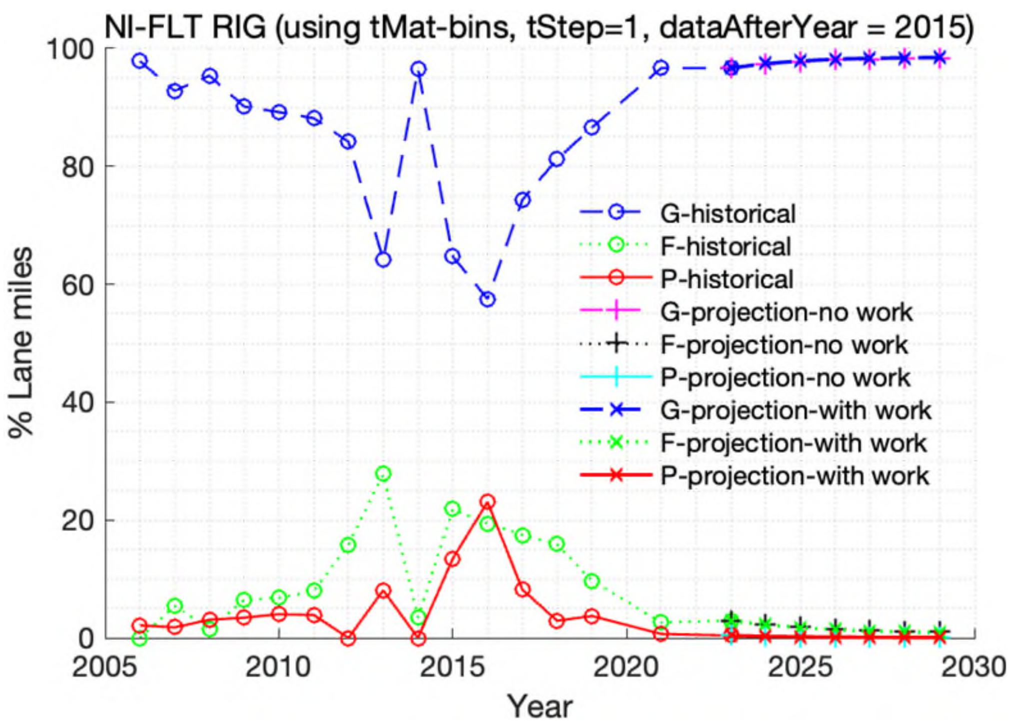


Figure 9-27. NI-FLT RIG projections

9.8 COMBINED PROJECTIONS FROM INDIVIDUAL MEASURES

In order to combine the results from the TPMs for individual distresses into an overall Good-Fair-Poor Rating, a multinomial logistic regression model was developed. Multinomial logistic regression is a type of regression performed to relate independent variables to categorical dependent variables as the relative probability of being in one category instead of another. In this case, the overall condition (Good, Fair or Poor) was used as the dependent variable, and the proportion of pavements in a given condition were the independent variables.

9.8.1 Asphalt Pavements

The logistic regression was performed by sampling from the HPMS data provided by MDOT. First, all of the data from 2017 through 2024 were combined into a single database. Then, the data were randomly divided into 300 individual samples. The samples included approximately 800 pavement segments apiece. Then, the proportion of good, fair and poor were calculated for each metric and for the composite GFP for the 300 samples. Figure 9-28 shows examples of the distributions of the proportion of good and poor for the composite measures.

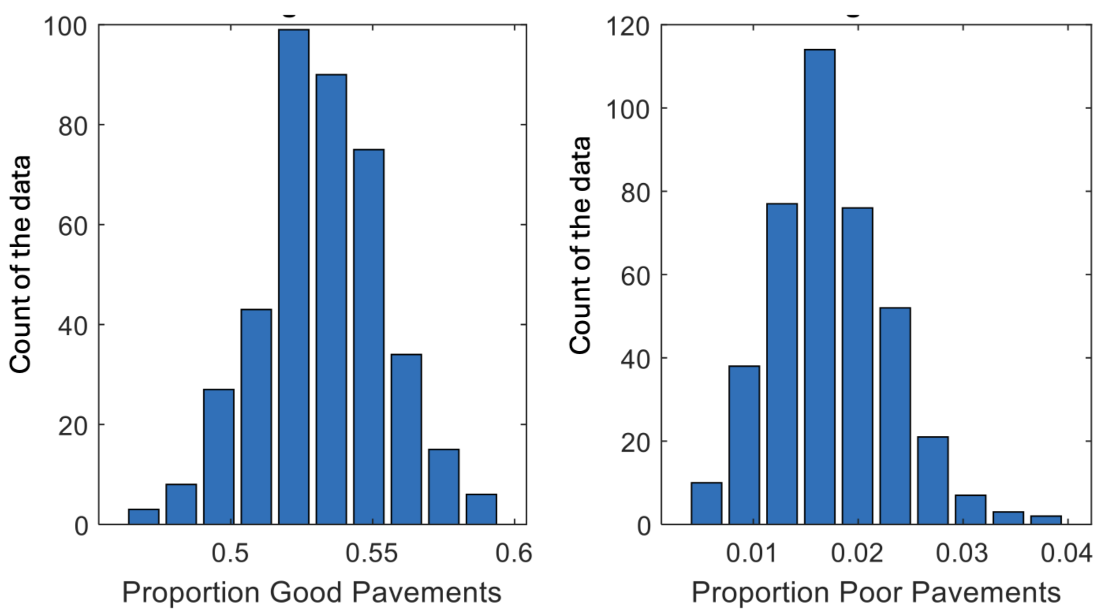


Figure 9-28. Distribution of proportion of good and poor asphalt pavements in samples

Next, the proportion of good, fair and poor values for cracking, rutting and IRI were used as independent variables, log ratios of the composite values were used as the dependent variables, and stepwise linear regression was performed. The results of the multinomial logistic regression for asphalt interstates are shown provided in equations 9.15 through 9.17, and the overall model along with each independent variable was shown to be statistically significant at the 95 percent confidence level. The equations express the relative odds of being in good or fair condition compared to being in poor condition, and the coefficients in each equation show the effect of each factor on the relative probabilities. It is important to note that the probability of not being in poor condition is very high to begin with (i.e., there are very few poor pavements), and so the relative probability of being in good or fair condition is expected to be high.

The approach to calculating the percent poor is as follows:

1. Calculate the natural logarithm of the ratio of good to poor pavements (equation 9.15)
2. Calculate $e^{\ln\left(\frac{\pi_{Good}}{\pi_{Poor}}\right)}$ where $\ln\left(\frac{\pi_{Good}}{\pi_{Poor}}\right)$ was calculated in step 1…this gives the value for $\frac{\pi_{Good}}{\pi_{Poor}}$.
3. Calculate the natural logarithm of the ratio of fair to poor pavements (equation 9.16)
4. Calculate $e^{\ln\left(\frac{\pi_{Fair}}{\pi_{Poor}}\right)}$ where $\ln\left(\frac{\pi_{Fair}}{\pi_{Poor}}\right)$ was calculated in step 3…this gives the value for $\frac{\pi_{Fair}}{\pi_{Poor}}$.
5. Calculate the proportion of poor pavements using equation 9.17 and the values calculated in steps 2 and 4.
6. Multiply the value of π_{Poor} by $\frac{\pi_{Good}}{\pi_{Poor}}$ to get the value for the proportion of pavements in good condition.
7. Multiply the value of π_{Poor} by $\frac{\pi_{Fair}}{\pi_{Poor}}$ to get the value for the proportion of pavements in fair condition.

$$\ln\left(\frac{\pi_{Good}}{\pi_{Poor}}\right) = 7.66 - -6.01 \times PGC - 17.44 \times PPC + 4.56 \times PGI - 15.87 \times PPI - 10.62 \times PFR \qquad 9.15$$

$$\ln\left(\frac{\pi_{Fair}}{\pi_{Poor}}\right) = 3.83 + 10.75 \times PFC - 8.47 \times PPC - 19.65 \times PPI - 7.80 \times PFR \qquad 9.16$$

$$\pi_{Poor} = \frac{1}{1 + \frac{\pi_{Good}}{\pi_{Poor}} + \frac{\pi_{Fair}}{\pi_{Poor}}} \qquad 9.17$$

where:

π_{Good} = proportion of pavements in good condition
π_{Fair} = proportion of pavements in fair condition
π_{Poor} = proportion of pavements in poor condition
PGC = proportion of cracking in good condition
PFC = proportion of cracking in fair condition
PPC = proportion of cracking in poor condition
PGI = proportion of IRI in good condition
PPI = proportion of IRI in poor condition

PFR = proportion of rutting in fair condition

A series of sensitivity analyses were conducted to evaluate the behavior of the model over a range of reasonable input values (based on HPMS data). The inputs to the sensitivity analysis for interstate asphalt pavements is shown in Table 9-11 and those values were input to equations 9.15 through 9.17 to derive a proportion of good, fair and poor, which were multiplied by 100 to arrive at percentages for each. Figure 9-29 shows the predicted percent good for the five segments in the sensitivity analysis, while Figure 9-30 shows the percent fair and Figure 9-31 shows the percent poor. The base case represents the network in the best condition, whereas cases one through three represent a worsening of each metric (cracking, IRI and rutting respectively). Case four represents all metrics worsening, and the results show that the model follows expectation.

Table 9-11. Input to sensitivity analysis

	Good Crack	Fair Crack	Poor Crack	Good IRI	Fair IRI	Poor IRI	Good Rut	Fair Rut	Poor Rut
Base Case	0.95	0.04	0.01	0.95	0.04	0.01	0.95	0.04	0.01
Case 1	0.75	0.15	0.1	0.95	0.04	0.01	0.95	0.04	0.01
Case 2	0.95	0.04	0.01	0.8	0.15	0.05	0.95	0.04	0.01
Case 3	0.95	0.04	0.01	0.95	0.04	0.01	0.8	0.15	0.05
Case 4	0.75	0.15	0.1	0.8	0.15	0.05	0.8	0.15	0.05

`

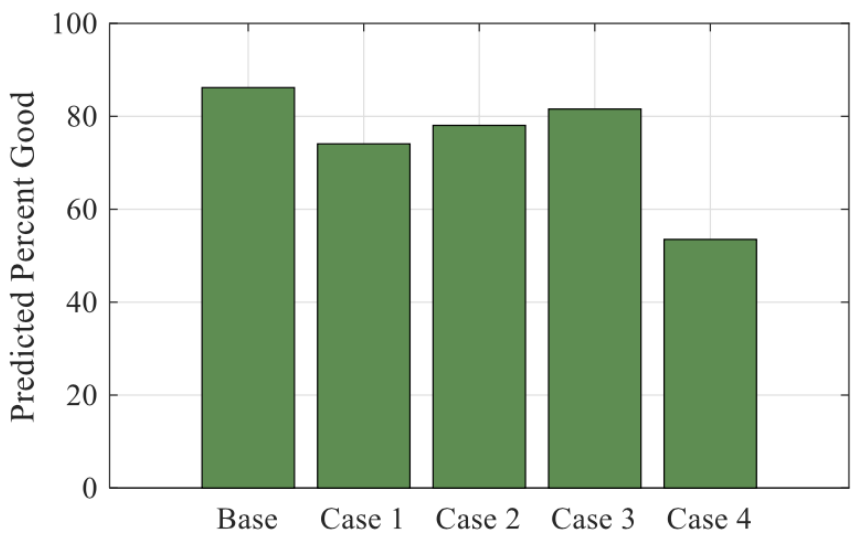


Figure 9-29. Predicted Percent Good from Sensitivity Study

Figure 9-30. Predicted Percent Fair from Sensitivity Study

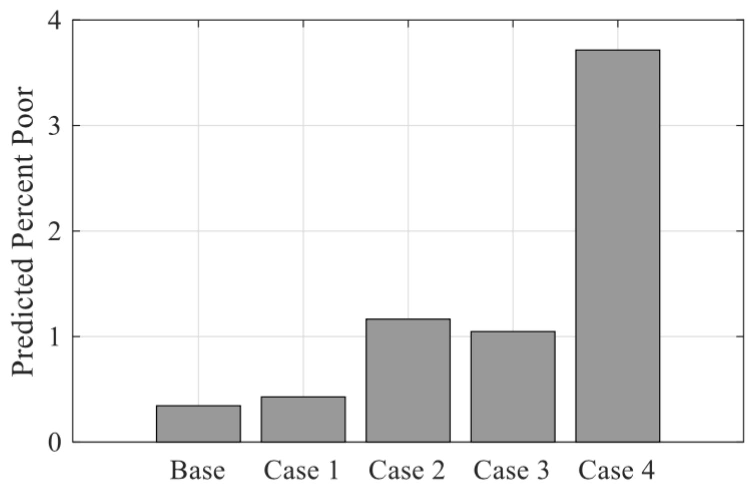


Figure 9-31. Predicted percent good from sensitivity study

Similarly, a set of multinomial logistic regression models was fit to non-interstate (trunkline) NHS asphalt pavements. The results are shown provided in equations 9.18 and 9.19, and the overall model along with each independent variable was shown to be statistically significant at the 95 percent confidence level. The approach to calculating the proportion of non-interstate NHS asphalt pavements in each condition is the same as the steps outlined previously for interstate pavements, and the same method is applicable to the results of concrete pavements.

$$\ln\left(\frac{\pi_{Good}}{\pi_{Poor}}\right) = -10.37 - 9.78 \times PPC + 20.34 \times PGI + 437.66 \times PPI - 71.83 \times PPR - 581.51 \times PGI \times PPI \quad 9.18$$

$$\ln\left(\frac{\pi_{Fair}}{\pi_{Poor}}\right) = -4.73 - 6.50 \times PGC - 13.82 \times PPC + 19.20 \times PGI + 446.27 \times PPI - 73.41 \times PPR - 595.57 \times PGI \times PPI \quad 9.19$$

where:

PPR = proportion of rutting in poor condition
All other variables as previously defined

9.8.2 Concrete Pavements

Concrete pavements were analyzed in the same way that asphalt pavements were, but the number of segments averaged into each sample was much smaller due to the small number of concrete pavements in the network. Figure 9-32 shows the distributions of the proportion of poor pavements and the proportion of good pavements. Compared to the distribution of asphalt pavements in Figure 9-28, concrete pavements have a higher proportion of poor pavements. The logistic regression models for interstate concrete pavements is provided in equations 9.20 and 9.21.

$$\ln\left(\frac{\pi_{Good}}{\pi_{Poor}}\right) = 2.96 + 1.26 \times PGC - 1.47 \times PPC - 14.15 \times PPI - 15.97 \times PPF + 115.61 \times PPI \times PPF \quad 9.20$$

$$\ln\left(\frac{\pi_{Fair}}{\pi_{Poor}}\right) = 3.830 + 10.748 \times PFC - 8.470 \times PPC - 19.646 \times PPI - 7.797 \times PFR \quad 9.21$$

where:

PPF = proportion of faulting in poor condition
PFI = proportion of IRI in fair condition
All other variables as previously defined

Similarly, the results of the multinomial logistic regression for non-interstate NHS asphalt pavements are shown provided in equations 9.22 and 9.23, and the overall model along with each independent variable was shown to be statistically significant at the 95 percent confidence level

$$\ln\left(\frac{\pi_{Good}}{\pi_{Poor}}\right) = 4.46 - 3.00 \times PPC - 16.59 \times PPI - 21.09 \times PPF + 164.61 \times PPI \times PPF \quad 9.22$$

$$\ln\left(\frac{\pi_{Fair}}{\pi_{Poor}}\right) = 8.46 - 2.59 \times PGC - 4.21 \times PPC - 3.29 \times PGI - 17.22 \times PPI - 18.80 \times PPF + 119.19 \times PPI \times PPF \quad 9.23$$

where: all variables are as previously defined

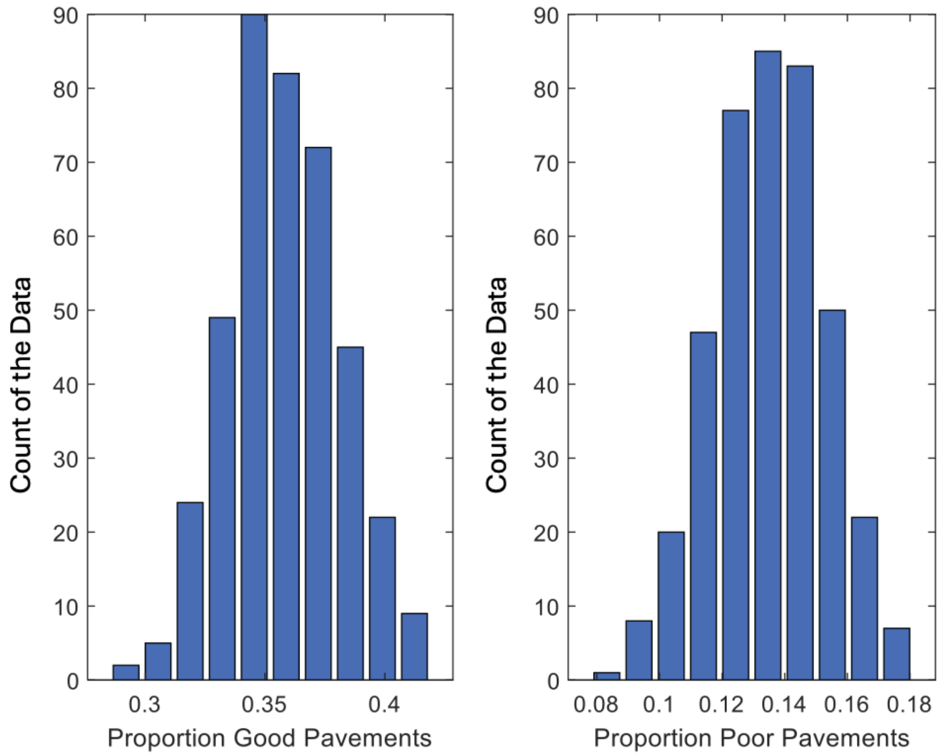


Figure 9-32. Distribution of proportion of good and poor asphalt pavements in samples

9.8.3 Combined projection results

Combined projection results based on the Logistic Regression for ***Interstate*** and ***Non-Interstate*** pavements are presented in Figure 9-33 and Figure 9-34. Finally, the overall Interstate/Non-Interstate summary (including both FLX and RIG pavements) is presented in Figure 9-35. The Logistic Regression (LR) process combines individual pavement distress parameters (IRI, rutting, faulting, and cracking) into unified condition projections using a weighted logistic regression model. Each distress parameter's projected value is multiplied by a calibrated regression coefficient that reflects its relative importance in determining overall pavement condition. These weighted values are summed with an intercept term and transformed through a logistic function to calculate the probability of pavement sections falling into Good, Fair, or Poor condition states. The regression coefficients are specific to both pavement type (Flexible or Rigid) and facility type (Interstate or Non-Interstate), having been calibrated from historical pavement condition data to optimize predictive accuracy. This approach accounts for the varying impact of different distress types on overall pavement performance and produces characteristic lane-mile distributions across condition categories. The resulting combined projections enable systematic prediction of future pavement conditions and support work-level planning by forecasting the percentage of lane miles requiring different intervention levels over time.

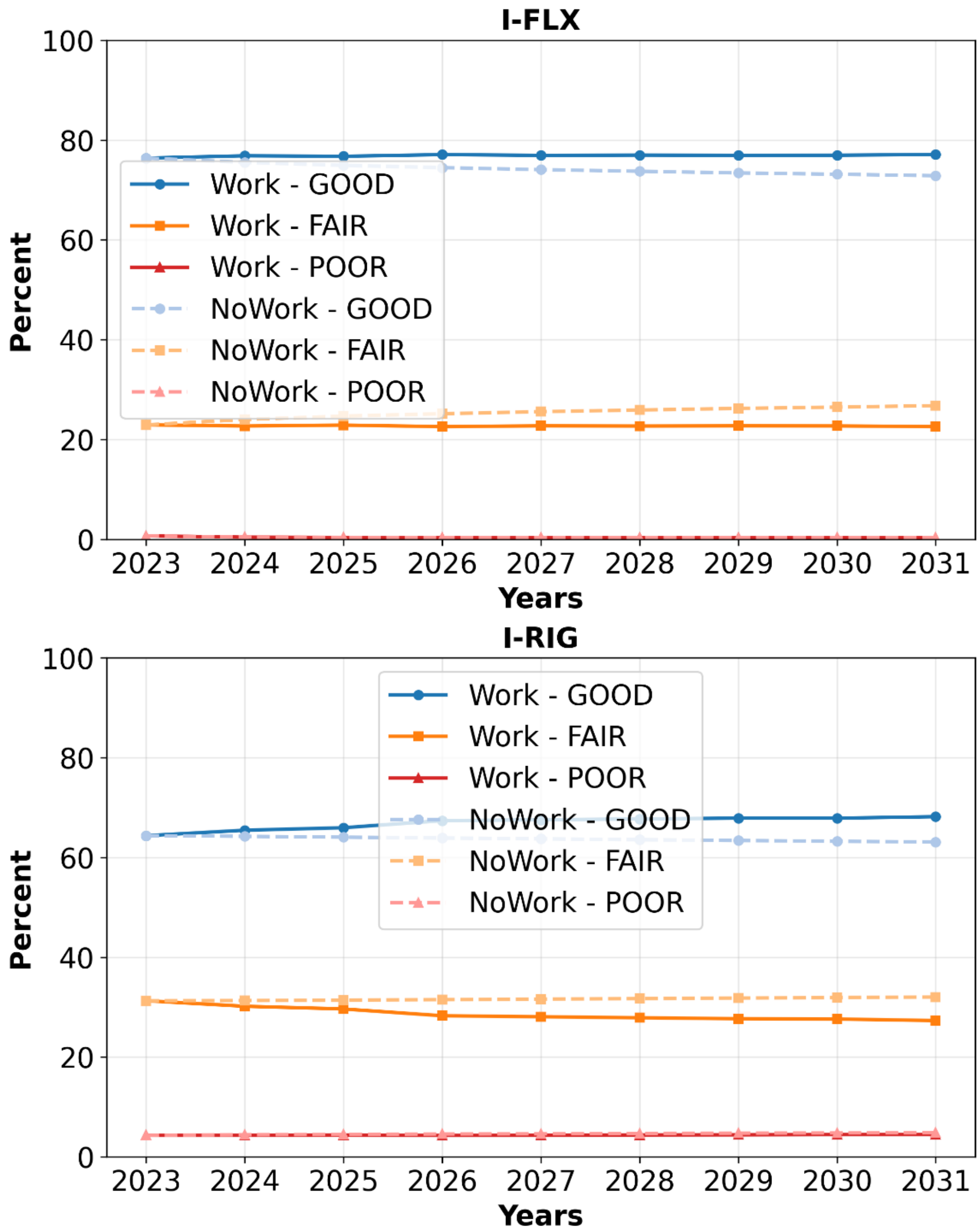


Figure 9-33. <u>Combined</u> projections for I-FLX, I-RIG based on the Logistic Regression

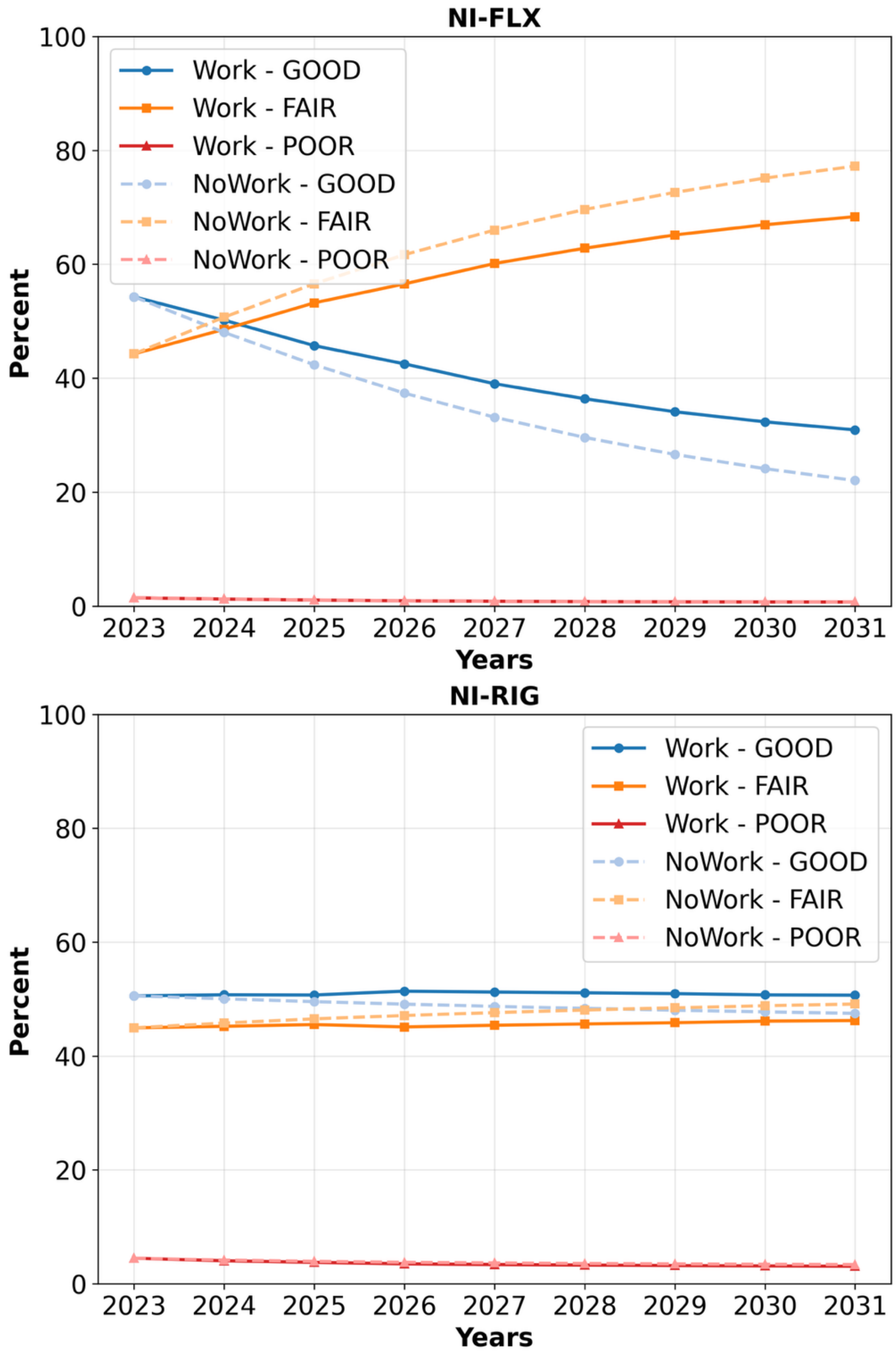


Figure 9-34. <u>Combined</u> projections for NI-FLX, NI-RIG based on the Logistic Regression

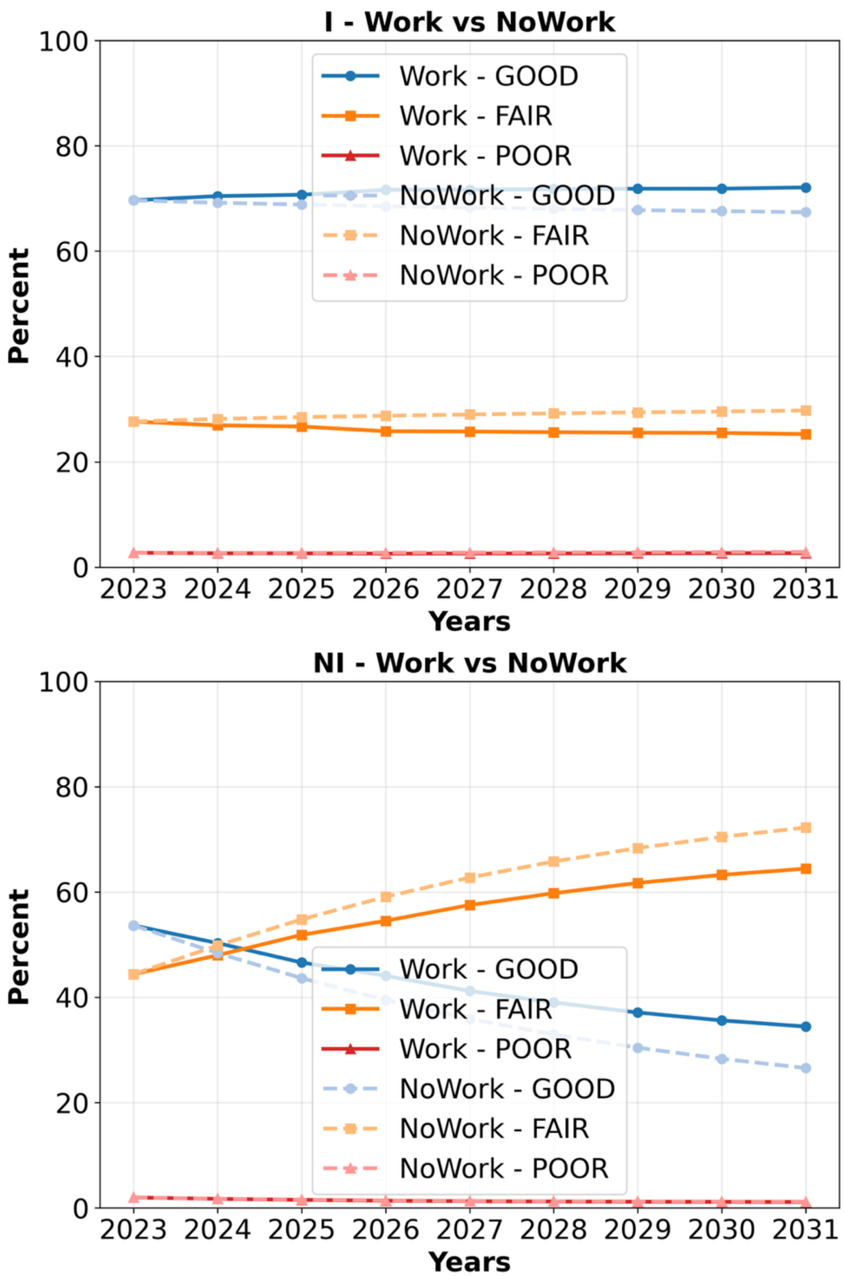


Figure 9-35. Overall Interstate and Non-interstate projections (including both FLX and RIG pavements).

10 CONCLUSIONS

A pavement condition index is a critical tool that transportation agencies rely on to evaluate the health of in-service pavements and guide decisions regarding maintenance, rehabilitation, and reconstruction. Due to challenges related to the methodology, structure, interpretation, and comparability of the Distress Index (DI), the Michigan Department of Transportation (MDOT) elected to discontinue its use and initiated this study to develop a nationally aligned, implementable alternative. In response, this study introduced the Pavement Distress Score (PDS)—a modern, objective, and scalable condition metric designed to support MDOT's pavement management needs while maintaining backward compatibility with historical records. To build a robust foundation for PDS, a comprehensive literature review (Task 1) was conducted to assess pavement condition indices used across the country. The review highlighted the diversity of approaches in practice and the need for a standardized metric that balances consistency, practicality, and compatibility with MDOT's existing data.

A national evaluation of five condition indices (Task 2) revealed that Minnesota's Surface Rating (SR) stood out for its strong ability to distinguish between treatment types, ease of interpretation, and alignment with MDOT's scoring direction. SR was therefore selected as the baseline framework for the development of PDS. The PDS itself was developed in Task 3 through a two-phase process. In Phase I, distress types, severity levels, and weighted scoring were defined using historical data. In Phase II, PDS was refined to align with MDOT's new Surface Defect Survey (SDS) format, and historical data were converted for continuity. The resulting metric was optimized using MDOT's maintenance history and validated to ensure accuracy, practicality, and scalability.

In Task 4, performance models were constructed for each pavement type using both traditional family definitions and a new approach grounded in SDS-PDS data. These models, using Logistic and ASigmoid functions, enabled the estimation of deterioration curves and fix lives tailored to MDOT's planning and investment needs. Task 5 reviewed MDOT's current Life Cycle Cost Analysis (LCCA) framework, which had been based on DI, and proposed a new approach rooted in PDS. The resulting service life curves offered a more data-driven and defensible means for estimating treatment timing and evaluating cost-effectiveness in LCCA applications. Task 6 developed and implemented a suite of MATLAB algorithms to automate service life estimation using both PDS and IRI models. Comparative analysis showed that IRI tends to overestimate service life, while PDS provided more realistic deterioration profiles. The finalized tools are ready for MDOT to begin to implement into IT systems.

Finally, Task 7 addressed future network-level condition modeling by evaluating two methodologies: integration with a pavement management system and use of Markovian Transition Probability Matrices (TPMs). Given MDOT's extensive historical data, the TPM approach was adopted and used to generate deterioration and improvement matrices for IRI, HPMS cracking, rutting, and faulting. These matrices support condition projections under various maintenance scenarios and were further enhanced by logistic regression models that aggregate multiple distress measures into a unified Good/Fair/Poor rating. MATLAB code…

The key outcomes of each task are summarized below:

- *Task 1: Literature Review and Review of Pavement Condition Indices*: A national review revealed that while many pavement condition indices are in use, none aligned well with MDOT's current data collection. The need for a unified, objective, and compatible metric established the basis for developing PDS.

- *Task 2: Evaluation of Pavement Condition Indices Used Nationwide*: Minnesota's Surface Rating (SR) was identified as the most suitable foundation for MDOT's condition metric due to its strong alignment with agency priorities, rating behavior, and data structure.

- *Task 3: Development of Pavement Distress Score (PDS)*: PDS was created through a structured two-phase process, including distress definition, weight optimization, and validation. It is fully compatible with MDOT's SDS format and supports historical data integration.

- *Task 4: Performance Modeling for PDS*: Performance models were developed using logistic and ASigmoid functions across both legacy and new pavement families. These models produced fix life estimates and deterioration profiles that support project- and network-level planning.

- *Task 5: Review of MDOT's LCCA Process and Recommendation of a PDS-Based Service Life Method*: A revised LCCA process using PDS-based service life curves was introduced, providing a more consistent, transparent, and data-driven foundation for economic evaluations.

- *Task 6: Algorithms for Determining Service Lives Based on PDS and IRI*: Custom MATLAB scripts were developed to compute fix lives and generate sawtooth deterioration curves. Results demonstrated the superiority of PDS over IRI in representing true pavement behavior.

- *Task 7: Evaluate and Recommend Network-Level Modeling Methods for IRI, HPMS Cracking, Rutting, and Faulting*: Markovian transition matrices were created for each condition metric, enabling scenario-based projections of network performance. A logistic regression model was used to consolidate individual metric projections into an overall pavement condition forecast.

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