DEVELOPMENT OF AN ENHANCED PAVEMENT CONDITION SCORE FOR MICHIGAN

By

Mumtahin Hasnat

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ABSTRACT

The Michigan Department of Transportation (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 MODT engineers in their decision-making process, budget allocation, and prioritization for 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), and MDOT has been having difficulty in finding vendors to collect PMS data. 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 is 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). The results were presented through statistical analysis and scatter plots. 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. The new condition parameter is backward compatible using MDOT's historical pavement management data. Moreover, while developing the new pavement condition index, important criteria such as policy sensitivity, ease of understanding, and usefulness in decision-making were considered. Furthermore, various performance models were used to predict the new condition index and International Roughness Index (IRI) data and pavement fix lives for both asphalt and rigid pavements.

To My Parents, To My Siblings and To My Wife

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1. INTRODUCTION

1.1 General

In the United States, the Department of Transportations (DOTs) use a pavement management system (PMS) to manage their highway system efficiently. PMS database works as a data-driven and informed decision-making tool that help state DOTs maintain their future budget allocation, repair needs, and prioritization of maintenance activities [1], [2]. Therefore, a functional PMS is very crucial for the overall decision-making process. An element of a PMS database is the vast collection of pavement performance 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 distresses, which can then point to the particular maintenance actions available for consideration [3]. 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, the performance measure is vital in determining the progress toward a goal [4]. Performance measure usually includes 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 in a given 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 [5]. Collectively, pavement performance measures should help to make strategic decisions on budget allocation, monitor and sustain 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 is often believed that fixing the worst pavement first would be the best option in M&R activity. But this is not necessarily the case; early minor treatment activities delay the deterioration of pavements and can be economical in the long run [6]. 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 [7]. An agency can save money 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 to every state agency to follow.

1.2 Research Motivation

Michigan Department of Transportation maintains 12,000 miles of its trunk line road. The parameter used by the MDOT to assess the condition of pavements has historically been the Distress Index (DI) [8]. MDOT has been using DI since the inception of its pavement management system (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 are conducted approximately every two years for each pavement. The distress surveys are based on the videos of the pavements, where vendors are required to classify visually distresses into numerous categories of distresses [different Principal Distress (PD)] codes for various types of pavements. This level of detail is inconsistent with the practice followed nationwide and causes issues such as the limited availability of vendors to perform this task. As a result, 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 % cracking, rutting, faulting, and the international roughness index (IRI).

Consequently, there is an urgent need for a new pavement condition parameter consistent with the new data acquisition practice. This research study produced a new pavement condition parameter that MDOT can easily implement soon. The new parameter was chosen to be backward compatible, and the required observed distresses that can be collected by the pavement data collection industry in an accurate and timely manner. Therefore, this study will help MDOT identify important distresses that MDOT must collect. Each distress definition with severity levels is defined so that vendors can easily capture those using their automated technology. Moreover, performance models were developed to estimate the road network's fix lives.

1.3 Objective and Research Plan

The overall goal of this study is to revisit the DI used by MDOT and revise it according to modern pavement data collection standards and calculation processes. The following specific objectives were established to achieve this goal:

- Review MDOT distresses and compare them with a nationwide practice
- Evaluate nationwide condition indices and compare with MDOT's Distress Index (DI)
- Develop a composite condition index for MDOT, consistent with a national practice
- Develop performance models to predict the fix life of pavements
- Network-level modeling for International Roughness Index (IRI) and fix life estimation

Figure 1.1 shows a simple flow chart diagram depicting the research plan for developing an enhanced pavement condition rating system for Michigan. Phase I of this research study focuses on creating a new version of the Distress Index (DI) to calculate the pavement's fix life. Then, in Phase II, an alternative approach to calculating pavement fix life was considered by analyzing raw International Roughness Index (IRI) data. The new condition index and IRI-based performance modeling and fix life estimation will better inform state engineers about their current pavement health condition. They will eventually help them to plan their maintenance actions and budget allocation.

1.4 Thesis Organization

Chapter 1 includes research objectives and motivations in addition to the scope of the research. Chapter 2 contains a comprehensive literature review on various pavement condition indices and performance models state agencies use. Chapter 3 discusses the recommendation for future distress survey lists for both asphalt and rigid pavement. Chapter 4 explains the method to evaluate five selected condition indices with MDOT PMS data. The results of evaluating those condition indices are presented in Chapter 5. Chapter 6 focuses on describing the new condition index developed for Michigan roads. Chapter 7 presents performance modeling effort and fix life estimation for the condition index with MDOT families. Chapter 8 deals with similar performance modeling and fix life estimation with new families developed in this study. Chapter 9 presents IRI-based performance modeling and fix life calculation. In Chapter 10, this study's overall summary and conclusion are presented alongside some recommendations for future studies.

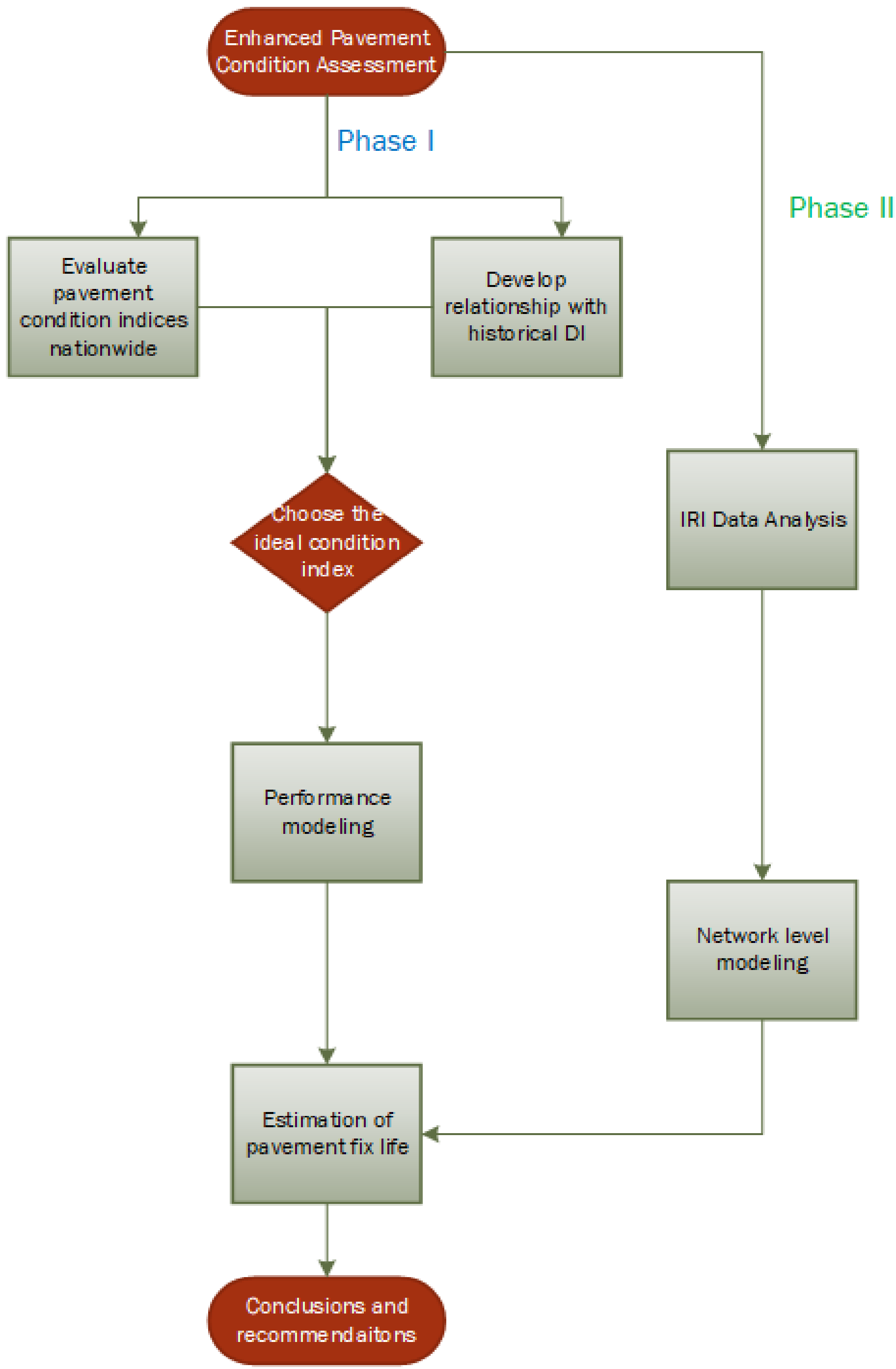


Figure 1.1 Research plan flow chart for developing an enhanced pavement condition assessment.

2. LITERATURE REVIEW

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

2.1 Pavement distress collection methods

To any state agency, appropriate and consistent pavement distress identification is crucial in maintaining its pavement management system database (PMS) [2]. However, pavement behavior and performance are highly variable due to many influential factors, e.g., structural design, traffic, climate, material, construction practices, etc. [9]. With these unavoidable issues, state agencies try 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[10]. The raters conducted condition surveys using pen and paper. At that period, different state highway agencies in the United States 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 [11]. 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 to facilitate data consistency among state highway agencies (SHAs). 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 distresses. A trained staff typically analyzes raw distress data within an office by reviewing images and video logs [3]. One type of semi-automated method, probably the most human interference involved, asks raters to classify distress, visually measure the extent of each distress from the computer screen, and then enter distress data directly into the pavement management system. 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 [12]. This process requires zero to minimal human involvement during pavement data collection, analysis, and compilation into a pavement database. Computer software reads downward images to classify each distress with severity level and quantify the actual measurements of each distress.

2.2 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 performance 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 (PSR). Later, a more objective and complex index called the U.S. Army Corps of Engineers developed the pavement condition index (PCI). PCI was valued on a scale of 100 to 0, where 100 represents the perfect condition. The original form of PCI was further standardized in ASTM D6433 [13]. The state agencies' condition indices described in the subsections below are based on the original PCI method.

2.2.1 Colorado DOT

The Colorado Department of Transportation (CDOT) has used Drivability Life (DL) as its performance measure index since 2013. Before that, CDOT used remaining service life (RSL). They shifted to DL because it represents pavement condition well (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 [14]

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 has no distresses, and 0 represents the pavement is in the worst condition. These cracking distress indices can be calculated using Equation 2.1, where the roughness and rutting index can be calculated using Equation 2.2 and Equation 2.3, respectively.

$$Cracking\ Index = 100\ \times \left(1 - \frac{Cracking_{LOW}}{Max_{LOW}} - \frac{Cracking_{MED}}{Max_{MED}} - \frac{Cracking_{HIGH}}{Max_{HIGH}}\right) \quad 2.1$$

$$Ride\ Index = 100\ \times \left(1 - \frac{IRI_{avg} - A_{min}}{B_{max}}\right) \quad 2.2$$

$$Rut\ Index = 100\ \times \left(1 - \frac{Rut_{avg} - B_{min}}{B_{max} - B_{min}}\right) \quad 2.3$$

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. Values of different parameters used to calculate distress indices for asphalt pavement can be found elsewhere [15].

2.2.2 Florida DOT

The Florida Department of Transportation (FDOT) translates its distress and smoothness data into a composite index called Pavement Condition Rating (PCR) [16]. 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.

2.2.3 Idaho Transportation Department

The 2011 Idaho Transportation Department (ITD) pavement rating guide was investigated to identify the distress severity and extent information [17]. The severity and extent definitions for ITD pavements seem similar to those derived for Virginia DOT pavements. ITD uses Cracking Index (CI) and Roughness Index (RI) as pavement condition indices. The rating scale ranges from 0 to 5, where 5 being the best score.

2.2.4 Illinois DOT

The Illinois Department of Transportation (IDOT) converts its measured distresses into a practical condition measure index called Condition Rating Survey (CRS). CRS has been used by IDOT for many years since 1974. Since 1994 IDOT has started using mathematical models to calculate CRS and to predict future pavement performance [18]. Future pavement performance prediction would help the state agency allocate the budget economically and effectively.

CRS is reported on a scale of 1 to 9. A road with nine represents newly constructed or resurfaced pavement, where 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 [19].

2.2.5 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 2.1 and Table 2.2 list the pavement surface distresses and their associated severity and extent definitions INDOT collects for asphalt and concrete pavements, respectively [20]. These two tables should be used as examples of how DOTs generally define their surveyed distresses to help readers.

INDOT uses Pavement Condition Rating (PCR) as the condition metric. PCR ranges from 0 to 100, where 100 is the best, and 0 is the worst condition. PCR helps rank the 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 2.4.

$$\text{PCR} = 100 - \sum deduct\ points \qquad 2.4$$

2.2.6 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 pavement 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 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 different pavement 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 [21] Whereas, for rigid pavement, longitudinal cracking index, transverse cracking index, patching index, and roughness index are the inputs [22]. PCI ranges from 1 to 100, where 100 is the perfect score.

Table 2.1 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/0.1 mile
	2) Fair Condition	2) 3 - 4 Patches/0.1 mile
	3) Deteriorated or Temp Patch	3) > 4 Patches/0.1 mile
3. Potholes	1) < 1" deep and < 1 syd	1) 1/0.1 mile
	2) < 1" deep and > 1 syd; OR > 1" deep and < 1 syd	2) 2 - 3/0.1 mile
	3) > 1" deep and > 1 syd	3) > 4/0.1 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 2.2 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 /0.1 mile
	2) Fair Condition	2) 3 – 4 Patches/0.1 mile
	3) Deteriorated or Temp Patch	3) > 4 Patches/0.1 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.

2.2.7 Minnesota DOT

The Minnesota DOT measures pavement condition in terms of the Ride Quality Index (RQI), Surface Rating (SR), and Pavement Quality Index (PQI) [23]. 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 better the pavement is. In MnDOT data collection practice, extents are not directly calculated; the count or lineal feet of distress 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.

2.2.8 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 [24]. The 'Fugro Roadware' device captures 3-D surface images through the laser crack measurement system (LCMS). This transition is because 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 was old and obsolete and needed replacement. Another motivation is that NYSDOT has already been collecting automatic crack data on a large portion of the NYS 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. 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 distress types. A pavement with no visual surface distress is rated 10, whereas an impassible condition is rated 1. In general, a Surface Rating of less than 5 is rare to be seen as rehabilitation or reconstruction is warranted for such pavements.

2.2.9 North Dakota DOT

The North Dakota Department of Transportation (NDDOT) uses a composite index known as Distress Score (DS) in assessing the pavement condition [25]. Like PCR, NDDOT's Distress score is also based on deduct point system. DS ranges from 0 to 99. A pavement with no distress is assigned a score of 99, and then based on associated severity and extent, deduct points are assigned and deducted from 99 for the overall distress score. 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.

2.2.10 Ohio DOT

The Ohio Department of Transportation (ODOT) has been using Pavement Condition Rating (PCR) to characterize surface distress since 1985 [18]. PCR is calculated using manually collected distress data by dedicated raters. As part of PCR calculation, ODOT collects several asphalt and JPCP rigid pavement distresses. The severity and extent definitions for this distress can be found in the PCR manual [26]. 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 mentioned above for flexible and rigid pavement carries deduct points based on the severity and extent. For a given pavement section, the summation of all these deduct values is subtracted from the perfect pavement condition, i.e., 100 to obtain PCR. PCR is calculated using Equation 2.5:

$$PCR = 100 - \sum_{I=1}^{n} Deduct_i \qquad 2.5$$

Where, n = number of observable distresses, and

Deduct = (Weight for distress) (Wt. for severity) (Wt. for Extent)

It is to be noted that ODOT has researched, to some extent, the possibility of using the 3-D downward imaging system to calculate PCR. They have found that rutting could easily be calculated with very high repeatability. However, the algorithms to calculate the many and varied other ODOT PCR distresses mentioned above would take significant time to develop. 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.

2.2.11 South Dakota DOT

The South Dakota Department of Transportation (SDDOT) uses the Surface Condition Index (SCI) to evaluate current overall pavement conditions [27]. SCI is a composite index computed from each road segment's overall distress rating. SCI is calculated using the following Equation 2.6:

$$SCI = \mu - 1.25\sigma \qquad 2.6$$

where, μ = mean of all contributing individual distress index, 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.

2.2.12 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; the best condition receives a CS of 100 [28]. Once the distresses are measured on a given pavement segment, they are translated into a utility value (between 0 and 1) using Equation 2.7.

$$U_i = 1 - \alpha e^{(\frac{\rho}{L_i})^{\beta}} \qquad 2.7$$

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. The CS is then calculated by taking the product of 100, the distress score, and the utility value related to the pavement roughness.

2.2.13 Virginia DOT

Rada et al. [29] explained 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). 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 deducting values for non-load-related distresses: block cracking, patching, longitudinal cracking out of wheel path, transverse cracking, reflection cracking, and bleeding [6].

2.2.14 Wisconsin DOT

The Wisconsin Department of Transportation (WisDOT) uses the Pavement Condition Index (PCI) as its pavement condition measure [30]. 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 the excellent condition, whereas 55 is the minimum PCI value to consider pavement in fair condition.

Table 2.3 and Table 2.4 summarize all the condition indices with the associated rating scales and distress inputs. It can be noticed that only Michigan DOT has the opposite trend of rating their pavement or, in other words, the perfect condition of a pavement defined with a zero (0) score, and the more a pavement deteriorates, the more the DI value computed.

Table 2.3 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
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)	0-100	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)

Table 2.3 (cont'd)

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
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 distress (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 2.4 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)	0-100	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)

Table 2.4 (cont'd)

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 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 (*Cor*ner 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

2.3 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 pavement maintenance, rehabilitation, and reconstruction decisions. 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.

2.3.1 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 2.8 [31]:

$$SDI = SDI_0 - e^{\left(A - B \times C^{\ln\left(\frac{1}{Age}\right)}\right)} \qquad 2.8$$

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. [31].

2.3.2 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 [32]. The model is shown in Equation 2.9.

$$PCR = C_0 + C_1 \times Age^{C_2} \qquad 2.9$$

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.

2.3.3 Delaware DOT's OPC performance model

Mills et al. developed a multiple regression model for DelDOT to predict the Overall Pavement Condition (OPC) rating [33]. The model is shown in Equation 2.10:

$$OPCx = a_o + a_1 AADT + a_2 AGE + a_3 EnvCr + a_4 FatCr + a_5 PAT + a_6 Sn + a_7 SurDe + a_8 EdCr + a_9 TraCr \quad 2.10$$

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

2.3.4 Michigan DOT's DI performance model

Kuo was the first who proposed a logistic growth curve model and Gompertz growth curve model for the Michigan Department of Transportation (MDOT) to predict pavement performance [34]. The models are expressed by the following Equation 2.11 and Equation 2.12.

$$DI_{Logistic} = \alpha(\left[\frac{(\alpha + \beta)}{\alpha + \beta e^{-\gamma t}}\right] - 1) \quad 2.11$$

$$DI_{Gompertz} = ((\alpha + \beta)\left(\frac{\alpha}{\alpha + \beta}\right)^{exp(-\gamma t)})) - \alpha) \quad 2.12$$

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 = Predetermined DI

2.3.5 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) [35]. The model is shown in Equation 2.13.

$$PCR = 76.10 - Age^{0.6696}\,(1 + CESAL^{0.7100}))MSN^{0.0979} \qquad 2.13$$

where,

Age = Pavement Age,

CESAL = Cumulative 18-kip ESAL

MSN = Modified structural number

MSN can be calculated as follows:

$$MSN = SN + SN_{sg} \qquad 2.14$$

where,

SN = Structural number,

SN_{sg} = Pseudo structural number for the subgrade

$$SN = a_1D_1 + a_2D_2m_2 + a_3D_3m_3 \qquad 2.15$$

$$SN_{sg} = 3.51 \times log_{10}CBR - 0.85(log_{10}CBR)^2 - 1.43 \qquad 2.16$$

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 (%)

2.3.6 Washington DOT's PSC performance model

Washington Department of Transportation (WSDOT) used a generalized performance model to predict Pavement Structure Condition (PSC) [36]. The model is shown in Equation 2.17.

$$PSC = c - m \times A^p \qquad 2.17$$

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

2.3.7 Virginia DOT's CCI performance model

Amarh et al. developed pavement performance models for recycled pavements in Virginia [37]. 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 2.18.

$$CCI = a - Age^b \times Exp\ (c) \qquad 2.18$$

where,

Age = Age in years since last rehabilitation or construction, and

a b, c = Model coefficients

2.3.8 Iowa DOT's PCI performance model

The Iowa Department of Transportation uses a statistical regression equation to calculate its pavement performance measures, 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. [1] 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 2.19 through 2.21 show PCI models for full-depth asphalt concrete, Portland cement concrete, and AC over old concrete, respectively.

$$PCI_{AC\ full\ depth} = 92.34 - 0.36\ \times (pavement\ age) - 11.11\ \times IRI - 2.041\ \times (alligator\ cracking) + 0.55\ \times (patching) \quad 2.19$$

$$PCI_{PCC} = 92.56 - 10.08\ \times IRI - 0.52 \times (pavement\ age) - 118.40\ \times (durability\ cracking) + 3.24\ \times (structural\ rating\ at\ joints) \quad 2.20$$

$$PCI_{AC\ composite} = 95.00 - 7.18\ \times (IRI) - 0.92\ \times (pavement\ age) - 0.96\ \times (transverse\ cracking) - 0.22\ \times (wheelpath\ cracking) - 0.07 \times (percentage\ of\ life\ used\ based\ on\ ESALs) \quad 2.21$$

2.4 *Performance models for International Roughness Index (IRI)*

This section presents a few of the network-level modeling methods used nationwide for the International Roughness Index (IRI). The IRI performance model is widely used in pavement engineering for evaluating the ride quality of road surfaces. It is a numerical indicator of the roughness of a pavement surface and is calculated based on the vertical deviations of the pavement surface from a reference plane over a distance of one meter. The IRI performance model is used to assess the ride quality of pavements and predict the deterioration of pavement surfaces over time. It is also used to identify sections of pavements that require maintenance or rehabilitation.

2.4.1 IRI performance model by Maher et al.

Maher et al. developed a sigmoidal increasing IRI model for the New Jersey Department of Transportation (NJDOT) as follows [38]. The model is presented in Equation 2.22.

$$IRI = IRI_0 + e^{(A - B\times C^{\ln(Age)})} \quad 2.22$$

where,

IRI_0 = Initial IRI at age zero (Recommended IRI = 70 inches per mile),

Age = Pavement age in years since last rehabilitation or construction activity, and

A, B, C = Model coefficients

2.4.2 IRI performance model by K.P. George

In 2000, George developed an IRI performance model with support from the Mississippi Department of Transportation and the FHWA [39]. The model is presented in Equation 2.23.

$$IRI = 2.4169 + Age^{0.2533}\,(1 + CESAL^{0.2572}))MSN^{-0.7753} \quad 2.23$$

where,

Age = Pavement Age,

CESAL = Cumulative 18-kip ESAL

MSN = Modified structural number

MSN can be calculated as follows:

$$MSN = SN + SN_{sg} \quad 2.24$$

where,

SN = Structural number,

SN_{sg} = Pseudo structural number for the subgrade

$$SN = a_1 D_1 + a_2 D_2 m_2 + a_3 D_3 m_3 \quad 2.25$$

$$SN_{sg} = 3.51 \times log_{10}CBR - 0.85(log_{10}CBR)^2 - 1.43 \quad 2.26$$

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 (%)

2.4.3 IRI performance model by Al-Suleiman et al.

Al-Suleiman and Shiyab [40] developed an IRI performance model for asphalt-surfaced pavement sections in Dubai. This exponential form of the model is also known as the Dubai IRI model. The general form of the equation can be represented using Equation 2.27.

$$IRI = a \times exp^{(b \times Age)} \quad 2.27$$

where IRI is the International Roughness Index, a measure of pavement roughness; Age is the pavement age in years; and a and b are coefficients. The equation shows that the IRI values increase with increasing pavement age, with the rate of increase being dependent on the values of the coefficients a and b.

2.4.4 IRI performance model by Amarh et al.

Like the Dubai model, Amarh et al. [37] also utilized a similar form of an IRI prediction model for the recycled pavements in Virginia [41]. The model is shown in Equation 2.28.

$$IRI = a \times exp\ (b \times Age) \quad 2.28$$

where,

Age = Pavement age in years since last rehabilitation or construction activity

3. RECOMMENDATION ON DISTRESSES TO BE COLLECTED BY MDOT AND SEVERITY DEFINITIONS

Historically, MDOT has been collecting many surface distresses with the help of vendors. Since 1992 MDOT has maintained its pavement management system (PMS) database, where all the raw distress data are stored. MDOT assigned Principal Distress (PD) codes alongside some Associate Distress (AD) codes to reflect the severity and extent of individual distress. MDOT collects around 30 different PDs for both asphalt and rigid pavements. Table 3.1 and Table 3.2 present pavement distresses that MDOT collects on their road network for asphalt and rigid pavements, respectively. Table 3.3 shows an example associated distress matrix table of flexible pavement transverse crack (TC) (PD 103) [42]. According to the MDOT's survey manual, the severity of a TC is estimated by transverse length (total accumulated length along crack alignment where associated distress observed) and maximum width (at any single location along crack alignment) of the ADs that occur within 2 feet of the TC [42]. As mentioned, this complex definition of crack severity is inconsistent with a nationwide practice. As a result, with vendors struggling to process the raw data due to the complex severity and extent definitions, MDOT experienced delays in calculating their pavement condition index and estimating remaining service life. Therefore, MDOT decided they might not need all of the currently captured distresses with such detailed information (with AD matrices). To address the issue, this section includes the nationwide practices for commonly collected distresses and corresponding severity definitions. It proposed a list of surface distresses that MDOT should focus on for more efficient data collection.

Table 3.1 MDOT surveyed distress list for flexible pavements

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 Cracking
205	Longitudinal Crack- LC- (Left Wheelpath - WP)	405	Raveling
234	Alligator Crack -Right WP	406	Flushing
235	Alligator Crack -Left WP	-	-

Table 3.2 MDOT surveyed distress list for rigid pavements

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 Cracking
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 3.3 MDOT Associated Distress Matrix Table for HMA Transverse Cracking

Transverse Length Across Lane (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.

A recent survey in 2018 conducted by Pierce et al. [3] showed that most state agencies capture a similar type of distress on their pavement surface except few distresses that are not commonly observed or captured in different states. Fifty-seven agencies participated in that survey, including 46 U.S. highway agencies and 11 Canadian provincial and territorial governments. Figure 3.1 and Figure 3.2 show all the distresses often seen on asphalt and rigid pavements, respectively.

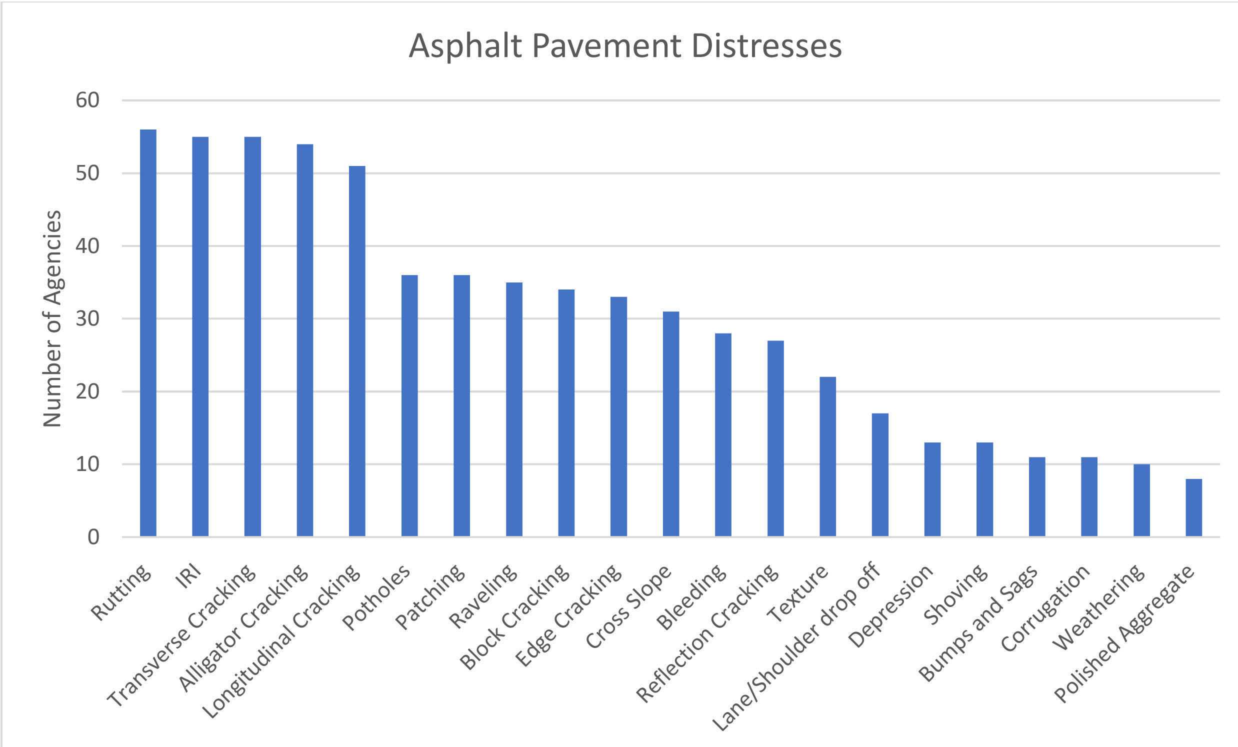


Figure 3.1 List of Asphalt Pavement distresses seen nationwide [3]

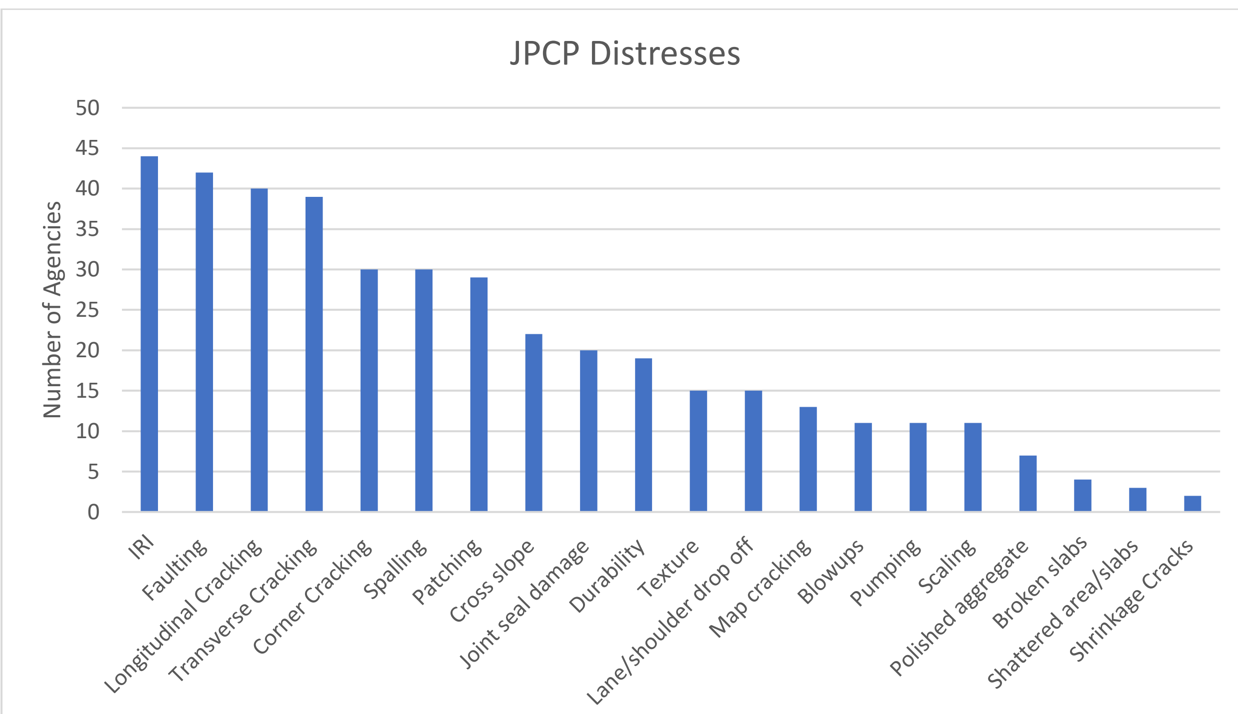


Figure 3.2 List of Jointed Plain Concrete Pavement (JPCP) distresses seen nationwide [3]

Referring to Table 3.1 and Table 3.2, 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) or PD codes that seem redundant to the existing data collection. 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. Also, Partial Width Patch (white) and Partial Width Patch (black) were recommended by MDOT to be removed from the distress list for the future survey.

For rigid pavements, PDs that were suggested to be eliminated are Partial Width Patch (white) and Partial Width Patch (black), Map Cracking, 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 Cracking and (ii) Punchout, in their list of rigid pavement surveys for future reference.

In summary, Table 3.4 and Table 3.5 show the final proposed distress list for flexible and rigid pavement, respectively. General definitions of flexible pavement distresses are provided below.

TC - Transverse Cracking: 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 a length in feet.

LCC - Longitudinal Centerline Cracking (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 0.001-mile segment along the lane has at least 50% of its length covered by the distress type occurrence. Reported as a length in feet.

LWC - Longitudinal Wheelpath Cracking: (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 0.001-mile segment along the lane covers at least 50% of its length by the distress type occurrence. Alligator Cracking is included in LWC and applies to high severity only. Alligator Cracking 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 34.5 inches 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.

LEC - Longitudinal Edge Cracking (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 0.001-mile segment along the lane has at least 50% of its length covered by the distress type occurrence. Reported as *LEC* length in feet.

BC - Block Cracking: A Block Cracking area is where transverse and longitudinal cracking has 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 cracking and later-induced longitudinal cracking. Reported as *BC* length in feet.

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. A pothole is a deep surficial cavity formed by the erosion of aggregates, especially by the action of water and traffic and reported as *RP* length in feet.

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 *FB* length in feet.

General definitions of rigid pavement distresses are provided below.

TJS - Transverse Joint Spalling: A Transverse Joint (TJ) is a regularly spaced saw cut across the slab width. Transverse Joint Spalling (TJS) is the breaking of the sides of Transverse

Joint into smaller pieces/fragments within 2 ft (0.6 m) of the side of the joint. Reported as *TJS* length in feet.

TC - Transverse Cracking: 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 off the sides of a Longitudinal Joint into smaller pieces/fragments within 2 ft (0.6 m) of the side of the joint. Reported as *LJS* length in feet.

LWC - Longitudinal Wheelpath Cracking: (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 0.001-mile segment along the lane has at least 50% of its length covered by the distress type occurrence.

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.

CC - Corner Cracking: A crack that intersects the concrete slab joints near the corner. "Near the corner" is typically defined as within about 6 ft (2 m).

PO - Punchouts: Localized slab portions broken into several pieces. Typically, a concern only with Continuously Reinforced Concrete Pavement (CRCP)

It should be noted that patching is not included in the distress collection procedure, with the idea that edges of the patching, if deteriorated, with be recorded as longitudinal or transverse cracking. However, in some cases, the lack of inclusion of patching in historical PDS calculations can lead to high PDS values when decisions have been made to perform reconstruction or major rehabilitation due to excessive patching.

Table 3.4 New proposed list for use in MDOT Pavement Distress Score (PDS) for flexible pavements

New PD Code	Old PD Codes (i)	New PD Title	Definition (ii)	Severity		
				Low	Medium	High
901	101, 103, 104, 110, 114, 701, 703, 704	Transverse Cracking	TC	Mean crack width <1/4" with no adjacent cracking (Unsealed)	Mean crack width 1/4" - 3/4" with adjacent low severity random cracking	Mean crack width >3/4" with adjacent low to high-severity random cracking
902	202, 218, 722	Longitudinal Center lane (center of the lane) Cracking (non-wheelpath)	LCC	Mean crack width <1/4"	Mean crack width 1/4"-1/2"	Mean crack width >1/2"
903	204, 205, 210, 220, 221, 222, 224, 234, 235, 724, 725, 730, 731	Longitudinal Wheelpath Cracking	LWC	Mean crack width <1/4" no/few interconnected cracks with no spalling	Mean crack width 1/4"-1/2" interconnected cracks with slight spalling	Mean crack width >1/2" interconnected cracks forming a pattern with spalling
904	201, 203, 236, 237, 721, 723	Longitudinal Edge Cracking (non-wheelpath)	LEC	Mean crack width <1/4" Cracks with no breakup/spall/ secondary cracks	Mean crack width 1/4"-1/2". Cracks with slight breakup/spall/ secondary cracks	Mean crack width >1/2". Cracks with severe breakup/spall/ secondary cracks
905	310, 345, 760	Block Cracking	BC	Mean crack width <1/4" with no adjacent cracking	Mean crack width 1/4" - 1/2" with adjacent low severity random cracking	Mean crack width >1/2" with adjacent low to high severity random cracking
906	405	Raveling + Potholes	RP	Light aggregate loss with no potholes or potholes <1" deep and <1yd^2	Medium aggregate loss with visible loss of surface and/or potholes with >1" deep+<1 yd^2 OR <1" deep+>1 yd^2	Severe aggregate loss with significant loss of surface and/or potholes with >1" deep and >1 yd^2
907	406	Flushing/Bleeding	FB	only has occurred to a very slight degree and is noticeable only during a few days of the year	has occurred to the extent that asphalt sticks to shoes and vehicles during only a few weeks of the year	has occurred extensively and considerable asphalt sticks to shoes and vehicles during at least several weeks of the year

Note: (i) Based on latest MDOT distress manual, (ii) definitions are provided within the text

Table 3.5 New proposed list for use in MDOT Pavement Distress Score (PDS) for rigid pavements

New PD Code	Old PD Codes (i)	New PD Title	Definition (ii)	Severity		
				Low	Medium	High
911	106, 706	Transverse Joint Spalling	TJ	Spalls < 3" wide measured to the face of the joint with no loss of material.	Spalls 3" to 6" wide measured to the face of the joint with loss of material.	Spalls > 6" wide measured to the face of the joint with loss of material, or spalls broken into two or more pieces
912	102, 105, 107, 112, 113, 712, 713	Transverse Crack	TC	Crack width < 1/8" with no spalling and no measurable faulting	1/8"≤Crack widths<1/4"; or spalling < 3 in; or faulting up to 1/4"	Crack widths ≥ 1/4"; or spalling ≥ 3"; or faulting ≥ 1/4"
913	208, 209	Longitudinal Joint Spalling	LJS	Spalls < 3" wide measured to the face of the joint with no loss of material.	Spalls 3" to 6" wide measured to the face of the joint with loss of material.	Spalls > 6" wide measured to the face of the joint with loss of material, or spalls broken into two or more pieces
914	206, 207, 212, 213, 214, 215, 227, 229, 230, 232, 737, 740, 742	Longitudinal Wheelpath Cracking	LWC	Crack widths < 1/8 in with no spalling and no measurable faulting	1/8"≤Crack widths<1/2" with spalling < 3"; or faulting up to 1/2"	Crack widths ≥ 1/2"; or with spalling ≥ 3"; or faulting ≥ 1/2"
915	219, 228, 231, 738, 741	Longitudinal Center lane (center of the lane) Cracking (non-wheelpath)	LCC	Crack widths < 1/8 in with no spalling and no measurable faulting	1/8"≤Crack widths<1/2" with spalling < 3"; or faulting up to 1/2"	Crack widths ≥ 1/2"; or with spalling ≥ 3"; or faulting ≥ 1/2"
916	301, 341, 751	Delaminated Area	DA	TBD	TBD	Pothole
917	NA	Corner Cracking	CC	Spalled crack < 10% crack length; no faulting	Spalled crack > 10% crack length; or faulting ≤ 1/2"	Spalled crack > 10% crack length; or faulting > 1/2"
918	NA	Punchout	PO	TBD	TBD	TBD

Note: (i) Based on latest MDOT distress manual, (ii) definitions are provided within the text; TBD = to be decided by discussing with MDOT

Another subtask of this section was to compile information on the distress severity definition from other state agencies' practices. It was found that the definitions of distress and severity are not always consistent across various agencies and standards. For example, high-severity transverse cracking measured during a Pavement Condition Index (PCI) survey is defined as having a crack width greater than 3 inches [13], while in the LTPP program, high-severity transverse cracking is determined to have a crack width greater than 0.75 inches, and in Indiana DOT (see Table 2.1), it is defined as having a width greater than 0.25 inches. In some cases, distress severities are defined in a non-quantitative manner. A recent NCHRP report 1-57A [43] detailed standard definitions that are seen nationwide and emphasized the importance of precision within a few millimeters using modern data collection techniques, which reinforces the significance of defining the width of cracks for severity.

After reviewing the collected information, it was suggested (shown in Table 3.4 and Table 3.5 for flexible and rigid pavements, respectively) that MDOT incorporate quantitative and qualitative data collection methods in their future pavement distress surveys to ensure accurate and timely data collection from vendors. With the recent improvements in automatic pavement distress surveys, measuring the crack width of individual distresses will be possible. As a result, MDOT can eliminate Associated Distress (AD) codes and utilize the national standard practice of classifying surface distresses, if necessary, to categorize the severity levels of distresses. MDOT can ensure a more efficient and effective distress survey process by adopting these measures.

4. METHODOLOGY OF EVALUATING A FEW 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, a similar 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. Also, Table 4.1 presents all these five condition indices and MDOT's Distress Index (DI) with corresponding rating scales. It can be observed that distress indices from each state have different scales, unlike MDOT's DI, which goes from zero to no upper bound. For comparison purposes only, to match MDOT's DI scale, all distress indices were linearly scaled on a scale of zero to 100, where zero 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, where a very small portion of MDOT's data exceeded a DI value of 100. In this evaluation process, 2081 flexible and 741 rigid pavement sections were selected, currently available in MDOT's pavement performance list. This section describes MDOT's DI and all the attempted condition indices in terms of distress inputs and calculation processes for both flexible and rigid pavement.

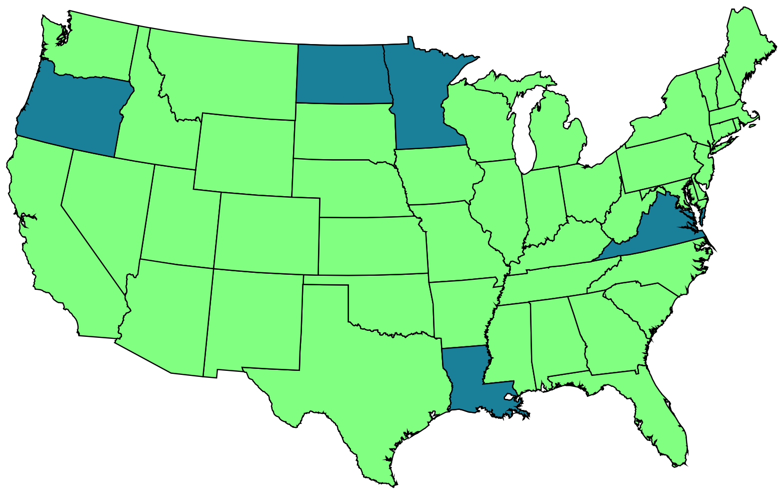


Figure 4.1. The geographical location of the selected pavement condition indices in the USA map

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 pavement

In the subsections below, calculation procedures for the Michigan DOT's Distress Index (DI), 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 flexible pavement are described. It is important to note that MDOT's Distress Index (DI) does not consider rutting and IRI. Thus, these sensor data inputs were ignored even if the original calculation of a condition index required them. Also, several assumptions were made based on AD matrices to define principal distress with different severity levels as needed for individual condition index calculations.

4.1.1 MDOT's Distress Index (DI)

Michigan DOT's DI is calculated as the total accumulated distress points for a road pavement section. In DI calculation, distress points do not act as deduct values; therefore, the DI does not have an upper bound. However, a threshold value of 50 represents a pavement in poor condition and warrants major rehabilitation or reconstruction for that section [8]. 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 represented by PD codes, and associated distress matrices are used to define the severity of each distress. Based on the associated distress combination, as shown in Table 3.3, 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.

$$DI = DI_1 + DI_2 \tag{4.1}$$

where, DI = Distress Index of the entire pavement segment

DI_1 = Distress Index from transverse PDs

DI_2 = Distress Index from longitudinal PDs

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

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

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

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 Critical Condition Index (CCI) is a composite index comprised of Load Related Rating (LDR) and Non-Load Related Rating (NDR) [6]. 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 unavailable 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. In contrast, this distress exists with a unique PD code in the MDOT PMS database. 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 distress 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.

Table 4.3 Assumed MDOT severity for LDR distress components

Distresses [PD Codes]	Severity	Severity Definition from MDOT PMS
Patching [326,327,501]	Good	Condition: Good (<3' Distress)
	Fair	Condition: Fair (3-6' Distress)
	Poor	Condition: Poor (>6' Distress)
Alligator Cracking [110,220,221,234,235,730, 731,501]	Low	Maximum width :>0 - 2 ft.
	Medium	Maximum width :>2 - 4 ft.
	High	Maximum width :>4 - 6 ft.
Longitudinal Cracking in WP [204,205,724,725,501]	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: 501 = PD code for No Distress; PD = Principal Distress; AD = Associated Distress

Table 4.4 Assumed MDOT severity for NDR distress components

Distresses [PD Codes]	Severity	Severity Definition from PMS
Transverse Cracking [101,103,104,110,114,701,703,704, 501]	Low	AD Matrix: (1,1), (2,1), (3,1), (4,1), (5,2), (5,3), (5,4), (6,2), (6,3)
Transverse Cracking [101,103,104,110,703,704,501]	Medium	AD Matrix: (5,5), (6,4), (6,5), (7,2), (7,3), (7,4)
Transverse Cracking [101,103,110,703,704,501]	High	AD Matrix: (7,5), (8,2), (8,3), (8,4), (8,5)
Longitudinal Cracking in Non-WP [201,202,203,236,237,721,722,501]	Low	Maximum width :>0 - 1 ft.
	Medium	Maximum width :>1 - 2 ft.
	High	Maximum width :>2 - 4 ft.
Block Cracking [310,345,760,501]	-	N/A
Bleeding [406,501]	-	N/A

Note: 501 = PD code for No Distress; PD = Principal Distress; AD = Associated Distress

Several MATLAB codes were written to extract PMS data according to the VDOT required units and calculate Load Related Rating (LDR), Non-Load Related Rating (NDR), and Critical Condition Index (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 [44]. 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.

Total deduct points for all tabulated distress components were calculated through corresponding deduct equations outlined in the "Development and Implementation of Pavement Condition Indices for the Transportation Phase I" report [6]. Equation 4.4 shows an example equation for calculating the low severity of alligator cracking. After calculating all deduct 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

$$A\_CR1\_DED = 0.000108*A\_CR1\_P^3 - 0.025576*A\_CR1\_P^2 + 2.056227*A\_CR1\_P \qquad 4.4$$

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 Surface Rating (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 [23]. Table 4.5 presents assumptions related to the severity levels of surface distress. 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.

Percent Cracks (%) = Number of crack occurrences × 1000/section length in feet   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 percentage, 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, Equation 4.7 calculated Surface Rating for a given year and road section.

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

It is noted that Surface Rating (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   4.8

4.1.4 NDDOT's Distress Score (DS)

North Dakota named their condition index as Distress Score (DS). The distress Score ranges from 0 to 99. Where 99 refers to the perfect score possible, and 0 means the worst condition of a pavement section. Table 4.6 shows the distresses considered in the DS calculation. Specific deduct points are assigned based on the extent and severity of each distress, 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 assumptions mentioned above for CCI severity levels (see Table 4.3 and Table 4.4) were considered to calculate the Distress Score (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; only the medium severity of these distresses was considered while choosing the deduct 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 Distress Score (DS). Then, a simple conversion was followed for comparing DS with DI using Equation 4.9.

$$DS\_adjusted = 100 - DS*100/99 \qquad 4.9$$

Table 4.5 Assumed MDOT severity for SR distress components

Distresses [PD Codes]	**Severity**	**Severity Definition from PMS**	**Weighting Factor**
Transverse Cracking [101,103,104,110,114,701,703,704, 501]	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 [101,103,104,110,703,704,501]	Medium	AD Matrix: (5,5), (6,4), (6,5), (7,2), (7,3), (7,4)	0.1
Transverse Cracking [101,103,110,703,704,501]	High	AD Matrix: (7,5), (8,2), (8,3), (8,4), (8,5)	0.2
Longitudinal Cracking [201,202,204,205,721,722,724,725,501]	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 [203,236,237,723,501]	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 [310,345,760,501]	-	N/A	0.15
Alligator Cracking [110,220,221,234,235,730, 731,501]	-	Maximum width :>0 - 2 ft.; Maximum width :>2 - 4 ft.; Maximum width :>4 - 6 ft.	0.35
Patching [326,327,501]	Good	Condition: Good (<3' Distress)	0.04
	Fair	Condition: Fair (3-6' Distress)	
	Poor	Condition: Poor (>6' Distress)	
Raveling [405,501]	-	N/A	0.02
Bleeding [406,501]	-	N/A	0.02

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

4.1.5 LADOTD's Pavement Condition Index (PCI)

Louisiana Department of Transportation and Development (DOTD) uses 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 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 [21]. 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 but exists with unique PD codes in the MDOT PMS database. Therefore, 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.

Like VDOT's CCI, the same assumptions 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 Pavement Condition Index (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, deduct points are also provided in ranges rather than in single numbers. An example deduct 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 deduct point. Then, the sum of all deduct 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 Equation 4.10.

$$PCI = [\max(\min(RNDM, ALCR, PTCH)), (\text{avg}(RNDM, ALCR, PTCH))] - 0.85\,(\text{std}(RNDM, ALCR, PTCH)) \qquad 4.10$$

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.

$$PCI\_adjusted = 100 - PCI \qquad 4.11$$

Table 4.7 Deduct values for alligator cracking based on severity and extent for PCI calculations [21]

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 are 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 [45]. 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 in the 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 assumptions 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.

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

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

where qty = quantity. A and B = coefficients. Along with A and B coefficients, "Maximum Distress" in a 0.1-mile segment for each distress is tabulated in Oregon DOT's reference guide [45].

Each of these weighted average / composite factors was 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.

$$\text{OCI\_adjusted} = 100 - \text{OCI} \qquad 4.14$$

4.2 Pavement condition indices for rigid pavements

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 VDOT's Slab Distress Rating (SDR)

The Virginia Department of Transportation (VDOT) addresses the visible distress on slab surface using Slab Distress Rating (SDR). It is based on a score of zero 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. Deduct points for each distress are calculated based on the deduct equation based on either extent or both extent and severity. For example, Equation 5.12 shows the deduct point equation for longitudinal joint spalling based on the extent, and Equation 5.13 shows the deduct point equation for longitudinal cracking based on both extent and severity [46]. Equations 4.15 through 4.17 show the overall SDR calculation formula.

$$\text{Deduct} = 1.3*(\%\text{Slabs\_SJ})^{0.6} \tag{4.15}$$

$$\text{Deduct} = 1*(\text{SEV1\_\%Slabs})^{0.7} + 2.9*(\text{SEV2\_\%Slabs})^{0.5} \tag{4.16}$$

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

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. This adjustment is required such that a pavement with multiple distresses have a similar rating compared to a pavement with divided slabs (considered as the worst situation). 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 as 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 [401,501]	-	-
Transverse joint spalling [106,501]	-	AD matrix: All combinations
Longitudinal joint spalling [208,209,501]	-	AD matrix: All combinations
Transverse cracking [112,113,501]	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 [227,228,229,230,231,232,501]	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, 501]	-	Shattered Area
PCC patches [326,501]	Good	Condition: Good (<3' Distress)
	Fair	Condition: Good (3-6' Distress)
	Poor	Condition: Good (>6' Distress)
AC patches [327, 501]	-	All conditions (Good, Fair, Poor)

4.2.2 Minnesota MnDOT's Surface Rating (SR)

Surface Rating (SR) by the Minnesota Department of Transportation (MnDOT) is a crack and surface distress index. 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 the percentage of joints, separately for each severity level. Weighted distresses are calculated by multiplying distress for each severity with their respective weighting factor. Total weighted distress (TWD) is calculated by summing up the individual weighted distresses. Finally, the SR is calculated using Equation 4.18 based on the TWD value. Table 4.9 shows the weighting factors for individual distress. 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.

$$SR = e^{(1.386-(0.045)(TWD))} \qquad 4.18$$

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

Distress	**PD Codes and Severity**
D Cracking	N/A
Transverse Joint Spalls	Severity : Slight [106,501] Severity: Severe [106] (see Associated Distress Matrix below)
Long. Joint Spalls	Severity: Slight [208,209,501] MAXIMUM WIDTH :>0 - 1 ft. MAXIMUM WIDTH :>1 - 2 ft. Severity: Severe [208,209] MAXIMUM WIDTH :>2 - 4 ft.
Cracked Panels	[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)
Broken Panels	[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.
Patched Panels	[326, 327,501]

ASSOCIATED DISTRESS MATRIX (AD1,AD2): AD_{12} 0001 x 0011

TRANSVERSE LENGTH Across Lane (AD1)	MAX WIDTH (Perpendicular to Transvers Joint) (AD2)				
	No Distress	>0 - 1 ft.	>1 - 3 ft.	>3 - 6 ft.	>6 - 8 ft.
No Distress	*(1,1)*	*xxxxx*	*xxxxx*	*xxxxx*	*xxxxx*
>0 - 1 ft.	*xxxxx*	*xxxxx*	*xxxxx*	*xxxxx*	*xxxxx*
>1 - 3 ft.	*xxxxx*	(3,2)	(3,3)	(3,4)	(3,5)
>3 - 6 ft.	*xxxxx*	(4,2)	(4,3)	(4,4)	(4,5)
>6 - 12 ft.	*xxxxx*	(5,2)	(5,3)	(5,4)	(5,5)

Note that cells marked with xxxxx are not applicable.

4.2.3 North Dakota NDDOT's Distress Score (DS)

North Dakota Department of Transportation (NDDOT) uses a condition rating system, Distress Score (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. 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. For example, Table 4.11 shows the deduct values for longitudinal cracking for different severity and extent. 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 [106,501]	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)
	High	AD matrix: (5,4), (5,5)
Longitudinal joint spalling [208,209,501]	Low	Maximum width > 0-1 ft.
	Medium	Maximum width > 1-2 ft.
	High	Maximum width > 2-4 ft.
Transverse cracking [112,113,501]	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 [227,228,229,230,231,232,501]	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 [326,501]	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 Department of Transportation and Development (LADOTD) calculates rigid Pavement Condition Index (PCI) from individual condition indices. The longitudinal cracking index, transverse cracking index, patching index, and roughness index are the inputs for the rigid pavement PCI [22]. It uses a rating scale from zero to 100, with 100 being the perfect score for brand-new pavement. Each distress is calculated in the required units separately for each severity level. The 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 severity and extent. Equation 4.19 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 4.20.

Table 4.13 Deduct Values for Longitudinal Cracking Based on Severity and Extent for PCI Calculations [22]

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

LONG = MIN(100,MAX(0,100-LNGCRK_L DEDUCT – LNGCRK_M DEDUCT – LNGCRK_H DEDUCT)) 4.19

JPCP PCI = [MAX(MIN(LONG, TRAN, PTCH, RUFF)), AVG(LONG, TRAN, PTCH, RUFF))] -0.85(STD(LONG, TRAN, PTCH, RUFF)) 4.20

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.

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 4.14 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, 501]	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 [227,228,229,230,231,232,501]	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, 501]	Good	Condition: Good (<3' Distress)
	Fair	Condition: Good (3-6' Distress)
	Poor	Condition: Good (>6' Distress)

4.2.5 Oregon ODOT's Overall Condition Index (OCI)

The Overall Condition Index (OCI) by the Oregon Department of Transportation and Development (ODOT) is calculated by combining condition indices for a pavement management section of 0.1 miles. 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 for each distress and each severity level as shown in Equation 4.21. The recommended values of A, B, and "Maximum Distress" given in the ODOT manual [45] are used for all OCI calculations. An average distress index is calculated for each distress by combining different severity levels as shown in Equation 4.22. Finally, the maximum of the individual indices multiplied by 100 is the OCI.

$$\text{Factor}(\text{typeX})_{\text{severityY}} = 1.00 - \text{A} \times \left(\frac{\text{Measured Distress}}{\text{Maximum Distress}}\right)^{\text{B}} \qquad 4.21$$

$$\text{Factor}(\text{typeX})_{\text{severityY}} = \frac{[(\text{factor}(\text{typeX}) \times \text{qty})_{\text{sev1}} + (\text{factor}(\text{typeX}) \times \text{qty})_{\text{sev2}} + (\text{factor}(\text{typeX}) \times \text{qty})_{\text{sev3}}\ ]}{\text{qty}_{\text{sev1}} + \text{qty}_{\text{sev2}} + \text{qty}_{\text{sev3}}} \qquad 4.22$$

where qty = quantity.

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 [106,501]	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 [208,209,501]	Low	Maximum width > 0-1 ft.
	Medium	Maximum width > 1-2 ft.
	High	Maximum width > 2-4 ft.
Transverse cracking [112,113, 501]	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 [227,228,229,230,231,232,501]	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, 501]	Good	Condition: Good (<3' Distress)
	Fair	Condition: Good (3-6' Distress)
	Poor	Condition: Good (>6' Distress)
Divided slabs [344, 501]	-	Shattered Area

5. RESULTS OF EVALUATING DIFFERENT CONDITION INDICES UTILIZING MDOT PMS DATA

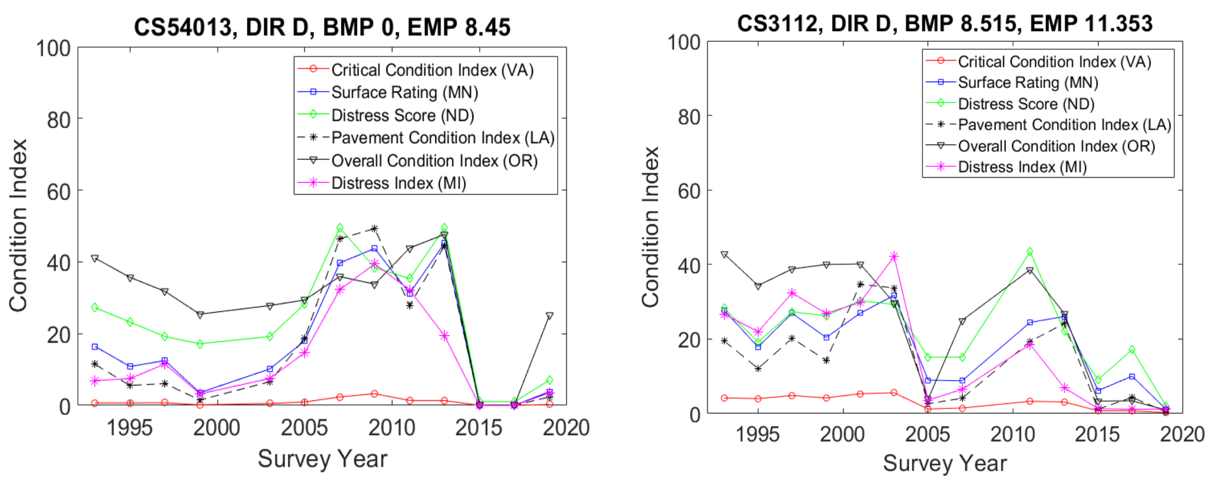
In this section, the evaluation results of five different condition indices are described. Both quantitative and qualitative approaches were followed to determine which condition index is more compatible with the MDOT PMS database. The findings of this section demonstrate the importance of careful evaluation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

5.1 Relationship between the condition indices and historical DI

This section presents comparisons between individual condition indices and historical DI to assess the compatibility of Michigan pavement distress data. Time series plots for 2081 flexible and 741 rigid pavement sections were plotted individually to observe how individual condition indices relate to historical DI values. For brevity, only a couple of example time series plots of five distress indices and DI for both flexible and rigid pavement sections are shown in Figure 5.1 and Figure 5.2, respectively. In both figures, 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, and therefore adjustments would need to be made.

Additionally, the CCI is calculated as the minimum of either index rather than adding the LDR and NDR indices. 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. [47], wherein the authors compared OCI with Texas DOT's Distress Score (DS) and Ohio DOT's Pavement Condition Rating (PCR) [48].

To better understand how the overall comparison between DI and individual condition indices looks like, separate plots of historical DI against individual condition indices were also plotted for all considered flexible and rigid pavement sections. Figure 5.3 through Figure 5.12 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 above mentioned comments on time series plots of different condition indices.



(a) (b)

Figure 5.1 Time series plots of all condition indices including DI for flexible sections: (a) CS54103 and (b) CS3112

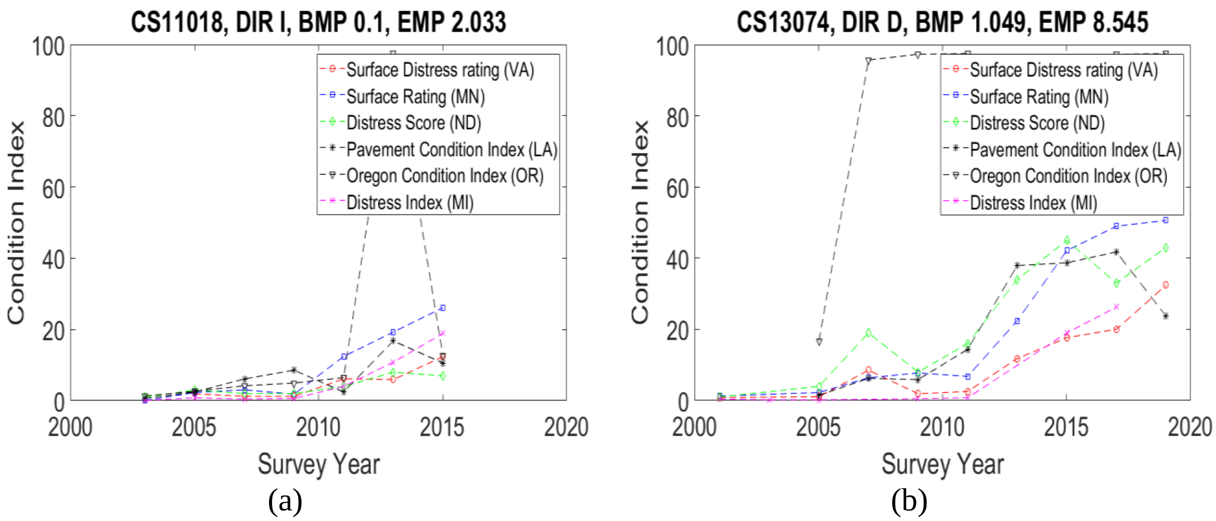


Figure 5.2 Time series plots of all condition indices, including DI for rigid sections: (a) CS11018 and (b) CS13074

To quantify the comparison results better, the Spearman correlation analysis was run for each comparison set. Results supported the above observation that among the attempted condition indices, Minnesota's Surface Rating (SR) correlated reasonably well with the historical DI values with a spearman correlation value of 0.89 and 0.75 for flexible and rigid sections, respectively. Spearman Correlation for the other indices are as follows: Louisiana's PCI - 0.82 (flexible) and 0.63 (rigid), North Dakota's DS - 0.76 (flexible) and 0.52 (rigid), Virginia's CCI - 0.71 (flexible) and SDR - is 0.73 (rigid), and Oregon's OCI - 0.65 (flexible) and 0.42 (rigid). Based on the foregoing, it can be concluded that Minnesota's Surface Rating (SR) seems the most compatible with the MDOT's distress data.

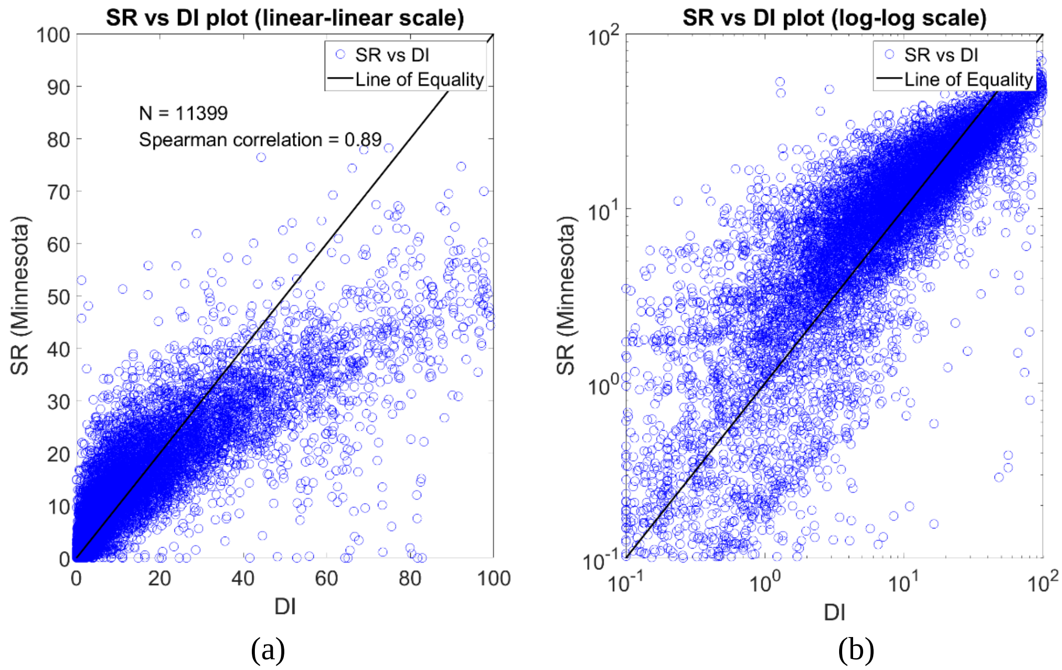


Figure 5.3 Overall comparison between Surface Rating (SR) vs. Distress Index (DI) for flexible sections: (a) linear-linear scale (b) log-log scale

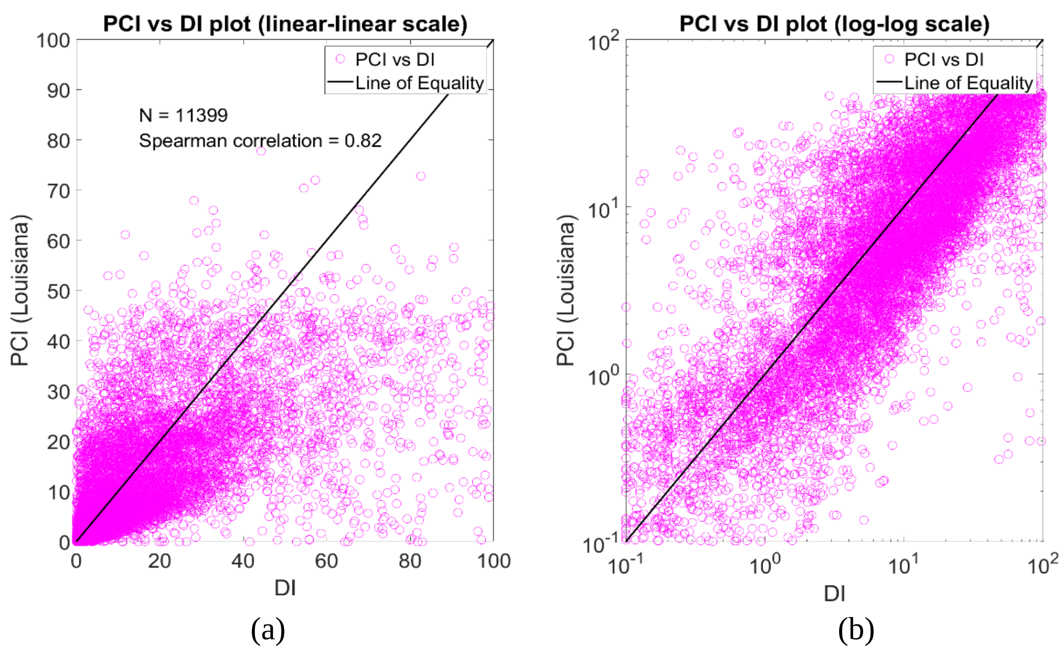
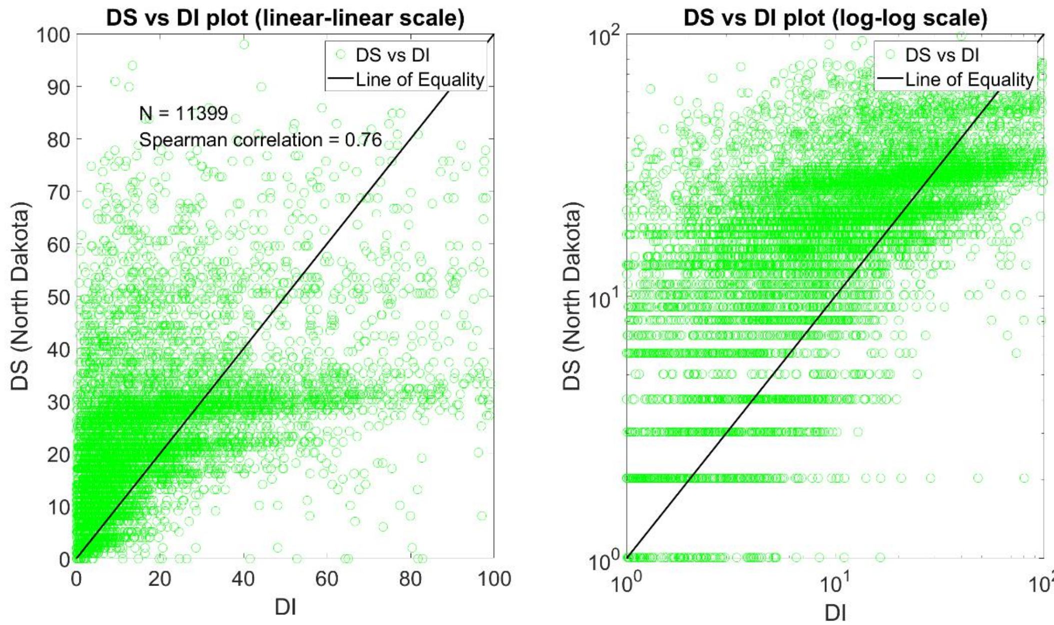
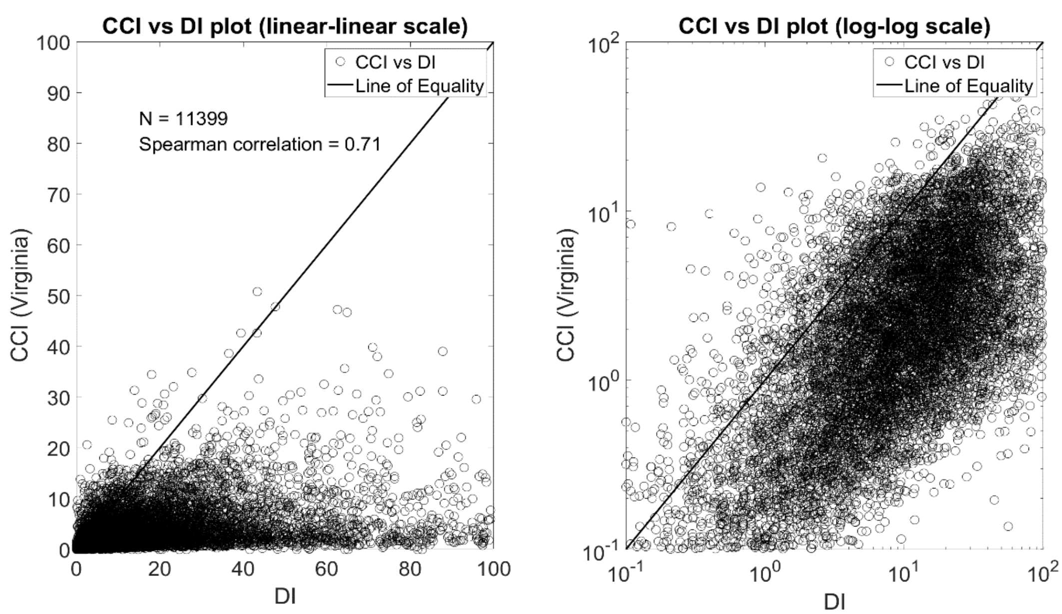


Figure 5.4 Overall comparison between Pavement Condition Index (PCI) vs. Distress Index (DI) for flexible sections: (a) linear-linear scale (b) log-log scale



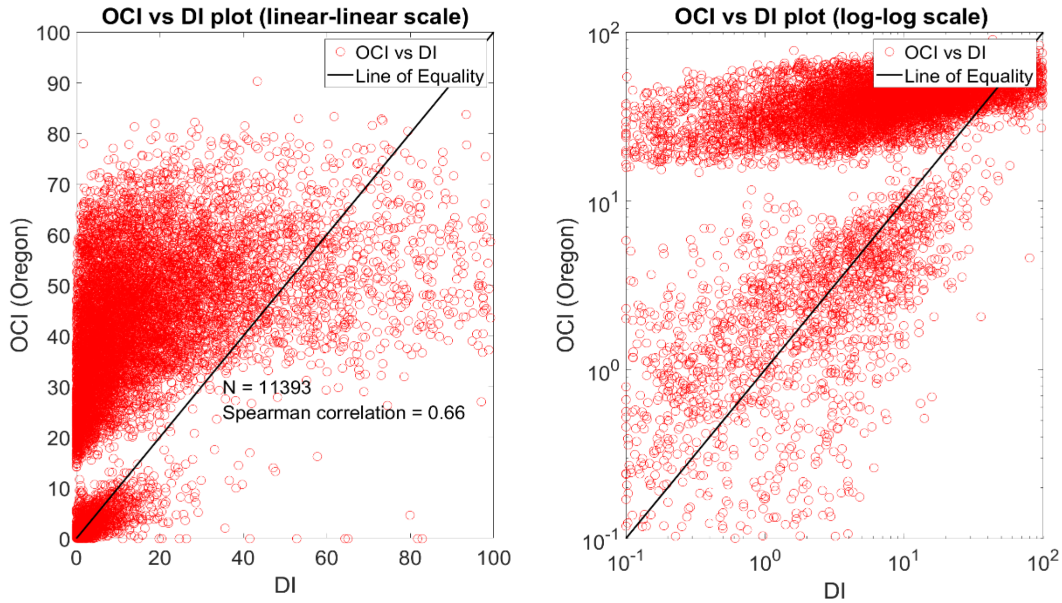
(a) (b)

Figure 5.5 Overall comparison between Distress Index (DI) vs. Distress Score (DS) for flexible sections: (a) linear-linear scale (b) log-log scale



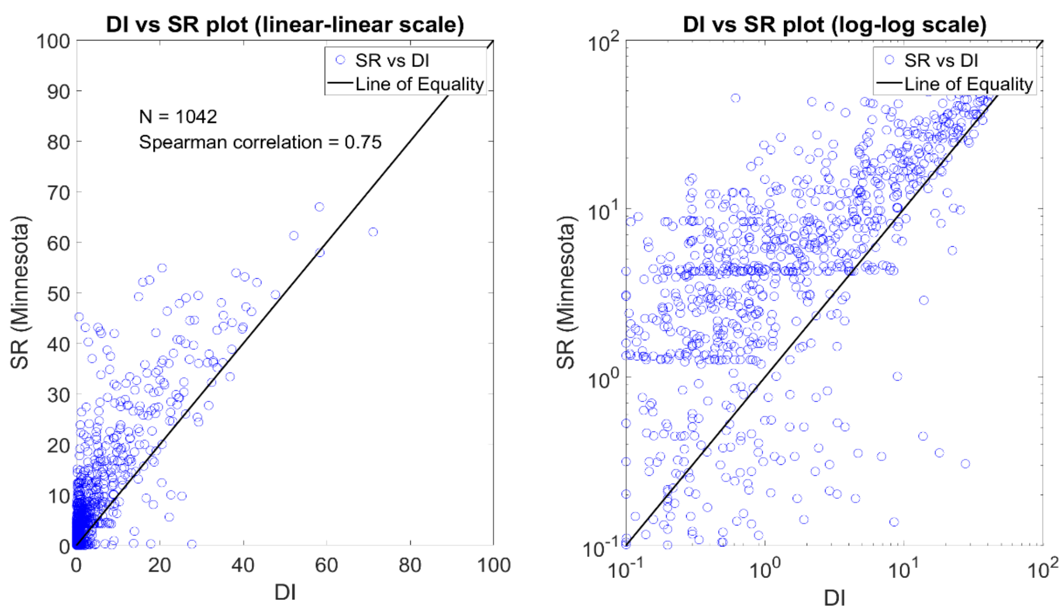
(a) (b)

Figure 5.6 Overall comparison between Critical Condition Index (CCI) vs. Distress Index (DI) for flexible sections: (a) linear-linear scale (b) log-log scale



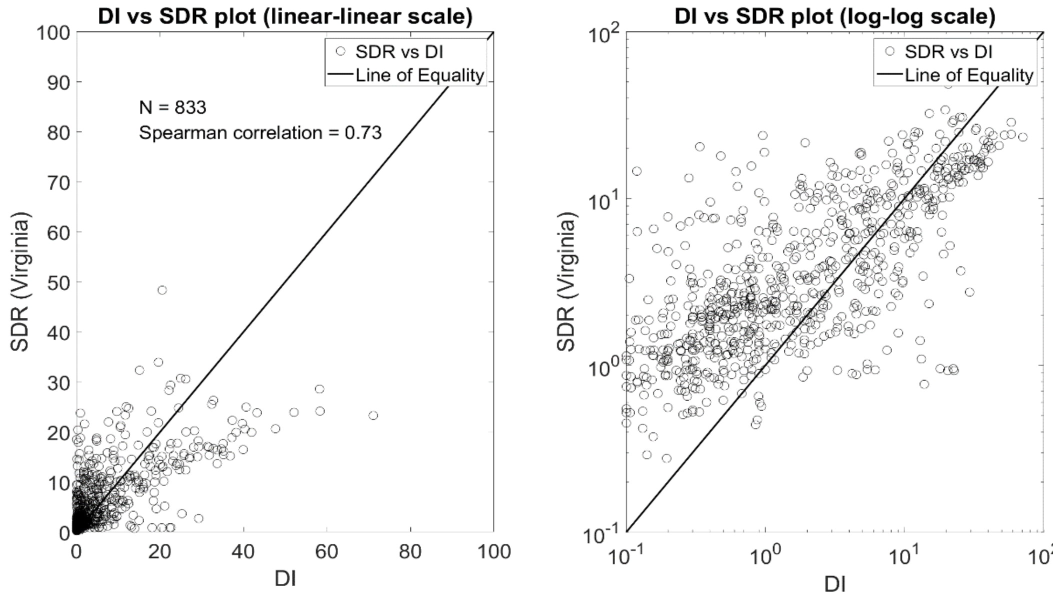
(a) (b)

Figure 5.7 Overall comparison between Overall Condition Index (OCI) vs. Distress Index (DI) for flexible sections: (a) linear-linear scale (b) log-log scale



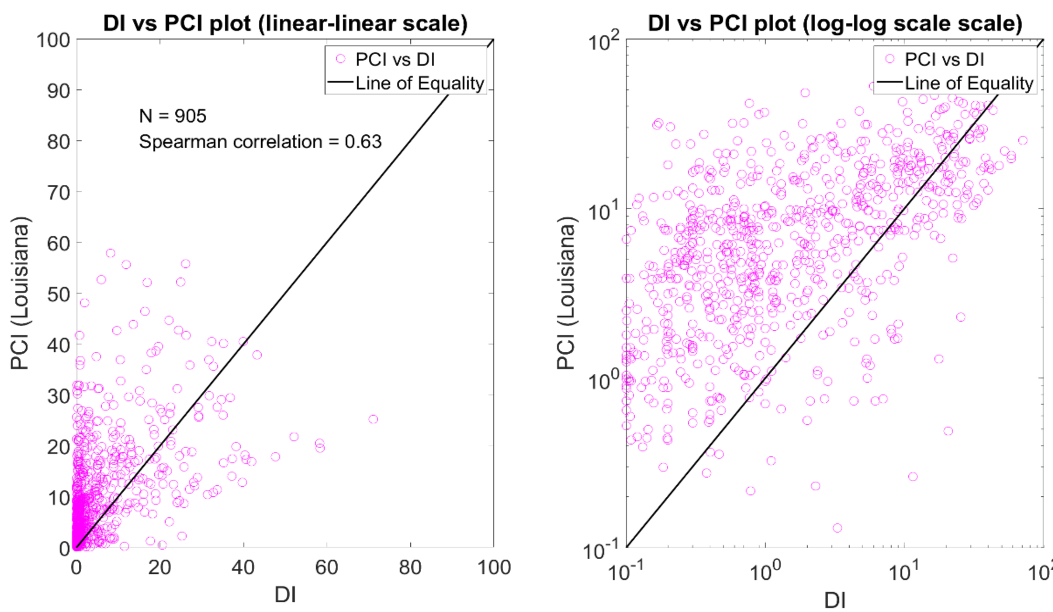
(a) (b)

Figure 5.8 Overall comparison between Surface Rating (SR) vs. Distress Index (DI) for rigid sections: (a) linear-linear scale (b) log-log scale



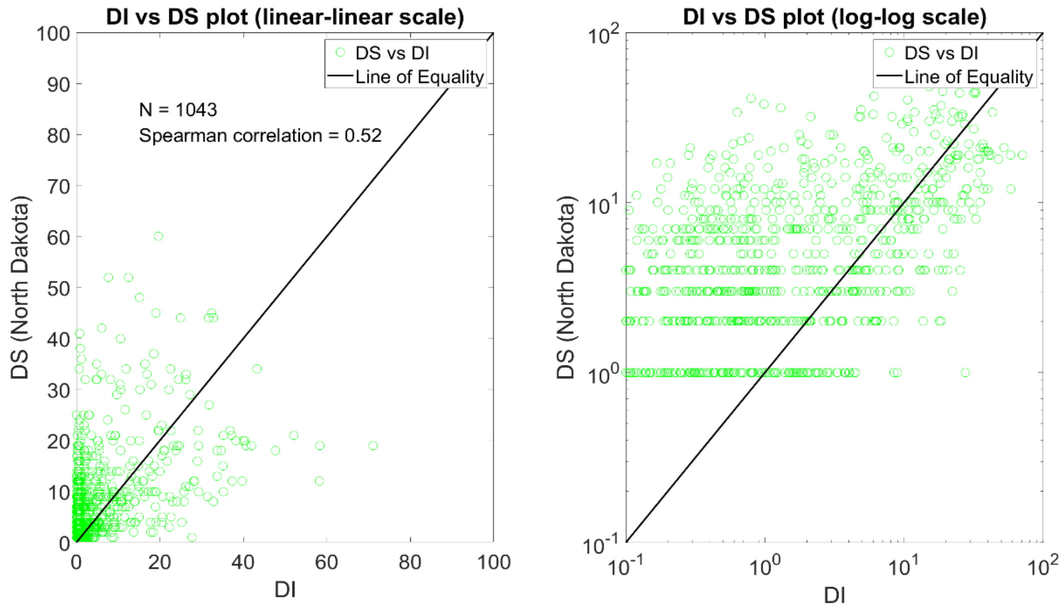
(a) (b)

Figure 5.9 Overall comparison between Slab Distress Rating (SDR) vs. Distress Index (DI) for rigid sections: (a) linear-linear scale (b) log-log scale



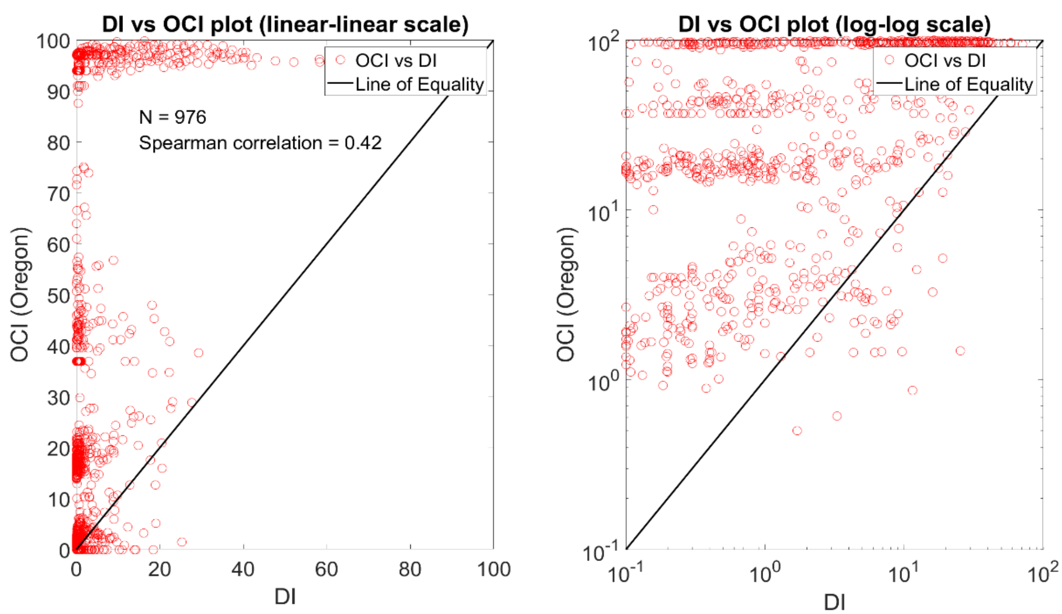
(a) (b)

Figure 5.10 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 5.11 Overall comparison between Distress Score (DS) vs. Distress Index (DI) for rigid sections: (a) linear-linear scale (b) log-log scale



(a) (b)

Figure 5.12 Overall comparison between Overall Condition Index (OCI) vs. Distress Index (DI) for rigid sections: (a) linear-linear scale (b) log-log scale

5.2 Magnitudes of condition indices before different types of maintenance were applied to flexible pavements

The MDOT's Project Scoping Manual, chapter 5 [49], provides guidelines for fixing flexible pavements based on DI values. Table 5.1 outlines these guidelines. 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 5.1 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 5.1.

Figure 5.13 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.). In contrast, 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 outside 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 Annual Average Daily Traffic (AADT), site location, budget constraints, etc., may have influenced the MDOT's decision-making process beyond DI values. Nonetheless, from Figure 5.13(a), it can be observed that measured DI could reflect on the recommended fix types. Figure 5.13(b) through Figure 5.15, 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 Surface Rating (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 overall condition index (OCI) displayed a higher magnitude, even for low categories of fix types. Whereas Virginia's Critical Condition Index (CCI) represented very low magnitude, rendering it incapable of differentiating different fix types. NDDOT's Distress Score (DS) also presented a similar trend as SR, but its median value was slightly high for the light maintenance group. Despite this, based on these analyses, the Minnesota DOT's Surface Rating (SR) seems promising for flexible pavements.

Table 5.1 MDOT fix types for the flexible pavement with the available number of records

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

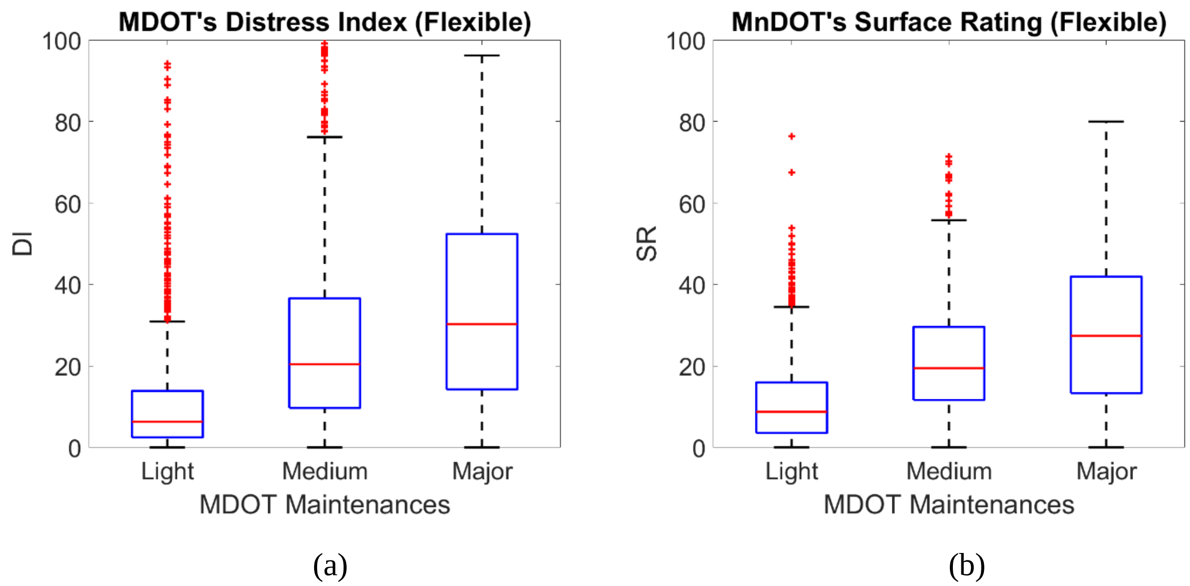


Figure 5.13 Box plots showing MDOT maintenance records and corresponding (a) Distress Index (Michigan) and (b) Surface Rating (Minnesota) for flexible sections

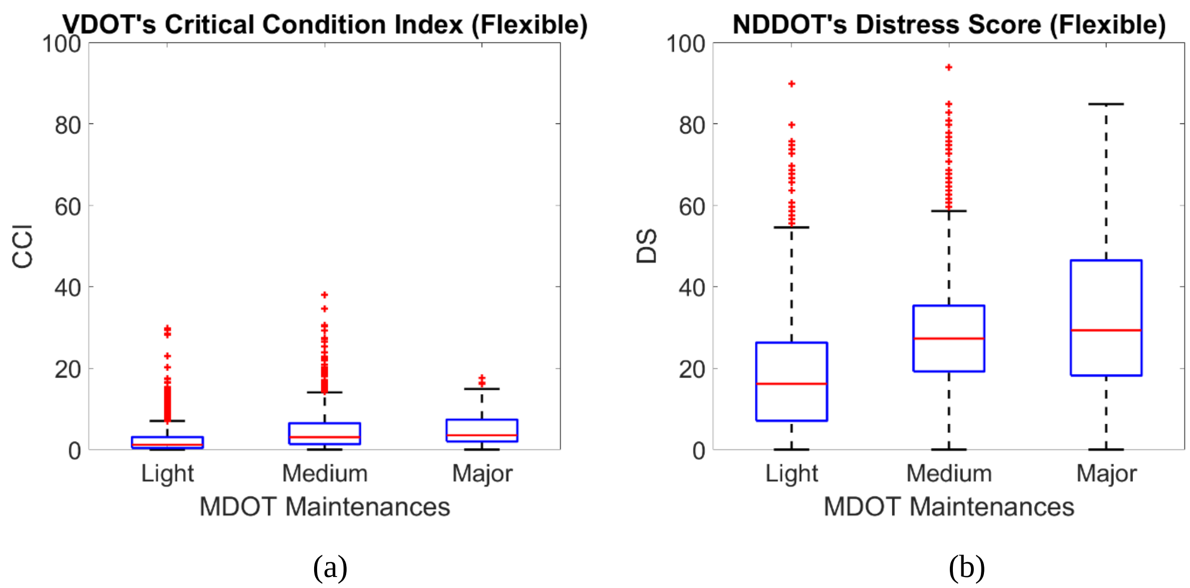
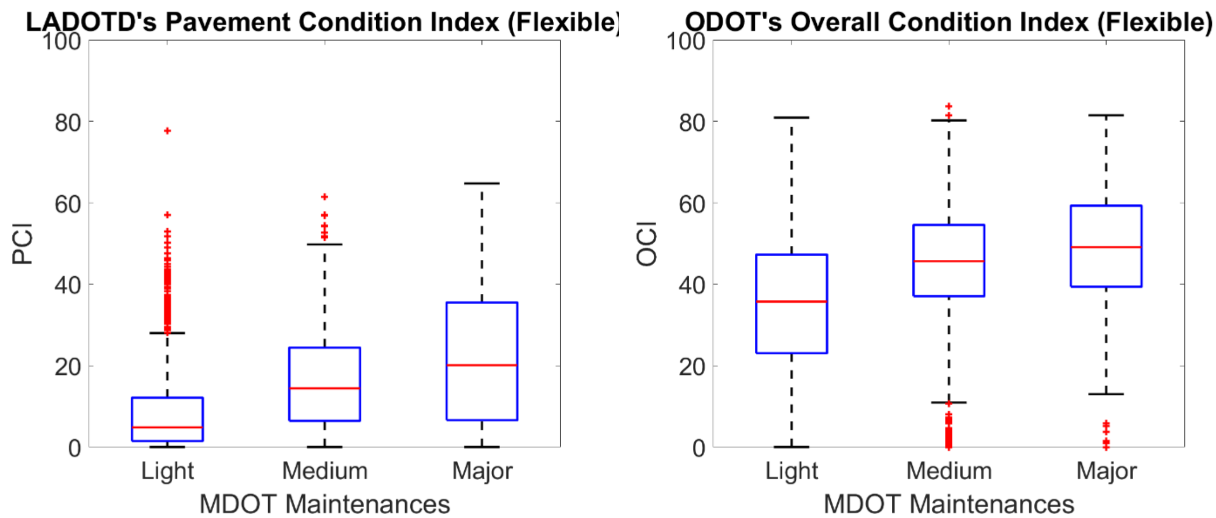


Figure 5.14 Box plots showing MDOT maintenance records and corresponding (a) Critical Condition Index (Virginia) and (b) Distress Score (North Dakota) for flexible sections



(a) (b)

Figure 5.15 Box plots showing MDOT maintenance records and corresponding (a) Pavement Condition Index (Louisiana) and (b) Overall Condition Index (Oregon) for flexible sections

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

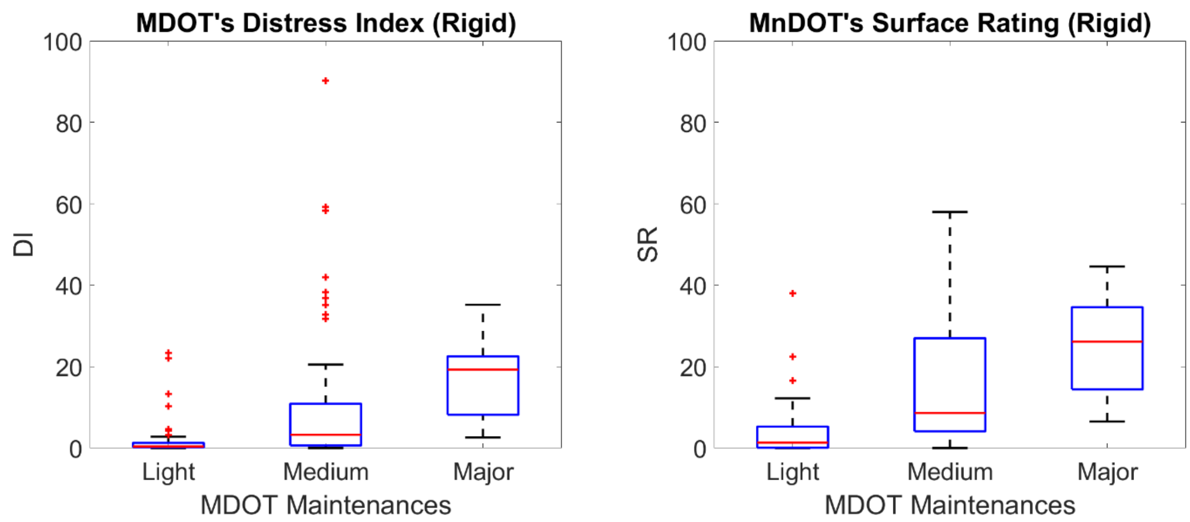
Michigan Department of Transportation (MDOT) performs various maintenance and reconstruction activities on rigid pavements depending on the distress level, type, and overall DI value. All maintenance activities were considered for the overall database of 741 rigid sections, and the DI value for up to 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 [49], the maintenance activities for rigid pavement were also divided into three categories, as shown in Table 5.2. It is to be noted that this grouping was made on the consensus of MDOT engineers.

Figure 5.16 through Figure 5.18 show the box plots of each maintenance activity for different rigid pavement condition indices. The MDOT Distress Index Figure 5.16 (a) shows 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 5.16 (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 5.17(a), VDOT's SDR, unlike CCI for HMA, shows more considerable 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 5.17(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 5.18(a), LADOTD's PCI demonstrated good distinct differences, with reasonable variability in the medium and major categories. Finally, in Figure 5.18(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.

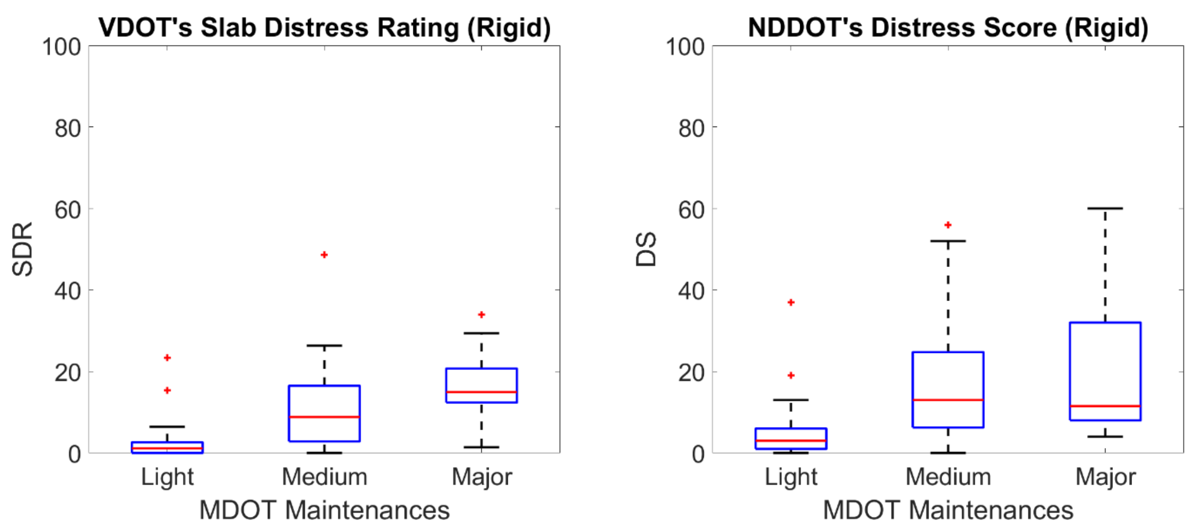
Table 5.2 MDOT fix types for rigid pavement with the available number of records

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



(a) (b)

Figure 5.17 Box plots showing MDOT maintenance records and corresponding (a) Slab Distress Rating (Virginia) and (b) Distress Score (North Dakota) for rigid sections

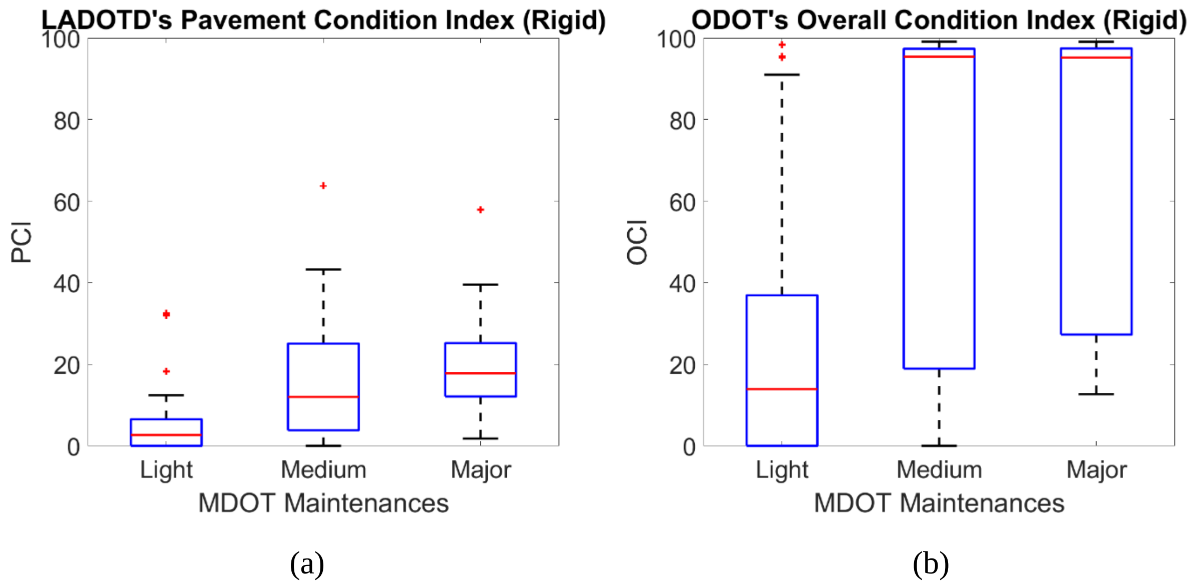


Figure 5.18 Box plots showing MDOT maintenance records and corresponding (a) Pavement Condition Index (Louisiana) and (b) Overall Condition Index (Oregon) for rigid sections

5.4 Qualitative evaluation for 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 [50]. However, there are several 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. [46] aimed to communicate the current pavement condition as concisely and accurately as possible in developing performance measures for the Virginia Department of Transportation. In contrast, Christiansen et al. [51] 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. [52] evaluated 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.

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.

Policy Sensitivity

The criterion of policy sensitivity aims to ensure that the new DI 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) [53] 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.

Ease of Understanding

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

- Like the ‘Feasibility’ criteria, this relates to interpreting 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 DI easily understood? In other words, is it clear whether a pavement with a given new DI 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.

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 DI 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 DI 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.

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.

Objectivity

The objectivity of the condition index relates to the consistency and repeatability of the gathered distress and roughness data. Objective metrics like the International Roughness Index (IRI) rely on standardized processes and leave little room for subjective interpretation. In contrast, personal biases and driver comfort levels may influence subjective measurements like the

Pavement Serviceability Rating (PSR). 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 5.3, the Surface Rating (SR) appears to be the most promising condition index for selection. Therefore, Minnesota's Surface Rating can serve as the basis for developing Michigan's enhanced pavement condition score.

Table 5.3 Overall assessment of each condition index

Index	**Feasibility**	**Policy Sensitivity**	**Ease of Understanding**	**Decision Making**	**Ease of Implementation and Backward Compatibility**	**Objectivity**	**Average**
CCI	4.0	2.9	4.0	2.0	2.2	4.0	3.29
OCI	4.0	3.0	4.0	2.8	2.2	4.0	3.31
SR	4.0	3.8	4.0	3.4	3.6	4.0	3.79
PCI	4.0	3.2	4.0	3.0	3.5	4.0	3.61
DS	4.0	2.8	4.0	3.3	2.4	4.0	3.44

The following rating scale was assumed: 1 = poorly meets criterion, 2 = partially meets criterion, 3 = mostly meets criterion, 4 = meets criterion very well

6. DEVELOPMENT OF PAVEMENT DISTRESS SCORE (PDS)

This chapter outlines the development of an enhanced condition index for Michigan DOT. Based on the previous chapter's analysis, the framework for developing the condition index was determined, and a few modifications were made per discussion with MDOT engineers. The MDOT engineers decided to name the proposed enhanced condition index Pavement Distress Score (PDS). The range of PDS was decided to start with 100 for a brand-new pavement and go down to zero (0), which represents a pavement in the worst possible condition.

As mentioned, MnDOT's Surface Rating (SR) was selected as the basis for developing MDOT's PDS. However, a few modifications were made to the original SR calculation. PDS is calculated using Equation 6.1 and Equation 6.2 based on the new distress list outlined in Table 3.4 and Table 3.5.

$$TWD = \sum_{i=1}^{n} w_i D_i \qquad 6.1$$

$$PDS = 25 * (e^{1.386294-(0.045*TWD)}) \qquad 6.2$$

where,

TWD = total weighted distress

n = number of distresses

D_i = the distress-severity combinations

w_i = the weights for each distress

PDS = Pavement Distress Score

Calculation of the average percentage of each distress at different severity levels (D_i) and calibrated distress weight factors are discussed in the following sections.

6.1 Conversion of existing MDOT PMS to PDS required distress unit

This section includes a description of the algorithm of PMS data extraction for flexible pavements. MDOT pavement management system (PMS) includes comprehensive data collected since 1992. Different PD codes denote different distresses, 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 calculating the new Pavement Distress Score (PDS), all the distresses must be converted to percentages. For flexible pavement, transverse cracking was converted to a percentage for each 0.1-mile segment using Equation 6.3.

$$Transverse\ crack(\%) = \frac{Transverse\ crack\ (count)}{\frac{Length\ of\ section\ (miles) \times 5280}{TC\ spacing\ (ft)}} \times 100 \qquad 6.3$$

Note: transverse crack (TC) spacing was assumed to be 10 feet.

On the other hand, for each 0.1-mile segment, all other distresses were converted to a percentage by simply dividing the length of the distress by the surveyed section length, shown in Equation 6.4.

$$Distresses_{except\ TC}\ (\%) = \frac{Distress\ length\ (miles)}{Length\ of\ section\ (miles)} \times 100 \qquad 6.4$$

To facilitate the raw data extraction and convert them to the required unit, an algorithm was written in MATLAB. The MATLAB code processes each PMS excel file corresponding to a given survey year (e.g., 1992 through 2019). This code conducts data extraction 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 begins with defining a list of current and historical PD codes related to that particular distress type. Then from the before mentioned pavement lists (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, represented by 'RW' and 'COL,' respectively.

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 MDOT PMS database as a length in miles or the number of counts. If the PD code is 501 (i.e., no distress), distress measurement is set as 0 (zero) for those filtered rows. Then to calculate the percentage of considered distress for each 0.1-mile interval, either Equation 1 or Equation 2 is utilized based on the distress type. In case multiple zones or wheel paths, such as left and right wheel path cracking, 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 whole section length as listed in the pavement 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 and standard deviation of the particular distress at one severity level is calculated.

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 another MATLAB function. The below section briefly describes 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.

PD Codes and Assumed Severity Levels for Different Flexible Pavement Distresses

Transverse Cracking

In MDOT's PMS database, a transverse crack is reported as a count. For a typical 0.1-mile segment, transverse cracking is converted to percent using Equation 6.5. It is noted that minimum transverse spacing (TC) is assumed to be 10 ft.

$$Transverse\ crack(\%) = \frac{Transverse\ crack\ (count)}{\frac{Length\ of\ section\ (miles) \times 5280}{TC\ spacing\ (ft)}} \times 100 \qquad 6.5$$

PDs considered in transverse cracking 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 6.1. It is assumed that four transverse tears are equivalent to one regular transverse crack.

Table 6.1 Assumed severity definitions of HMA transverse cracking

Distress [PD Codes]	**Severity**	**Severity Definition from PMS**
Transverse Cracking [101,103,104,110,114,701,703,704, 501]	Low	AD Matrix: (0,0), (1,1), (2,1), (3,1), (4,1), (5,2), (5,3), (5,4), (6,2), (6,3)
Transverse Cracking [103,104,110,703,704,501]	Medium	AD Matrix: (0,0), (6,4), (7,2), (7,3), (7,4)
Transverse Cracking [103,104,110,703,704,501]	High	AD Matrix: (0,0), (8,2), (8,3), (8,4)

Longitudinal Wheel-path Cracking

Longitudinal wheel-path cracking that exists in the two-wheel paths is called longitudinal wheel-path (WP) cracking. It is measured as length. For a typical 0.1-mile segment, longitudinal wheel path cracking is converted to percent using Equation 6.6.

$$Longintudinal\ WP\ Crack\ (\%) = \frac{\sum Longitudinal\ WP\ cracking\ length\ (miles)}{2 \times Length\ of\ segment\ (miles)} \times 100 \qquad 6.6$$

A surveyed lane usually consists of five zones where 'zone 2' and 'zone 4' represent the left and right wheel-path, respectively. In Figure 6.1, two hypothetical LC crack scenarios are shown to better explain the longitudinal wheel-path cracking calculation. Figure 6.1(a) shows only 'zone 2' is 100% cracked, which results in overall 50% longitudinal wheel-path cracking for the specified 0.1-mile interval. If the two wheel-paths are 100% cracked, the overall longitudinal wheel-path cracking will be calculated as 100%, as shown in Figure 6.1(b). Also, it is noted that if two parallel LC cracks exist within the same zone, then using Equation 6.6. may yield a cracking percentage of more than 100%.

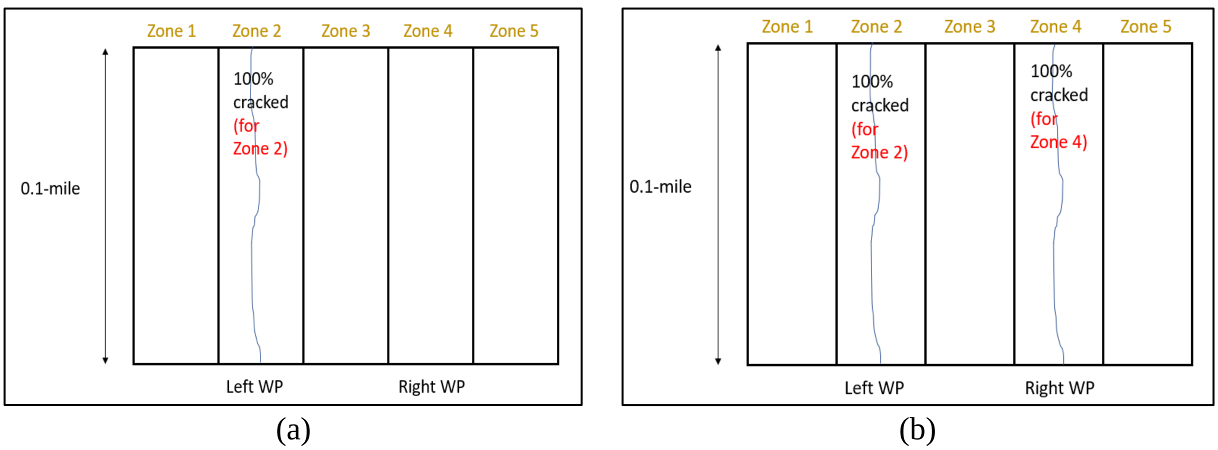


Figure 6.1 Longitudinal wheel-path cracking scenarios (a) 50% cracked and (b) 100% cracked for a 0.1-mile interval segment

PDs considered in longitudinal cracking data extraction are 202, 204, 205, 218, 722, 724, 725, and 501. Table 6.2 shows the severity assumption based on the AD matrix.

Table 6.2 Assumed severity definitions of HMA longitudinal wheel-path cracking

Distress [PD Codes]	**Severity**	**Severity Definition from PMS**
Longitudinal Cracking [204,205,724,725,501]	Low	AD Matrix: (0,0), (1,0), (2,0), (3,0), (4,0), (5,0)
Longitudinal Cracking [204,205,724,725,501]	Medium	AD Matrix: (0,0), (6,0)
Longitudinal Cracking [204,205,724,725,501]	High	AD Matrix: (0,0), (7,0)

Longitudinal Center Lane Cracking

Longitudinal center lane cracking between the two-wheel paths (i.e., zone 3 as shown in Figure 6.1) is called longitudinal center lane (CL) cracking. It is measured as length. For a typical 0.1-mile segment, longitudinal center lane cracking is converted to percent using Equation 6.6.

$$Longintudinal\ CL\ Crack\ (\%) = \frac{\sum Longitudinal\ CL\ cracking\ length\ (miles)}{Length\ of\ segment\ (miles)} \times 100 \quad 6.7$$

Two example cracking scenarios for longitudinal center lane cracking are shown in Figure 6.2; where Figure 6.2(b) depicts when longitudinal center lane cracking may exceed 100% cracking.

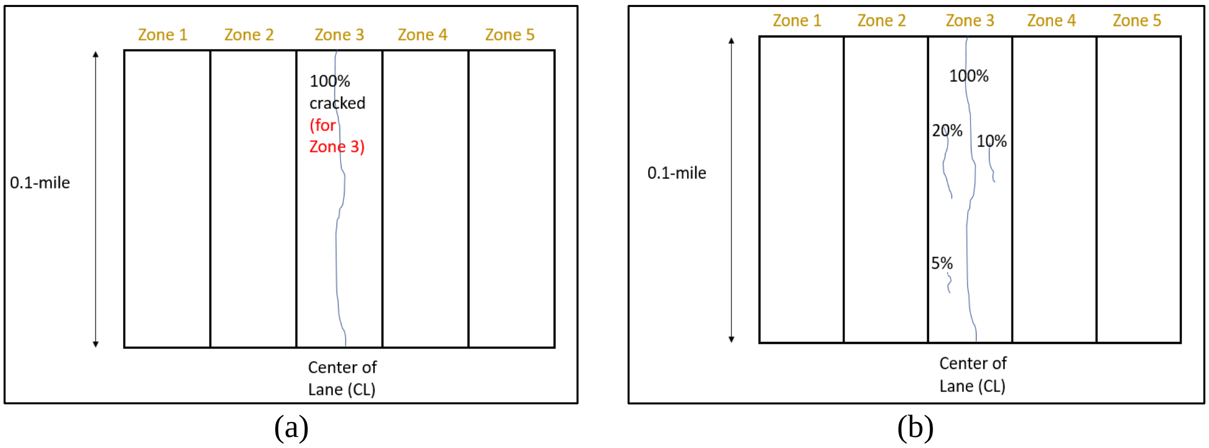


Figure 6.2 Longitudinal center lane cracking scenarios (a) 100% cracked and (b) 135% cracked for a 0.1-mile interval segment

PDs considered in longitudinal cracking data extraction are 202, 204, 205, 218, 722, 724, 725, and 501. Table 6.2 shows the severity assumption based on the AD matrix.

Table 6.3 Assumed severity definitions of HMA longitudinal center lane cracking

Distress [PD Codes]	**Severity**	**Severity Definition from PMS**
Longitudinal Center Lane Cracking [202, 218,722,501]	Low	AD Matrix: (0,0), (1,0), (2,0), (3,0), (4,0), (5,0)
Longitudinal Center Lane Cracking [202, 218,722,501]	Medium	AD Matrix: (0,0), (6,0)
Longitudinal Center Lane Cracking [202, 218,722,501]	High	AD Matrix: (0,0), (7,0)

Longitudinal Edge Cracking

Left and right edge longitudinal cracking are considered longitudinal edge cracking, measured as length. For a typical 0.1-mile segment, longitudinal edge cracking is converted to percent using Equation 6.8.

$$Longintudinal\ Edge\ Cracking\ (\%) = \frac{\sum Longitudinal\ edge\ cracking\ length\ (miles)}{2 \times Length\ of\ segment\ (miles)} \times 100 \qquad 6.8$$

Two example cracking scenarios for longitudinal edge cracking are shown in Figure 6.3.

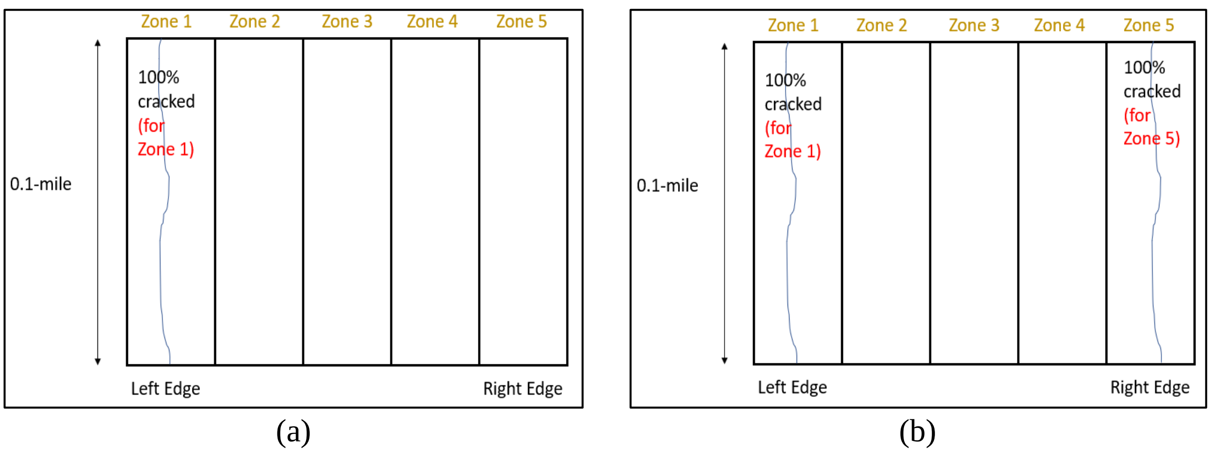


Figure 6.3 Longitudinal edge cracking scenarios (a) 50% cracked and (b) 100% cracked for a 0.1-mile interval segment

PDs considered in longitudinal edge cracking data extraction are 201, 203, 236, 237, 721, 723, and 501. Table 6.4 shows the severity assumption based on the AD matrix.

Alligator Cracking

Alligator cracking is measured as length, and it involves two wheel-paths as well. For a typical 0.1-mile segment, alligator cracking is converted to percent using Equation 6.9.

$$Alligator\ Cracking\ (\%) = \frac{\sum Alligator\ cracking\ length\ (miles)}{2\ \times\ Length\ of\ section\ (miles)} \times 100 \qquad 6.9$$

Alligator cracking was not divided into severity levels; all combinations of the AD matrix were considered. PDs considered in alligator cracking data extraction are 210, 220, 221, 222, 224, 234, 235, 730, 731, and 501. Table 6.5 shows the alligator cracking severity assumption based on the AD matrix.

Table 6.4 Assumed severity definitions of HMA longitudinal edge cracking

Distress [PD Codes]	**Severity**	**Severity Definition from PMS**
Edge Cracking [201,203,236,237,721,723,501]	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); For PD code 501, AD matrix – (0,0)
	Medium	For PD codes 201, 203, 721, and 723, AD matrix – (6,0); For PD codes 236 and 237, AD matrix – (2,0); For PD code 501, AD matrix – (0,0)
	High	For PD codes 201, 203, 721, and 723, AD matrix – (7,0); For PD codes 236 and 237, AD matrix – (3,0); For PD code 501, AD matrix – (0,0)

Table 6.5 Assumed severity definitions of HMA alligator cracking

Distress [PD Codes]	**Severity**	**Severity Definition from PMS**
Alligator Cracking [210, 220, 221, 222, 224, 234, 235, 730, 731, 501]	N/A	AD Matrix: (0,0), (1,0), (2,0), (3,0), (1,2), (1,3), (1,4), (1,5), (2,2), (2,3), (2,4), (2,5)

Block Cracking

In MDOT's PMS database, block cracking is reported as length. For a typical 0.1-mile segment, block cracking is converted to percent using Equation 6.10.

$$Block\ Cracking\ (\%) = \frac{Block\ cracking\ length\ (miles)}{Length\ of\ segment\ (miles)} \times 100 \qquad 6.10$$

The currently available MDOT survey manual represents block cracking 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 cracking and those involved in the AD matrix shown in Table 6.6. Particularly, PD code 310 involves all ten different combinations.

Table 6.6 Assumed severity definitions of HMA block cracking

Distress [PD Codes]	**Severity**	**Severity Definition from PMS**
Block Cracking [310, 345, 760, 501]	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)

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 6.11.

$$Raveling\ (\%) = \frac{Raveling\ length\ (miles)}{Length\ of\ segment\ (miles)} \times 100 \qquad 6.11$$

In raveling data extraction, PD codes 405 and 501 are used. As raveling has no severity level, the AD matrix (0,0) is only called.

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 6.12.

$$Bleeding\ (\%) = \frac{Bleeding\ length\ (miles)}{Length\ of\ segment\ (miles)} \times 100 \qquad 6.12$$

In bleeding data extraction, PD codes 406 and 501 are used. As bleeding has no severity level, the AD matrix (0,0) is only called.

PD Codes and Assumed Severity Levels for Different Rigid Pavement Distresses

Longitudinal Joint Spalling

Longitudinal joint spalling is measured in the PMS database as length. This is converted to percent using Equation 6.13.

$$Logitudinal\ Joint\ Spalling\ (\%) = \frac{Logitudinal\ joint\ spall\ length\ (miles)}{Length\ of\ section\ (miles)} \times 100 \qquad 6.13$$

Two example scenarios for longitudinal joint spalling are shown in Figure 6.4.

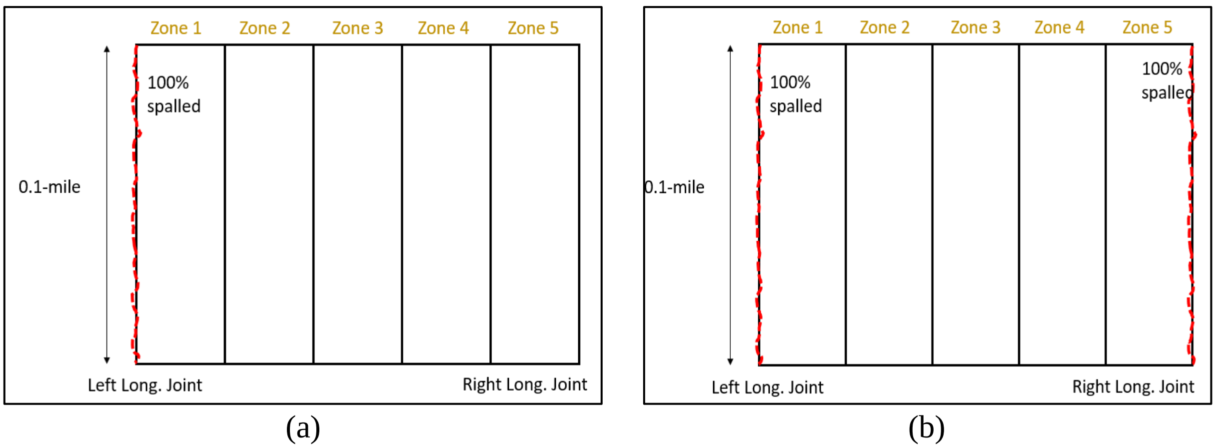


Figure 6.4 Longitudinal joint spalling scenarios (a) 50% spalled and (b) 100% spalled for a 0.1-mile interval segment

The PD codes and severity levels for longitudinal joint spalling are summarized in Table 6.7.

Table 6.7 PD codes and severity levels for rigid longitudinal joints

Distresses [PD codes]	Severity	Severity Definition from PMS
Longitudinal joint spalling [208,209,501]	Low	AD matrix: (0,0) and (2,0)
Longitudinal joint spalling [208,209,501]	Medium	AD matrix: (0,0) and (3,0)
Longitudinal joint spalling [208,209,501]	High	AD matrix: (0,0) and (4,0)

Transverse Joint Spalling

Transverse joint spalling is measured in the PMS database as a count. This is converted to percent using Equation 6.14. 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 6.8.

$$Transverse\ Joint\ Spalling(\%) = \frac{Transverse\ joint\ spall(count)}{\frac{Length\ of\ section\ (miles) \times 5280}{joint\ spacing\ (ft)}} \times 100 \quad 6.14$$

$$Transverse\ Joint\ Spalling(\%) = \frac{Transverse\ joint\ spall\ (count)}{No.of\ joints} \times 100$$

Table 6.8 PD codes and severity levels for rigid transverse joints

Distresses [PD codes]	Severity	Severity Definition from PMS
Transverse joint spalling [106,706,501]	Low	AD matrix: (0,0), (2,2), (2,3), (2,4), (2,5)
Transverse joint spalling [106,706,501]	Medium	AD matrix: (0,0), (3,2), (3,3), (3,4), (4,2), (5,2)
Transverse joint spalling [106,706,501]	High	AD matrix: (0,0), (3,5), (4,3), (4,4), (4,5), (5,3), (5,4), (5,5)

Longitudinal Wheel-path Crack

Longitudinal wheel-path cracking that exists in the two-wheel paths is called longitudinal wheel-path (WP) cracking. This is converted to percent using Equation 6.15. The PD codes and severity levels for longitudinal crack are summarized in Table 6.9.

$$Logitudinal\ Wheelpath\ Crack(\%) = \frac{\sum Logitudinal\ WP\ crack\ (length)}{2\ \times\ Length\ of\ section\ (miles)} \times 100 \quad 6.15$$

Longitudinal Center Lane Crack

The rigid longitudinal center lane (CL) crack is converted to percent using Equation 6.16. The PD codes and severity levels for longitudinal crack are summarized in Table 6.10.

$$Logitudinal\ CL\ Crack(\%) = \frac{\sum Logitudinal\ CL\ crack\ (length)}{Length\ of\ section\ (miles)} \times 100 \quad 6.16$$

Table 6.9 PD codes and severity levels for rigid longitudinal wheel path crack

Distresses [PD codes]	**Severity**	**Severity Definition from PMS**
Longitudinal Wheel path Crack [206,207,212,213,214,215,227,229,230,232,737,740, 742,501]	Low	AD matrix: (0,0), (1,0), (2,0), (3,0), (4,0), and (5,0)
Longitudinal Wheel path Crack [206,207,212,213,214,215,227,229,230,232,737,740, 742,501]	Medium	AD matrix: (0,0) and (6,0)
Longitudinal Wheel path Crack [206,207,212,213,214,215,227,229,230,232,737,740, 742,501]	High	AD matrix: (0,0) and (6,0)

Table 6.10 PD codes and severity levels for rigid longitudinal center lane crack

Distresses [PD codes]	**Severity**	**Severity Definition from PMS**
Longitudinal center lane crack [219,227,228,231,738,741,501]	Low	AD matrix: (0,0), (1,0), (2,0), (3,0), (4,0), and (5,0)
Longitudinal center lane crack [219,227,228,231,738,741,501]	Medium	AD matrix: (0,0) and (6,0)
Longitudinal center lane crack [219,227,228,231,738,741,501]	High	AD matrix: (0,0) and (6,0)

Transverse crack

Transverse crack is measured in the PMS database as a count. Transverse crack is converted to percent crack using Equation 6.17. Joint spacing has been assumed as 15 ft as no data is available. The PD codes and severity levels for transverse crack are summarized in Table 6.11.

$$Transverse\ Crack(\%) = \frac{Transverse\ crack\ (count)}{\frac{Length\ of\ section\ (miles) \times 5280}{joint\ spacing\ (ft)}} \times 100 \qquad 6.17$$

$$Transverse\ Crack(\%) = \frac{Transverse\ crack\ (count)}{No.of\ joints} \times 100$$

Table 6.11 PD Codes and Severity Levels for Transverse Crack

Distresses [PD codes]	**Severity**	**Severity Definition from PMS**
Transverse crack [102,105,107,712,713,112,113,501]	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 [102,105,107,712,713,112,113,501]	Medium	AD matrix: (0,0), (6,3), (6,4), (6,5), (7,3), (8,3)
Transverse crack [102,105,107,712,713,112,113,501]	High	AD matrix: (0,0), (7,4), (7,5), (8,4), (8,5)

Delamination

Delamination is measured in the PMS database as length. Delamination is converted to percent slabs using Equation 6.16. The PD codes and severity levels for delamination are summarized in Table 6.12.

$$Delamination\ (\%) = \frac{Delamination\ (miles)}{Length\ of\ section\ (miles)} \times 100 \qquad 6.18$$

Table 6.12 PD Codes and Severity Levels for Delamination

Distresses [PD codes]	Severity	Severity Definition from PMS
Delamination [301,751,341,501]	NA	AD matrix: All combinations

6.2 Optimization of distress weight factors

This section describes the optimization of PDS weight factors. This optimization aimed to link the performance measure to past decisions of fix-types made by Michigan DOT. The 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 to evaluate multiple objective functions to demonstrate the PDS's sensitivity to Michigan DOT pavement conditions and fix types.

The PDS formulations are shown in Equations 6.1 and Equation 6.2. The distress-severity combinations for flexible pavement used in this optimization analysis were (in order): low, medium, and high severity longitudinal cracking; alligator cracking (all severities); low, medium, and high severity transverse cracking; low, medium, and high severity edge cracking; block cracking (all severities); raveling, and; bleeding. For flexible pavement, this results in n = 13 values for weights.

Similarly, the distress-severity combinations for rigid pavement used in this analysis were (in order): delamination (all severities); low, medium, and high severity longitudinal joint spalling; low, medium, and high severity transverse joint spalling; low, medium and high severity transverse cracking; low, medium and high severity longitudinal cracking. This also results in n = 13 values for weights.

Michigan DOT 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 ultimate goal of this optimization effort is to maximize the difference among the light, medium, and major maintenance actions, as shown in chapter 5, while evaluating each condition score against MDOT maintenance records.

First, the matrix $\mathbf{X}_{ijk}$ was defined as the distress severity combinations required to calculate the PDS taken before each maintenance action (those values were obtained from the Michigan DOT database), and w_i as the vector of weights for calculating PDS, where i is the distress-severity value (13 unique values for both flexible and rigid), j represents different pavement segments that received a fix type. Those are grouped into k fix type categories. For the first analysis for flexible pavements, the following fix type categories (k) were defined: crack treatment (e.g., crack filling); single microsurfacing; overband crack filling; ultrathin overlay; single layer chip seal; double course microsurfacing; double course chip seal; added HMA; cold mill and overlay (any depth); crush and shape; and, reconstruction. So, total 11 types of fixes were used for flexible pavements. Similarly, the following fix type categories (k) were defined for rigid pavement: diamond grinding and joint sealant; concrete pavement repair (CPR); AMZ; added HMA; and reconstruction. So, total 5 type of fixes were used for rigid pavements. Next, objective functions were defined for flexible and rigid pavements, as shown in Equation 6.19 and Equation 6.20, respectively.

$$\min \boldsymbol{z}_{\boldsymbol{flexible}} = \frac{\sum_{j=1}^{n}\left(k_j - \bar{k}\right)\left(median(PDS_j^k) - \overline{PDS_j^k}\right)}{\sum_{j=1}^{n}\left(k_j - \bar{k}\right)^2} + \frac{PDS_{crack\ treatment}^{90th\ percentile}}{5} - \frac{PDS_{crush\&shape}^{10th\ percentile}}{10} \qquad 6.19$$

$$\min \boldsymbol{z}_{\boldsymbol{rigid}} = \frac{\sum_{j=1}^{n}\left(k_j - \bar{k}\right)\left(median(PDS_j^k) - \overline{PDS_j^k}\right)}{\sum_{j=1}^{n}\left(k_j - \bar{k}\right)^2} + \frac{PDS_{DG\ and\ JS}^{90th\ percentile}}{5} - \frac{PDS_{reconstruction}^{10th\ percentile}}{10} \qquad 6.20$$

where PDS is calculated using each set of weights ($\mathbf{Z}_{ik}$) 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. Note that the choice of numerical assignments to group categories can significantly affect the results of Equation 6.4, so the assumption was made that equal spacing between groups is adequate. $\bar{k}$ is the average group value (5.5 and 2.5 given the selected categorization for flexible and rigid, respectively). As mentioned before, 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 minimize 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). The denominator on the last two terms 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 last item necessary to setup the analysis is to account for the relationship between each of the weights (w_i). Therefore a separate vector¸ $\boldsymbol{Z}_i$, was defined as the input for the optimization and was related to w_i as: $w_1 = \boldsymbol{Z}_1$; $w_2 = \boldsymbol{Z}_1 + \boldsymbol{Z}_2$; $w_3 = \boldsymbol{Z}_1 + \boldsymbol{Z}_2 + \boldsymbol{Z}_3$; $w_4 = \boldsymbol{Z}_4$; $w_5 = \boldsymbol{Z}_5$; $w_6 = \boldsymbol{Z}_5 + \boldsymbol{Z}_6$; $w_7 = \boldsymbol{Z}_5 + \boldsymbol{Z}_6 + \boldsymbol{Z}_7$; $w_8 = \boldsymbol{Z}_8$; $w_9 = \boldsymbol{Z}_9$; $w_{10} = \boldsymbol{Z}_{10}$; $w_{11} = \boldsymbol{Z}_{10} + \boldsymbol{Z}_{11}$; $w_{12} = \boldsymbol{Z}_{10} + \boldsymbol{Z}_{11} + \boldsymbol{Z}_{12}$; $w_{13} = \boldsymbol{Z}_{13}$. Finally, constraints were placed such that $0 < Z\text{i} \leq 1 \; \forall \; \text{i}$.

A boxplot showing the PDS for the different maintenance categories using the original weights is shown in Figure 6.5 and Figure 6.6, respectively, for flexible and rigid pavement. After optimization, similar boxplots calculated using the revised weights are shown in Figure 6.7 and Figure 6.8, respectively, for flexible and rigid pavement. A table of the original and revised weights for each flexible pavement distress is shown in Table 6.13. Similarly, Table 6.14 shows the original and revised weights for each rigid pavement distress.

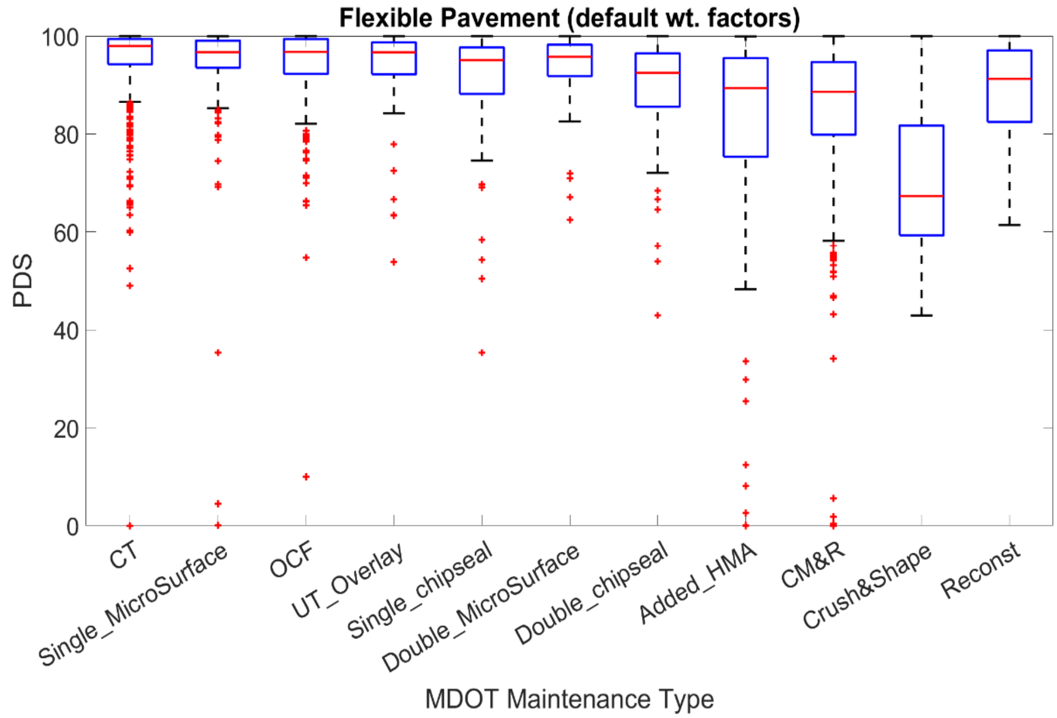


Figure 6.5 PDS boxplot with original flexible pavement weights; the box represents the 25th to 75th percentile, with the whiskers covering approximately the 99th percentile, the asterisks the individual data points that are considered outliers

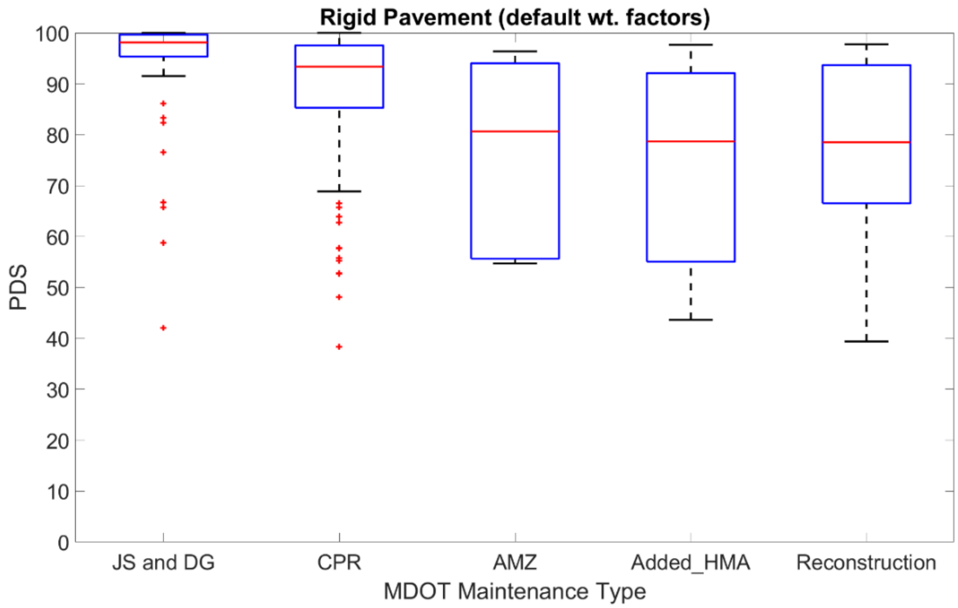


Figure 6.6 PDS boxplot with default rigid pavement weights; the box represents the 25th to 75th percentile, with the whiskers covering approximately the 99th percentile, the asterisks the individual data points that are considered outliers

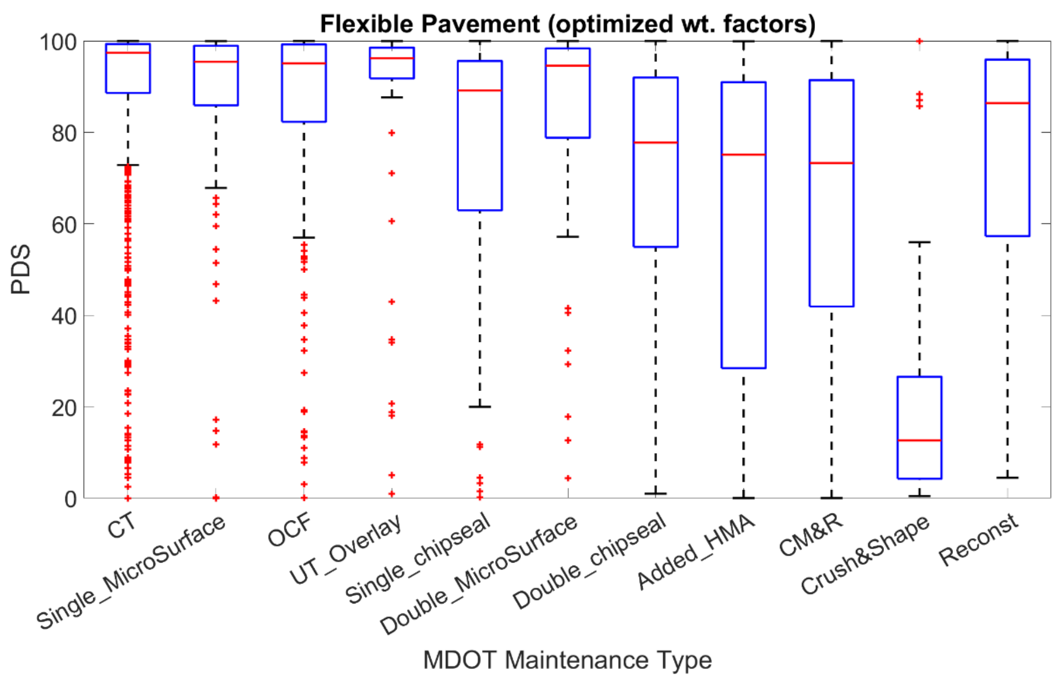


Figure 6.7 PDS boxplot with revised flexible pavement weights; the box represents the 25th to 75th percentile, with the whiskers covering approximately the 99th percentile, the asterisks the individual data points that are considered outliers

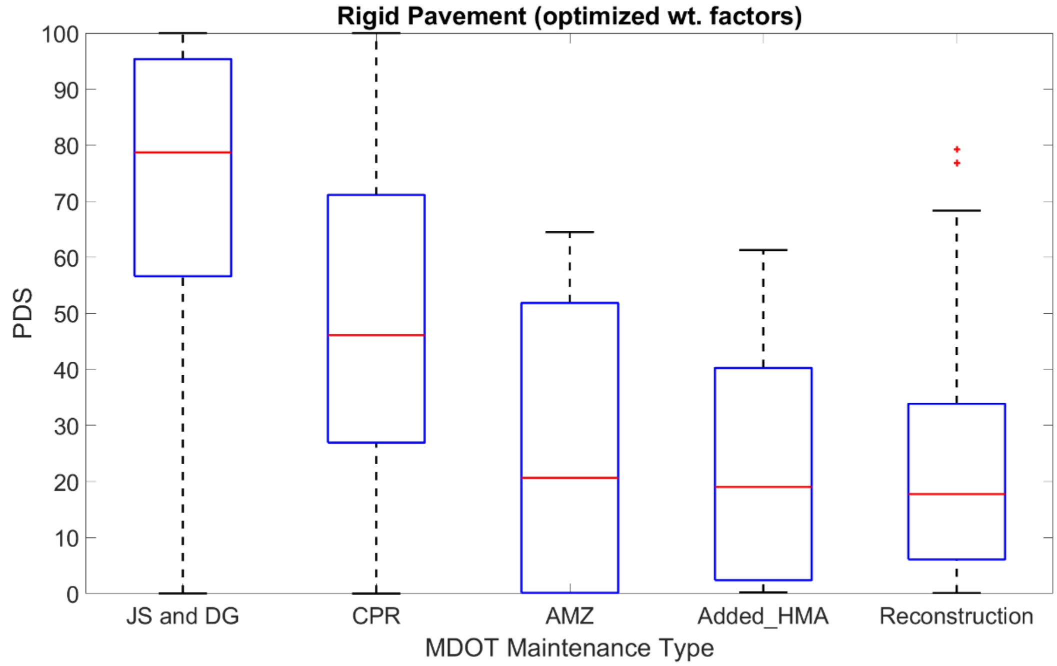
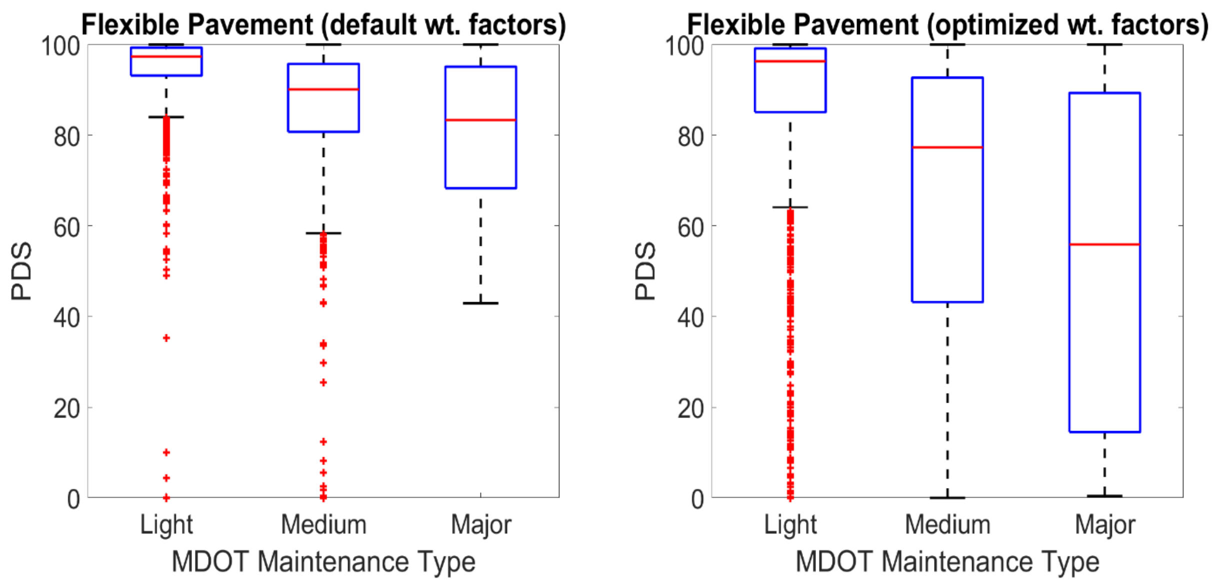


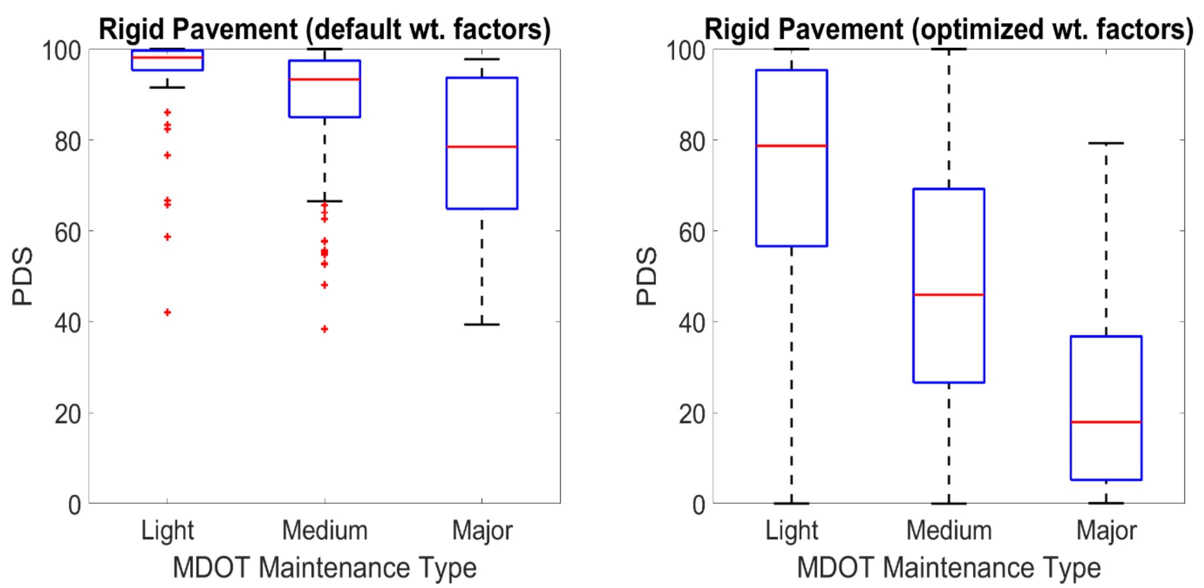
Figure 6.8 PDS boxplot with revised rigid pavement weights; the box represents the 25th to 75th percentile, with the whiskers covering approximately the 99th percentile, the asterisks the individual data points that are considered outliers

All fix types can be grouped into three categories to better facilitate the boxplot representation, as shown in Table 5.1 and Table 5.2 for flexible and rigid pavement, respectively. As a result, Figure 6.5 through Figure 6.8 can be re-created as Figure 6.9 and Figure 6.10 respectively, for flexible and rigid pavement.



(a) (b)

Figure 6.9 Combine boxplot for MDOT’s flexible pavement maintenance records (light, medium and major) based on PDS (a) with default wt. factors and (b) with revised wt. factors



(a) (b)

Figure 6.10 Combine boxplot for MDOT’s rigid pavement maintenance records (light, medium, and major) based on PDS (a) with default wt. Factors and (b) with revised wt. factors

Table 6.13 Flexible pavement default and revised distress weight factors

Distress Type	**Severity**	**Default Factor (w_i)**	**Revised Factor (w_i)**
Transverse Cracking	Low	0.01	0.017
	Medium	0.1	0.028
	High	0.2	0.884
Longitudinal Cracking	Low	0.02	0.011
	Medium	0.03	0.218
	High	0.04	0.831
Edge Cracking	Low	0.02	0.011
	Medium	0.03	0.031
	High	0.04	0.084
Block Cracking	-	0.15	0.943
Raveling	-	0.02	0.490
Bleeding	-	0.01	0.012

Table 6.14 Rigid pavement default and revised distress weight factors

Distress Type	**Severity**	**Default Factor (w_i)**	**Revised Factor (w_i)**
Longitudinal Joint	Low	0.10	0.314
	Medium	0.15	0.419
	High	0.20	0.923
Transverse Joint	Low	0.10	0.988
	Medium	0.15	1.976
	High	0.20	2.104
Longitudinal Cracking	Low	0.02	0.118
	Medium	0.03	0.316
	High	0.04	0.613
Transverse Cracking	Low	0.01	0.263
	Medium	0.10	0.291
	High	0.20	0.363
Delamination	-	0.07	0.564

Later, these calibrated weight factors for both asphalt and rigid pavement were further evaluated by MDOT engineers by comparing PDS values with the visual observation of many road segments from seven regions of the MDOT road network. While MDOT engineers thought PDS values for flexible pavements were generally reasonable, they thought PDS values for rigid pavements were too low. After a quick investigation, it was found that transverse joint spalling has 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 relative difference between weight factors at three severity levels is not too different, and calculated rigid PDS will align with the visual observations of the roads. Before doing so, the default rigid weight factors highlighted in Table 6.14 are slightly changed and labeled as “revised default” weight factors, as presented in Table 6.15. More specifically, transverse joint weight factors are changed so that they are similar to the transverse cracking weight factors. Also, delamination was given the highest weight following the MDOT engineers’ suggestion. After a few trials and errors, a 1.5 to the “revised default” weight factor multiplier provided reasonable PDS numbers that matched a few MDOT comments, as shown in Figure 6.11 and Figure 6.12, with the previous PDS value calculated using the former revised wt. factors in Table 6.14. Table 6.15 shows the latest revised wt. factor for rigid pavement, which will be further used in performance modeling and fix-life estimation in this study.

Table 6.15 Rigid pavement modified default and re-revised distress weight factors

Distress Type	Severity	Revised Default Factor (w_i)	New Revised Factor (w_i)
Longitudinal Joint	Low	0.10	0.15
	Medium	0.15	0.225
	High	0.20	0.3
Transverse Joint	Low	0.01	0.015
	Medium	0.10	0.15
	High	0.20	0.3
Longitudinal Cracking	Low	0.02	0.03
	Medium	0.03	0.045
	High	0.04	0.06
Transverse Cracking	Low	0.01	0.015
	Medium	0.10	0.15
	High	0.20	0.30
Delamination	-	0.27	0.40

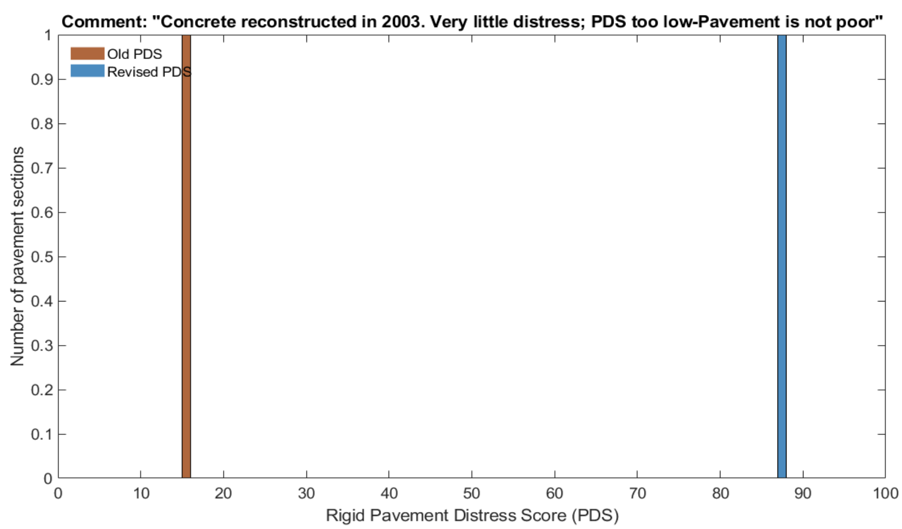


Figure 6.11 Example 1: new revised rigid PDS value satisfies MDOT comment

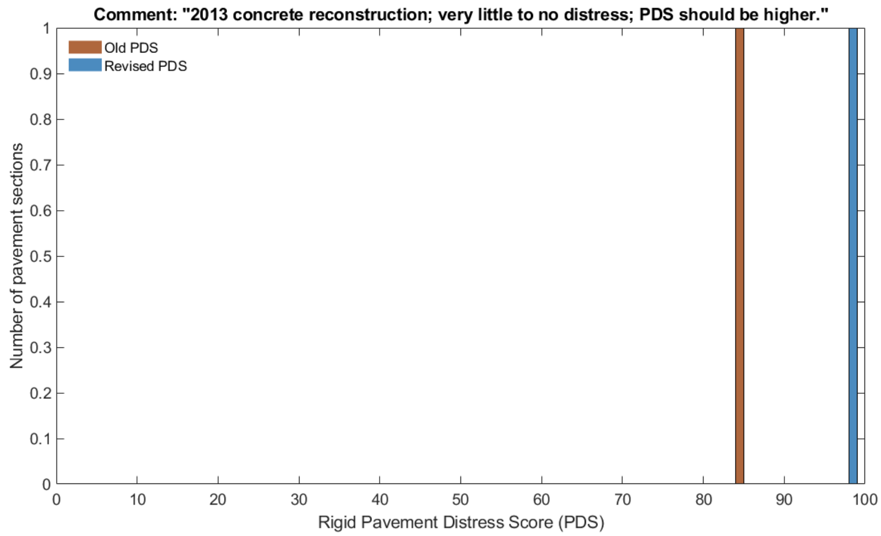


Figure 6.12 Example 2: new revised rigid PDS value satisfies MDOT comment

7. PERFORMANCE MODELING FOR PDS WITH MDOT FAMILIES

Performance modeling is integral to the pavement management system [55]. 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, state DOTs develop their performance models based on pavement families [56] at the network level. Pavement families represent pavement sections with similar performance, surface type, similar underlying structures, traffic load, and similar routine maintenance activities.

There are two levels of performance curves: site-specific and default curves. Site-specific curves are based on previous 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. State agencies opt for default curves when no previous data are available [8]. While less accurate than site-specific curves, default curves provide useful information when specific data is 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 [57]. Accurate performance modeling can optimize budget allocation and pavement maintenance strategies by using a systematic approach to data collection and analysis, ensuring the safe and efficient operation of road networks. In this chapter, performance modeling for PDS is outlined. Also, the fix life estimation method for different MDOT surface types is explained.

7.1 Performance 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) [58], [59]. Deterministic models are useful for predicting pavement conditions and identifying 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. Probabilistic models can provide more detailed information on the potential future condition of a pavement section, but they require more data and computational resources.

This study evaluated several deterministic performance models, as shown in Equations 7.1 through 7.4, including the logistic growth curve and the Gompertz model that MDOT has used. The other two models are the New Jersey DOT performance and North Carolina DOT's power models. It is important to note that MDOT's logistic growth curve and Gompertz model 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) following the national norm.

All four models are a function of pavement age (i.e., years since the last major rehabilitation or reconstruction happened). There are other models also available in the literature, which are a function of other 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 age were only considered in this study.

$$PDS_{MDOT_{Logistic}} = 100 - \alpha\left(\left[\frac{(\alpha + \beta)}{\alpha + \beta e^{-\gamma t}}\right] - 1\right) \qquad 7.1$$

$$PDS_{MDOT_{Gompertz}} = 100 - \left((\alpha + \beta)\left(\frac{\alpha}{\alpha + \beta}\right)^{exp(-\gamma t)}\right) - \alpha \qquad 7.2$$

where,

$PDS_{MDOT_{Logistic}}$ = PDS calculated based on Michigan DOT's logistic growth model,

$PDS_{MDOT_{Gompertz}}$ = PDS calculated based on Michigan DOT's Gompertz growth model,

α = Potential initial PDS,

β = Limiting PDS,

t = Age in years, and

γ = Deterioration pattern index

$$PDS_{NJDOT} = 100 - e^{\left(A - B \times C^{\ln\left(\frac{1}{Age}\right)}\right)} \quad 7.3$$

where,

PDS_{NJDOT} = PDS calculated based on New Jersey DOT's model,

Age = Pavement age in years since last rehabilitation or construction activity, and

A, B, C = Model coefficients

$$PDS_{NCDOT} = 100 - C_0 + C_1 \times Age^{C_2} \quad 7.4$$

where, PDS_{NCDOT} = PDS calculated based on North Carolina DOT's model. C_0, C_1, and C_2 are regression coefficients. C_0 determines the highest point on the flat portion of the curve.

Like other state DOTs [60]–[62], MDOT also classified their pavements into different families to develop family curves for different surface types. Four types of flexible pavements are available in the MDOT's database for freeway and non-freeway functional classes. They are (a) crush and shape, (b) 2-course overlay, (c) rubblized, and (d) reconstruction. Two types of pavements are usually maintained for rigid pavements: (a) reconstruction and (b) unbonded.

Pavements are typically numbered into three families: Family 1, Family 2, and Family 3, representing good, fair, and poor pavement conditions, respectively. For grouping pavement sections into families, MDOT took their DI values before any major rehabilitation 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. It is noted that crack treatment (CT) and overband crack fill (OCF) are considered minor treatments; thus, these two maintenances were ignored in family assignments of different pavement sections.

In the attempt to model the PDS, at first, individual excel files were created for both flexible and rigid pavements. These excel files contain all family groups with section-specific information, pavement age, and corresponding Old DI and PDS values. Such organized excel files would help filter different families for developing performance model curves. A snapshot of an example excel file for HMA crush and shape pavement is shown in Figure 7.1. 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 7.1 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 [56], [63], [64]. 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 this rate. Figure 7.2 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.

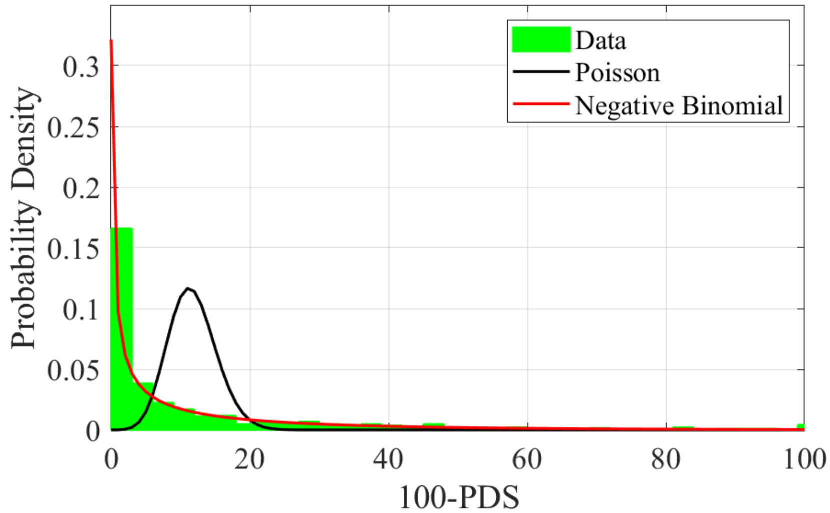


Figure 7.2 PDS data distribution for crush and shape Family 2

Once the distribution of PDS data is determined, the likelihood function is used in PDS model predictions. The likelihood is a powerful statistical method that can be applied to a wide range of probability distributions, including the negative binomial distribution. 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. 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., negative binomial distribution in this study.

The '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. Initially, an initial set of model coefficients was specified, and then the fmincon function was used with a wide range of coefficient boundaries 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. Once the optimal set of coefficients was obtained, performance model curves were constructed for each model and pavement family group.

7.2 Performance modeling for HMA PDS with MDOT Families

This section includes a discussion of performance modeling for HMA PDS with MDOT families. Using all four performance models, the reconstruction Family 1 and crush and shape Family 2 are shown as examples in Figure 7.3 and Figure 7.4, respectively. All other PDS performance curves with MDOT families for flexible pavement families are attached in Appendix A.

To check 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 which represents that predicted observations are closer to those measured observations. Among these four models for both cases outlined in this section, NJDOT model prediction shows the highest R^2 with the least root mean square (RMSE). However, other models' R^2 and RMSE are not much different. In these two cases, four models reasonably give similar prediction curves.

Nevertheless, 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 worst. Therefore, cautions and engineering judgment are necessary when choosing one performance model over others. However, from general observation, the NJDOT and logistic growth models show better goodness-of-fit statistics for flexible pavement modeling.

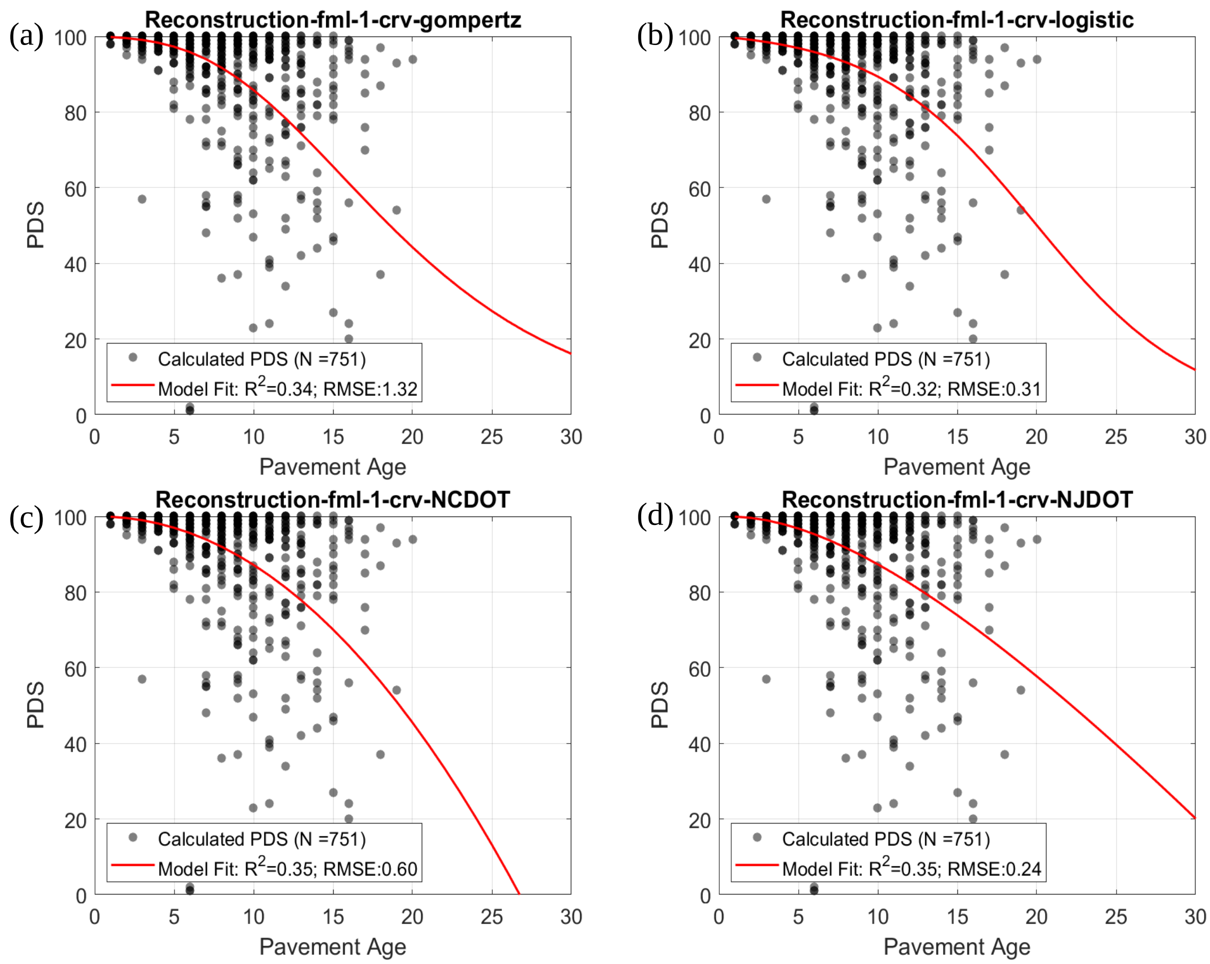


Figure 7.3 HMA reconstruction modeling for PDS with MDOT Family 1 using: (a) Gompertz, (b) Logistic, (c) NCDOT and (d) NJDOT models

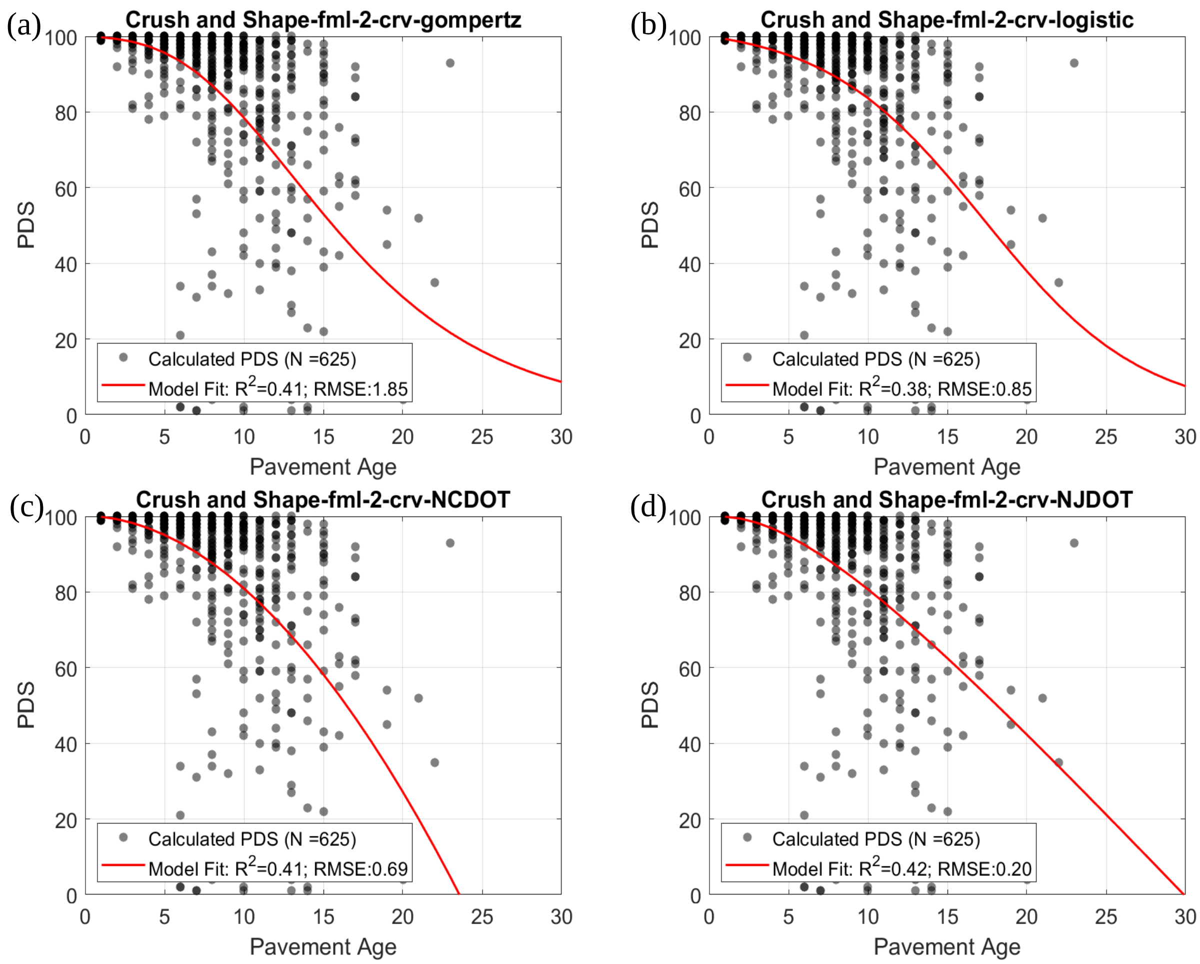


Figure 7.4 HMA crush and shape modeling for PDS with MDOT Family 2 using: (a) Gompertz, (b) Logistic, (c) NCDOT, and (d) NJDOT models

7.3 Performance modeling for Rigid PDS with MDOT Families

This section includes a description of performance modeling for rigid PDS with MDOT families. For illustration purposes, rigid reconstruction Family 3 and rigid unbonded Family 2 are shown in Figure 7.5 and Figure 7.6, respectively. All other rigid pavement performance curves with MDOT families are attached in Appendix A.

As can be observed for both cases, the NCDOT performance model gives a better deterioration curve with the highest R^2 and the least RMSE. In rigid pavements, general observation revealed that NCDOT and the logistic model can predict PDS better for all rigid family groups.

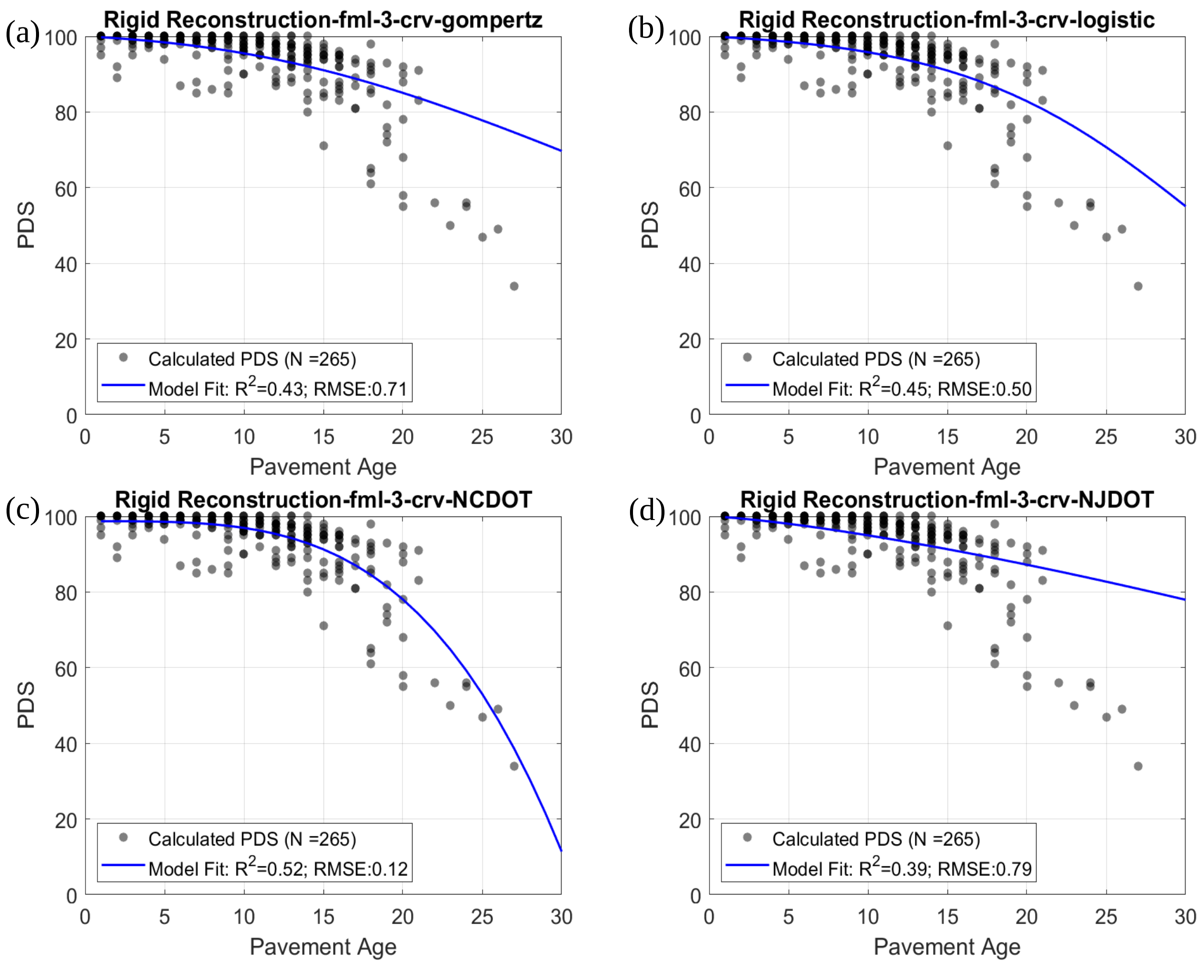


Figure 7.5 Rigid reconstruction modeling for PDS with MDOT Family 3 using: (a) Gompertz, (b) Logistic, (c) NCDOT and (d) NJDOT models

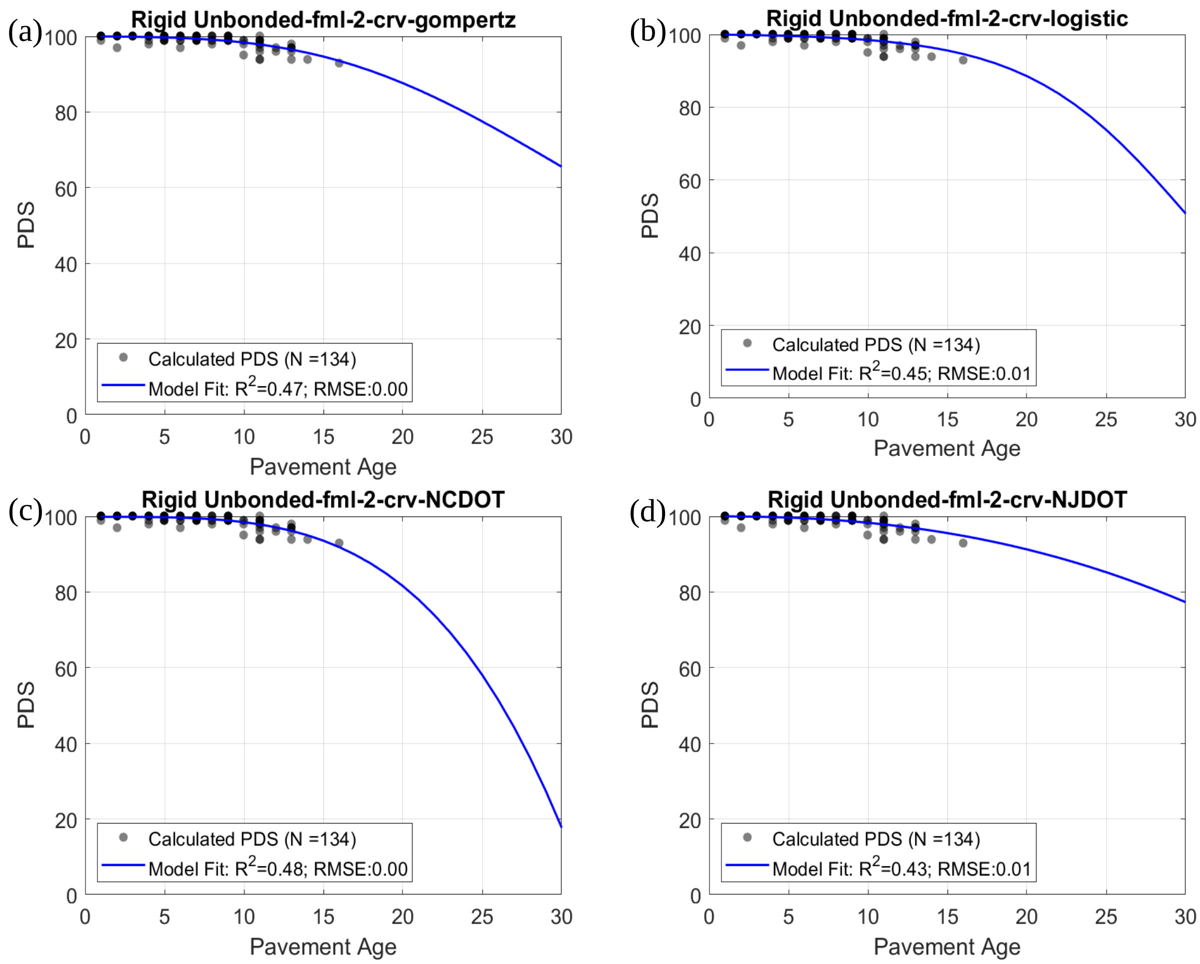


Figure 7.6 Rigid unbonded modeling for PDS with MDOT Family 2 using: (a) Gompertz, (b) Logistic, (c) NCDOT and (d) NJDOT models

7.4 *Fix Life Estimation for PDS with MDOT Families*

The term "pavement fix life" refers to the period between when a pavement surface is first constructed or rehabilitated and when it reaches a point where major rehabilitation is the only option left to restore its functionality and appearance. During this time, the pavement will naturally experience wear and tear from traffic, weather, and other environmental factors, which can cause a variety of forms of distress, such as cracking, rutting, and potholes. In the fix-life calculation, the assumption is that if no major surface treatment is applied, how many years can a pavement section last until a major rehabilitation needs to be applied? 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. 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. Composite Pavement Distress Score (CPDS) can be mathematically calculated using Equation 7.5.

$$Composite\ PDS = \frac{PDS(age, family_1) \times L_1 \ + \ PDS(age, family_2) \times L_2 + \cdots\cdots + \ PDS(age, family_n) \times L_n}{L_1 \ + \ L_2 + \cdots\cdots + \ L_n} \qquad 7.5$$

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

Table 7.1 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. And most cases, Family 1 (i.e., good condition pavement group) represents the largest length for a particular surface type. As a result, we can expect that the PDS composite curve will tend to shift towards the Family 1 curve.

Table 7.1 Total section length for the MDOT's DI-based pavement families

Surface Type	Asphalt Pavement Families				
	Family1 (miles)	Family2 (miles)	Family3 (miles)	Family4 (miles)	Family5 (miles)
Crush and Shape	723	568	252	246	NA
Reconstruction	314	199	106	NA	NA
2-Course overlay	578	950	820	419	NA
Rubblize	222	158	96	NA	NA
Surface Type	**Rigid Pavement Families**				
	Family1 (miles)	**Family2 (miles)**	**Family3 (miles)**	**Family4 (miles)**	**Family5 (miles)**
Reconstruction	781	311	112	168	188
Unbonded	83	154	41	NA	NA

Note: NA = not available

Due to the good fit of the NJDOT and logistic growth model shown in the previous section for all types of surface types and pavement families, composite curves of all families of flexible pavement were constructed based on the NJDOT and logistic growth performance model. Figure 7.7 and Figure 7.8 show all family curves alongside composite curves for crush and shape, reconstruction, 2-course overlay, and rubblize with NJDOT and logistic growth model, respectively. Also, the fix life for each surface type is reported when the PDS composite curve reaches a threshold value of 50; the fix life is calculated up to that year since the pavement was opened to traffic.

Similarly, the NCDOT and logistic growth model were better for all rigid surface types and pavement families. As a result, composite curves were presented herein for all families of rigid pavement using the NCDOT and logistic growth performance model. In Figure 7.9 and Figure 7.10, the composite curve for rigid reconstruction and rigid unbonded with NCDOT and logistic growth model are displayed alongside the curves for all rigid pavement families.

Table 7.2 presents the fix life of each surface flexible and rigid pavements calculated from the composite curves mentioned above. Moreover, in Table 7.2, MDOT's current fix life for these pavement types is reported as well. With the consensus of region engineers, MDOT determined these current fix lives based on past DI performance curves and engineering judgment. It can be observed that, in general, asphalt pavement PDS with the revised weight factors provides a relatively similar level of fix lives. However, for rigid pavement, except for the NCDOT model, all other performance models show high fix lives as compared to MDOT's current fix life. It dictates that only cracking-based index may not influence MDOT in their rigid pavement's fix life determination.

However, an advantage of having multiple models is that it will give MDOT the flexibility to choose the best model which gives the optimum fix life and it satisfies their past engineering experience and information. As mentioned in the previous section, one model may not be suitable to acquire desired fix life for all pavement surface types.

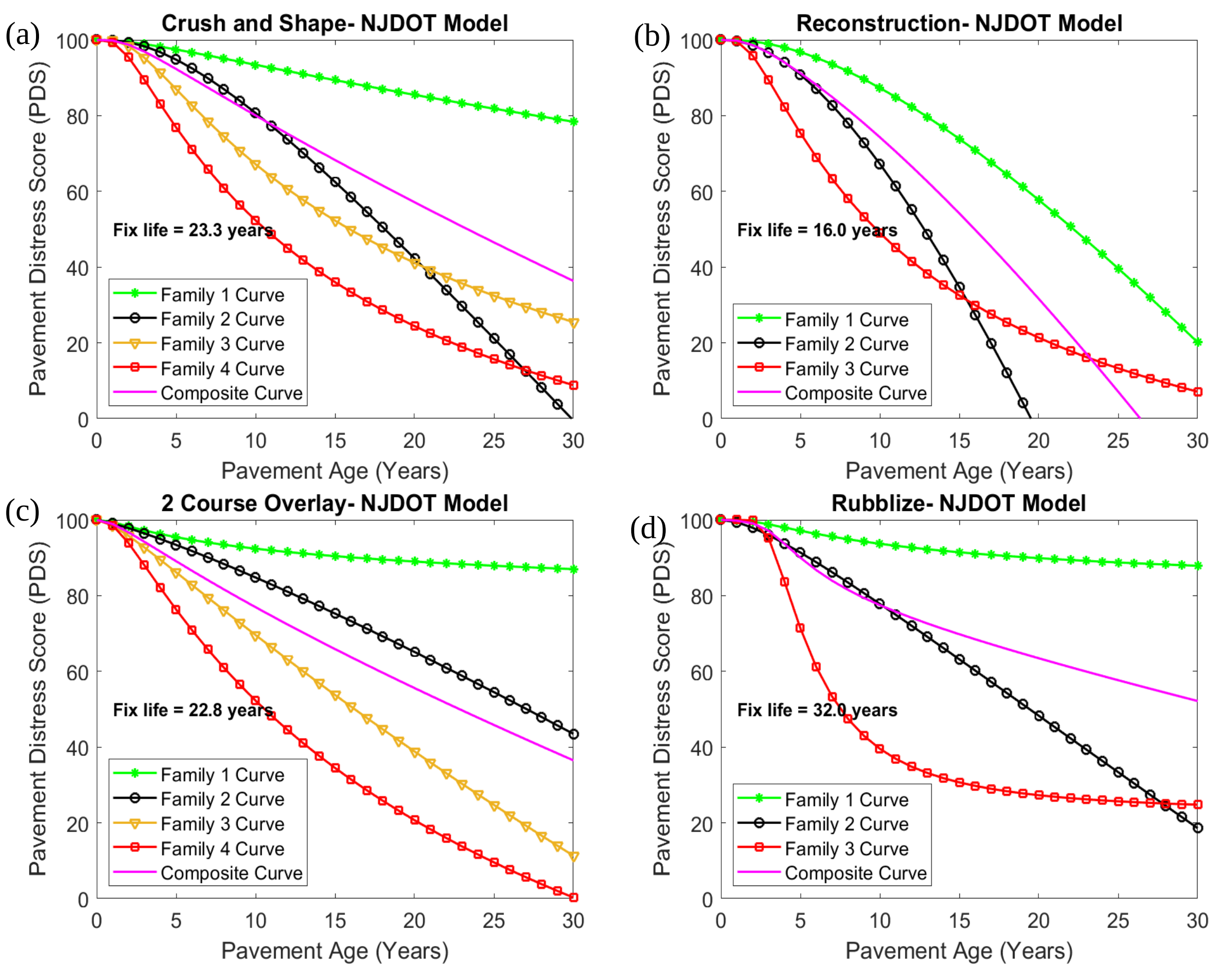


Figure 7.7 HMA PDS composite curves with MDOT families using the NJDOT growth model for (a) crush and shape, (b) reconstruction, (c) 2-course overlay, and (d) rubblize

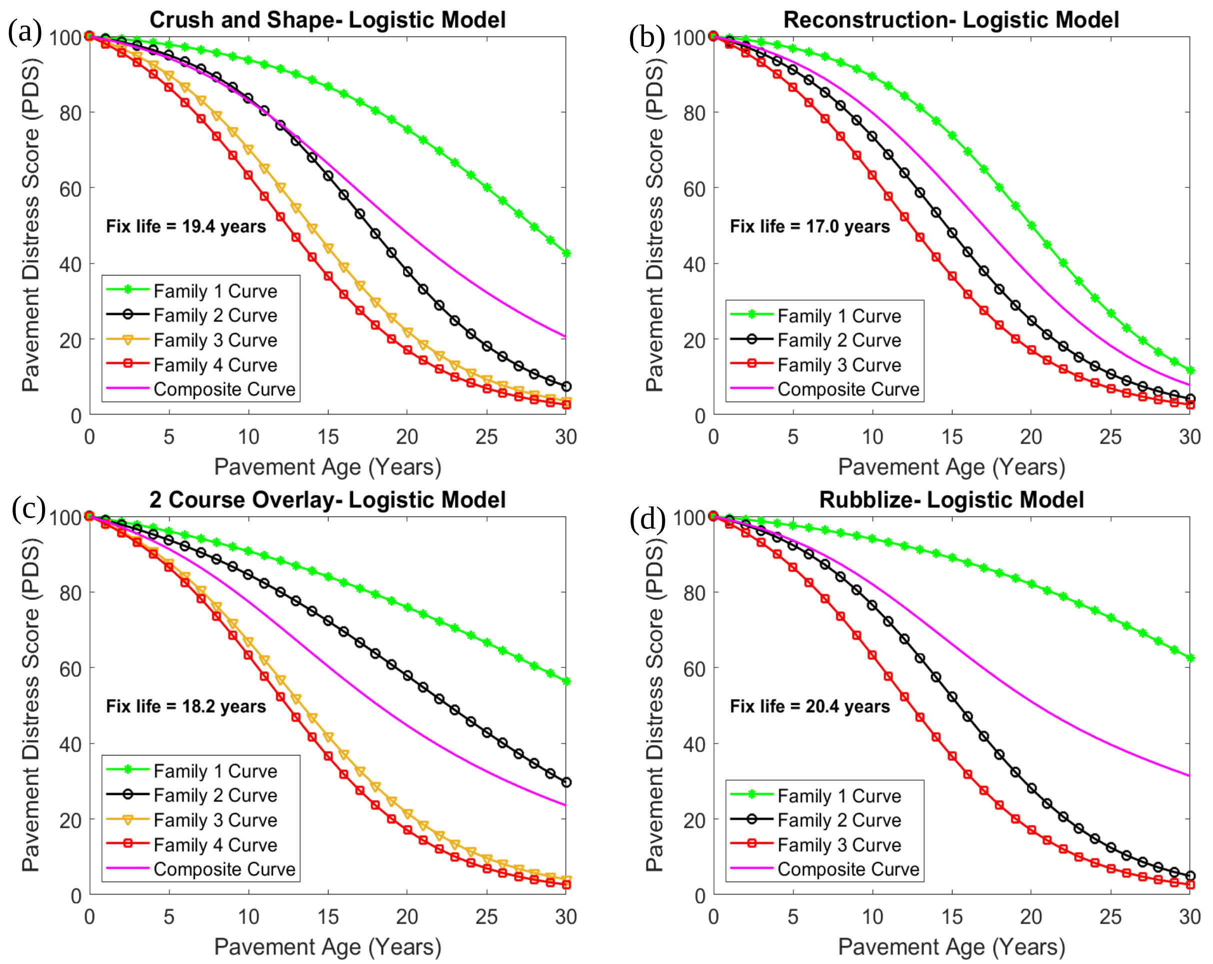


Figure 7.8 HMA PDS composite curves with MDOT families using the logistic growth model for (a) crush and shape, (b) reconstruction, (c) 2-course overlay, and (d) rubblize

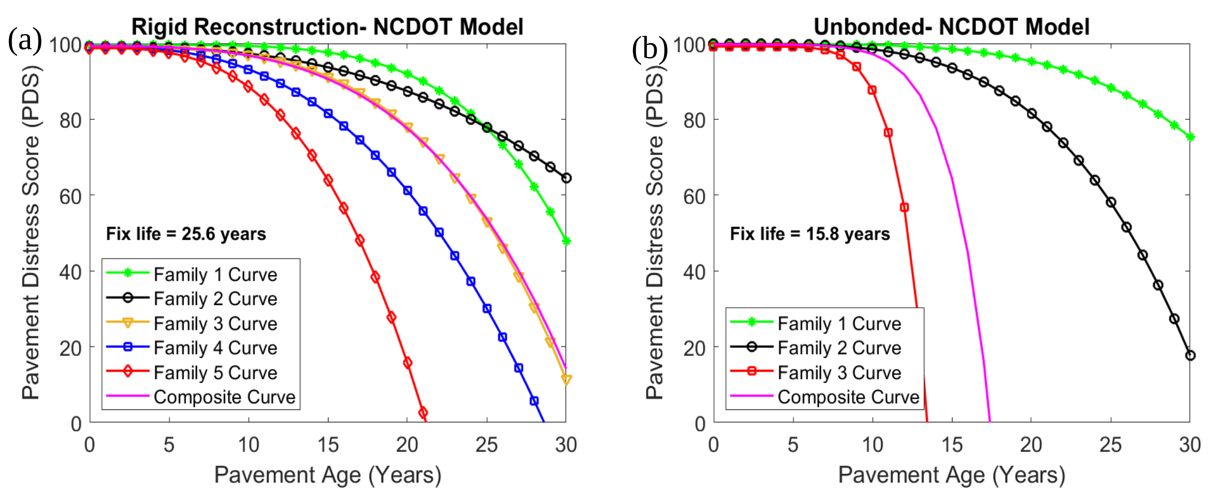


Figure 7.9 Rigid PDS composite curves with MDOT families using the NCDOT growth model for (a) reconstruction and (b) unbonded

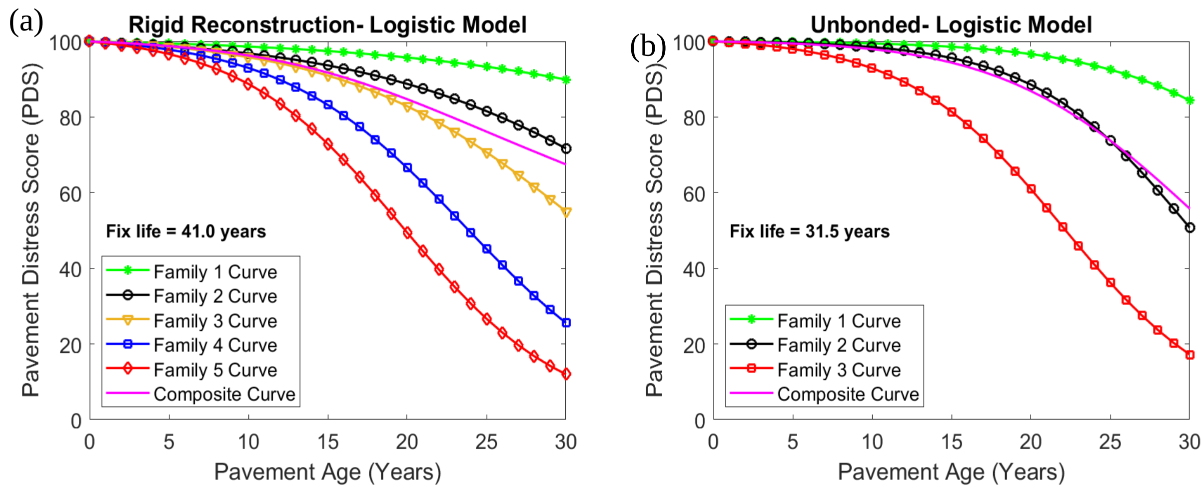


Figure 7.10 Rigid PDS composite curves with MDOT families using the logistic growth model for (a) reconstruction and (b) unbonded

Table 7.2 Fix life using PDS composite curves with MDOT families

Models	**Asphalt Pavement**				**Rigid Pavement**	
	Crush & Shape	**HMA Recon**	**2-Course Overlay**	**Rubblize**	**Concrete Recon**	**Unbonded**
NJDOT	23	16	23	32	65	48
NCDOT	19	15	20	12	26	16
Logistic	19	17	18	20	41	32
Gompertz	18	15	19	21	58	41
MDOT Current (DI-based)	19	18	18	16	26	19

8. PERFORMANCE MODELING FOR PDS WITH NEW FAMILIES

In this chapter, a couple of methods for developing different families based on PDS were explored. As previous MDOT families were based upon historical DI trends for individual sections, those families may not be appropriate while developing performance curves using PDS.

8.1 Modified FHWA family classification method

Khazanovich et al. [65] proposed some pavement performance criteria for FHWA. In that study, the criteria were set to identify the site conditions and design/construction features of flexible pavements that lead to good or poor pavement performance. Long-Term Pavement Performance (LTPP) pavement sections were used to obtain the necessary data. Separate criteria were developed for each performance measure, including roughness (IRI), rutting, and fatigue cracking. These criteria were utilized to determine the practical significance of inputs for different performance measures [65], [66].

Later, this concept of classifying family was modified to Michigan road conditions by Haider et al. [43] in their Pavement ME local calibration project. In this chapter, the same concept was borrowed in classifying pavement sections into three family groups (good, fair, and poor) based on PDS, with some adjustments in the rating scale, reference lines, and the method of identifying family groups. As shown in Figure 8.1(a), the original FHWA criteria are set based on IRI values at certain pavement age, and two reference lines (i.e., blue and red) are constructed. If a pavement's time series plot is below the red line, it will be classified as good pavement; if the time series plot is above the blue line, it will be classified as poor pavement; and anything between the blue and red line is rated as fair condition pavement. However, a time series plot does not always remain within a single zone (either below or above a reference line); it crosses these lines. When the performance trend passes through more than one category zone, the zone with the maximum number of points is considered the category for that section. Also, the low-performance category is selected in the case of an equal number of points for two different categories.

In order to apply this method to PDS-based performance trends, those reference lines were recreated on the PDS scale shown in Figure 8.1(b). In this process, linear interpolation was used, and it was assumed that IRI values of 30 inch/mile and 172 inch/mile are equivalent to PDS values of 100 and 50, respectively.

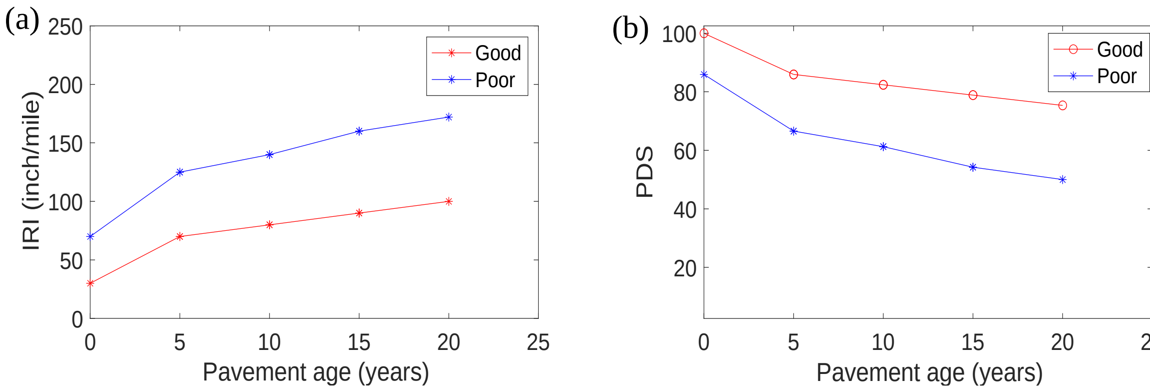


Figure 8.1 Family classification based on (a) FHWA IRI criteria and (b) modified FHWA criteria for PDS

After developing the modified FHWA criteria for PDS, three options were tried to classify pavement sections into reasonable categories based on their performance trends.

1. Default method

Similar to the original FHWA criteria for IRI, all performance measurements were considered in this option, and performance trend was observed to see in which zone the maximum number of measurement points could be found. Accordingly, a pavement section was categorized as good, fair, or poor. Figure 8.2(a) demonstrates an example pavement section with this method.

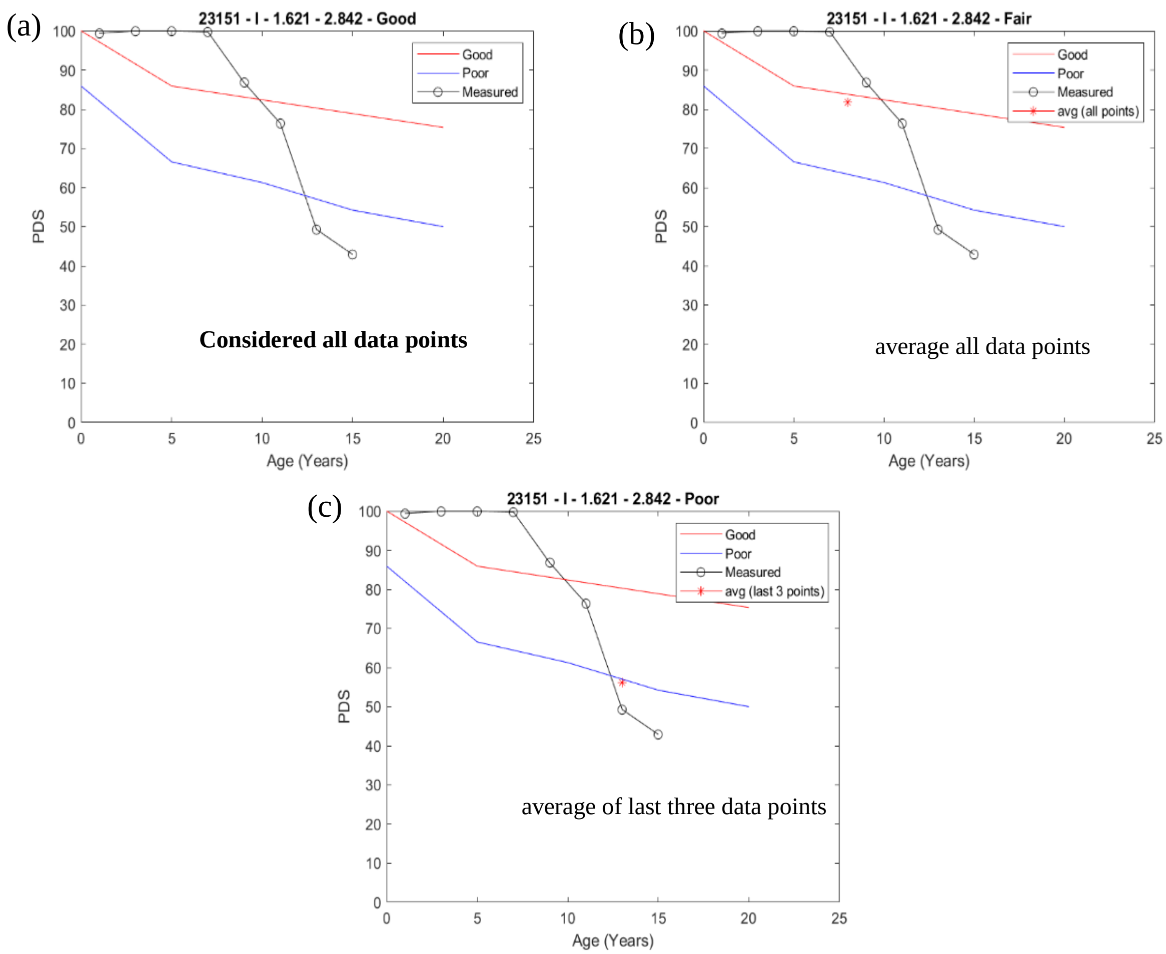


Figure 8.2 Modified FHWA family classification (a) default method (b) Avg_{all} method and (c) Avg_{L3} method

2. Average of all data points (Avg_{all}) method

In this option, instead of considering all data points, the average of all data points (i.e., PDS and corresponding pavement age) was calculated and plotted on the same plot to see where the single data point lies, as shown in Figure 8.2(b). Then, based on the position of the 'red' Avg_{all} data point, a pavement section was categorized into a family group.

3. Average of last three data points (Avg_{L3}) method

In this option, it was thought that the last three years of available measurements might better represent a pavement section's condition. Therefore, the average of the last three data points of the performance trend was calculated and plotted on the same plot. Then, based on the position of the ‘red’ Avg_{L3} data point, a pavement section was categorized into a family group. Figure 8.2(c) shows an example plot for this method.

Overall, it is interesting to see how differently a pavement section may be classified into different families following either one of these modified FHWA criteria methods. However, it seems the Avg_{L3} method can represent pavement deterioration better. The following results of this report are based on the Avg_{L3} method.

8.2 Distribution and time series plots of sections with the avg_{L3} method

In this section, for illustration purposes, distribution and time series plots of reconstruction pavement for both flexible and rigid with the Avg_{L3} method are presented. Also, distribution and time series plots of MDOT’s old family classification are presented here for comparison purposes. It is to be noted that the Avg_{L3} method classifies all pavement sections into three groups, whereas MDOT classification ranges from three to five groups. Therefore, not in every surface type can a direct comparison be made.

In Figure 8.3, with the Avg_{L3} method for flexible reconstruction pavement, more pavement sections (66%) are in the good category compared to Family 1 (52%) of the MDOT classification method. However, with the Avg_{L3} method for rigid reconstruction, most pavement sections (95%) are classified as ‘good’ category, as shown in Figure 8.4.

However, the advantages of the new family method become more apparent when we observe the time series plots for the AvgL3 families in Figure 8.5, which result in better classification. For instance, in the Avg_{L3} method’s good family category, sections with relatively higher PDS values are included, while MDOT's Family 1 time series plot includes some sections with very low PDS. The same observation can be made in the time series plot for rigid reconstruction pavement, as shown in Figure 8.6. Overall, the new family method demonstrates the potential for more effective grouping of sections.

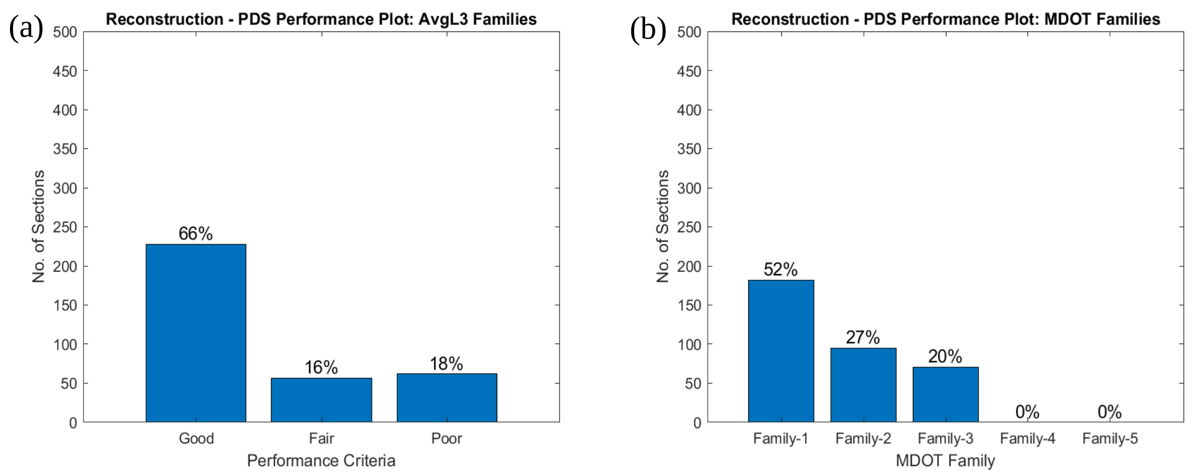


Figure 8.3 Distribution of different families based on (a) AvgL3 method and (b) MDOT DI-based method for HMA ‘reconstruction’ surface type

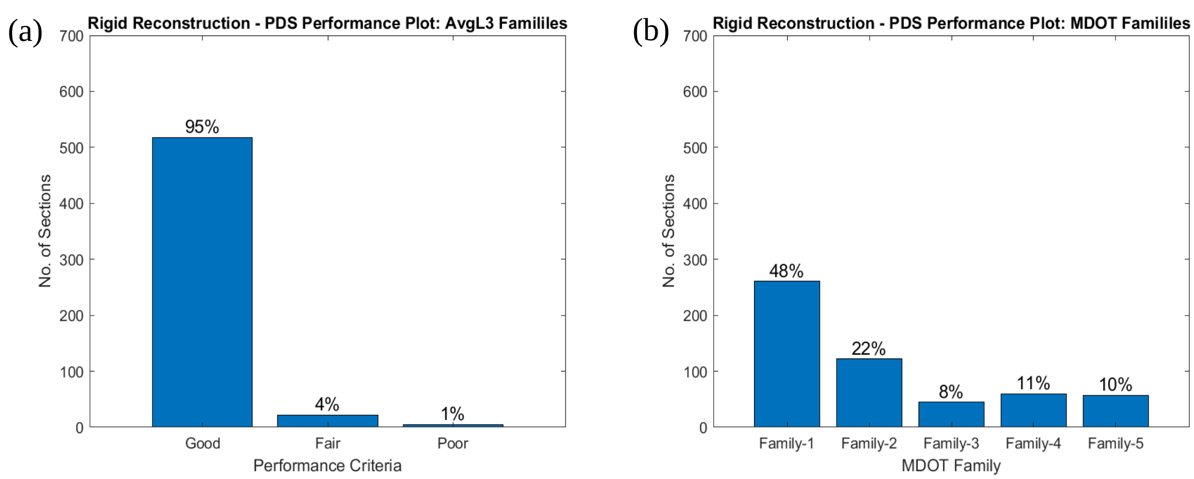
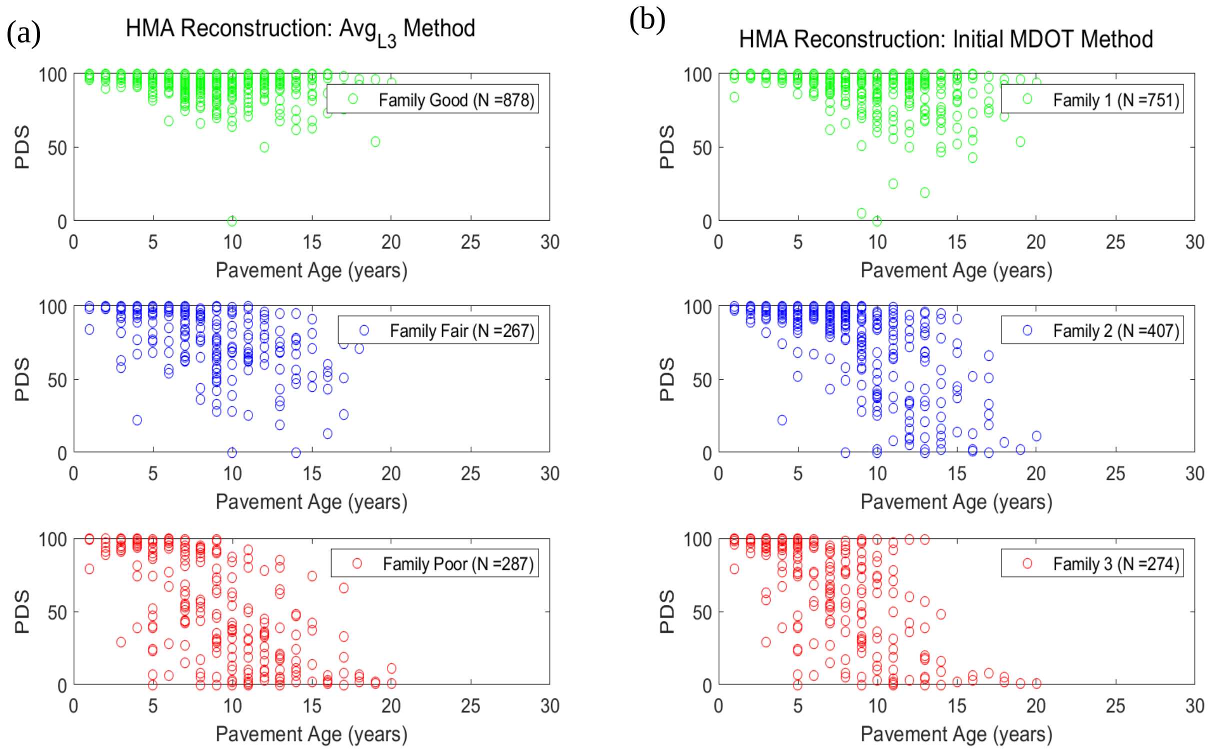
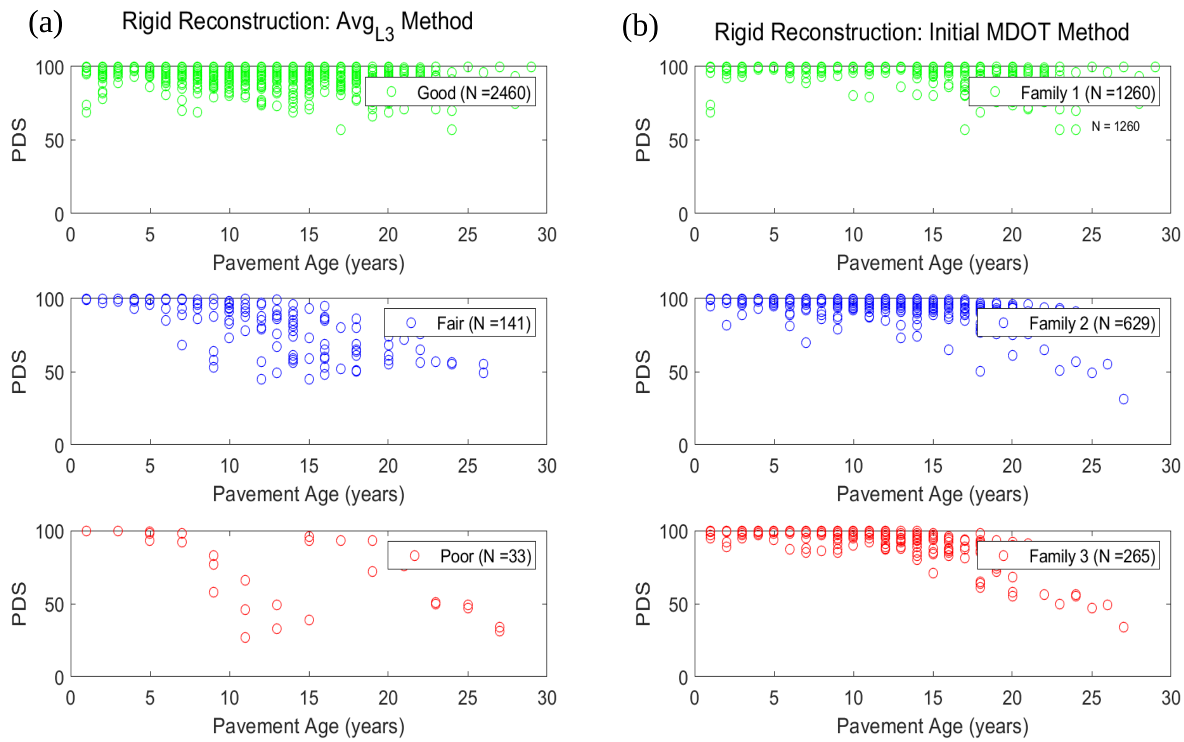


Figure 8.4 Distribution of different families based on (a) AvgL3 method and (b) MDOT DI-based method for rigid ‘reconstruction’ surface type



Note: "N" denotes the number of data points

Figure 8.5 Time series plots of three families based on (a) Avg$_{L3}$ method and (b) MDOT DI-based method for HMA 'reconstruction' surface type



Note: "N" denotes the number of data points

Figure 8.6 Time series plots of three families based on (a) Avg$_{L3}$ method and (b) MDOT DI-based method for Rigid 'reconstruction' surface type

8.3 Performance modeling for HMA PDS with Avg$_{L3}$ Families

In this section, performance modeling for HMA PDS with Avg$_{L3}$ families is discussed. By utilizing all four performance models, good reconstruction family and fair crush and shape family are shown as examples in Figure 8.7 and Figure 8.8, respectively. All other PDS performance curves for the flexible pavement with Avg$_{L3}$ families are attached in Appendix B.

For both cases outlined in this section, all performance models show low RMSE with reasonable R^2. From general observation of all flexible surface types with different families, NJDOT and logistic growth models show better goodness-of-fit statistics for flexible pavement modeling.

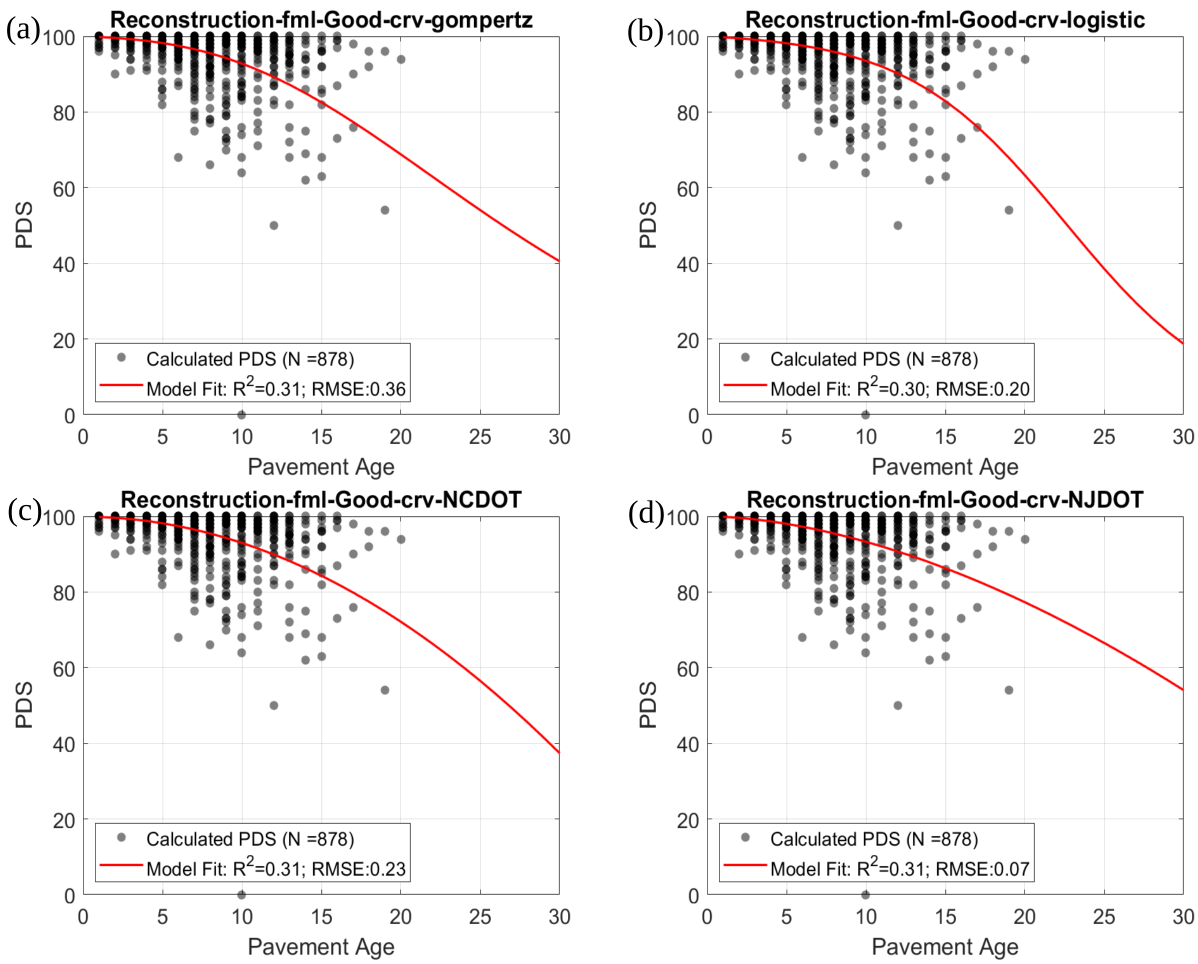


Figure 8.7 HMA reconstruction modeling for PDS with Avg_{L3} good family using: (a) Gompertz, (b) Logistic, (c) NCDOT, and (d) NJDOT models

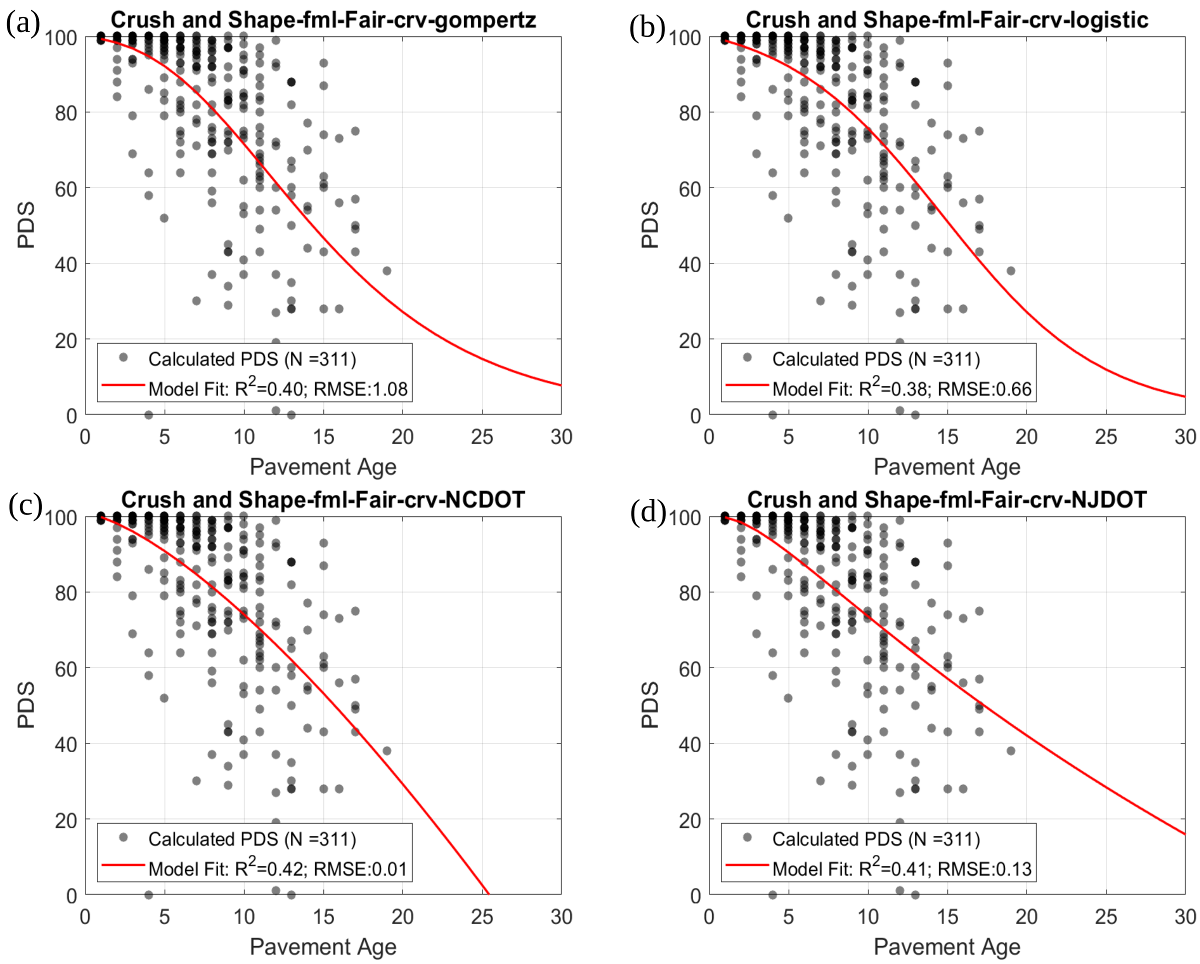


Figure 8.8 HMA crush and shape modeling for PDS with Avg_{L3} fair family using: (a) Gompertz, (b) Logistic, (c) NCDOT, and (d) NJDOT models

8.4 Performance modeling for Rigid PDS with Avg_{L3} Families

In this section, performance modeling for rigid PDS with Avg_{L3} families is presented. For illustration purposes, rigid reconstruction fair family and rigid unbonded good family are shown in Figure 8.9 and Figure 8.10, respectively. All other rigid pavement performance curves with Avg_{L3} families are attached in Appendix B.

As observed for both cases presented here, the NCDOT performance model gives a better deterioration curve with the highest R^2 and the least RMSE. However, other performance models are not too different regarding their goodness of fit statistics. In rigid pavement, general observation revealed that NCDOT and the logistic model could predict PDS better for all rigid family groups. This similar observation was also observed for rigid performance modeling with MDOT families, as discussed earlier.

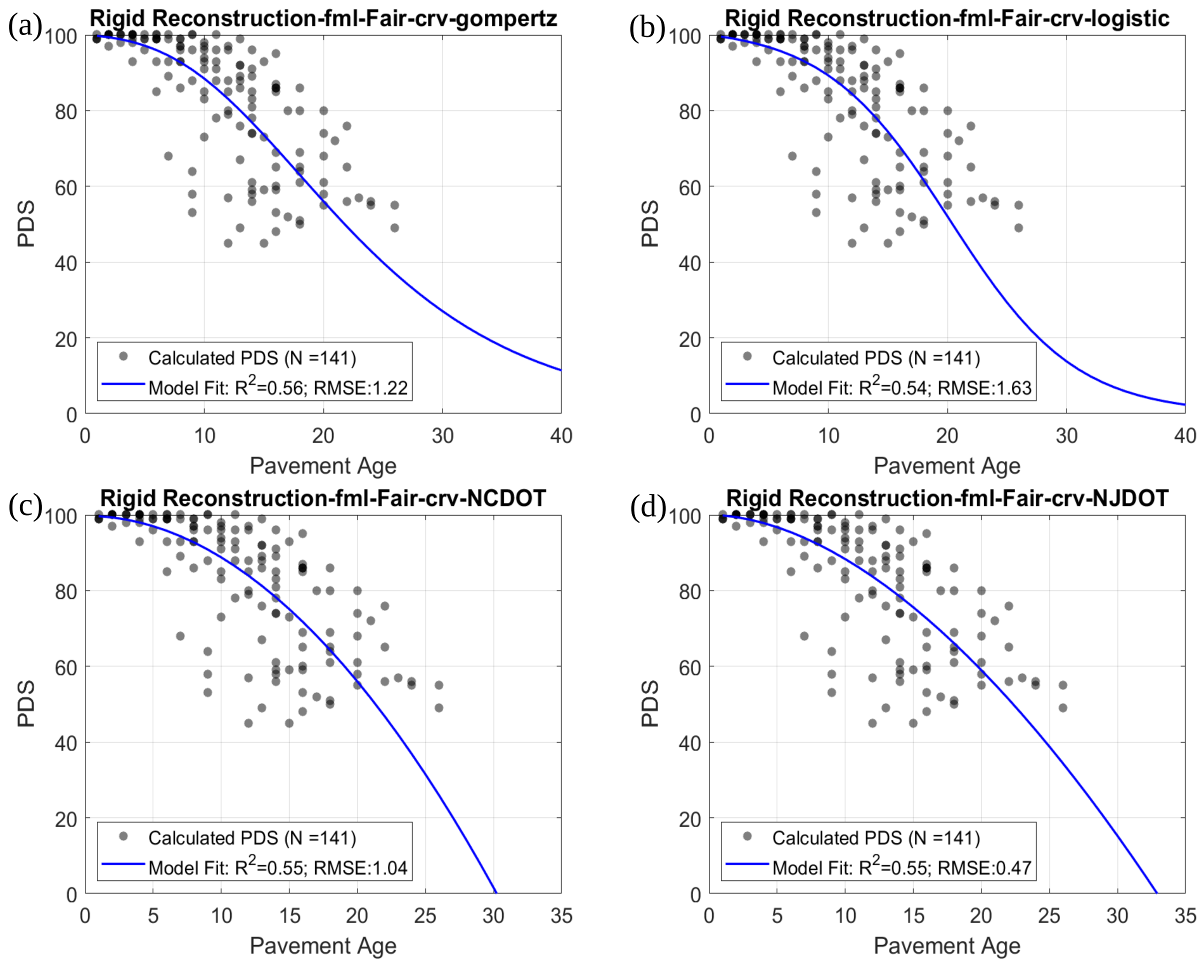


Figure 8.9 Rigid reconstruction modeling for PDS with Avg_{L3} fair family using: (a) Gompertz, (b) Logistic, (c) NCDOT and (d) NJDOT models

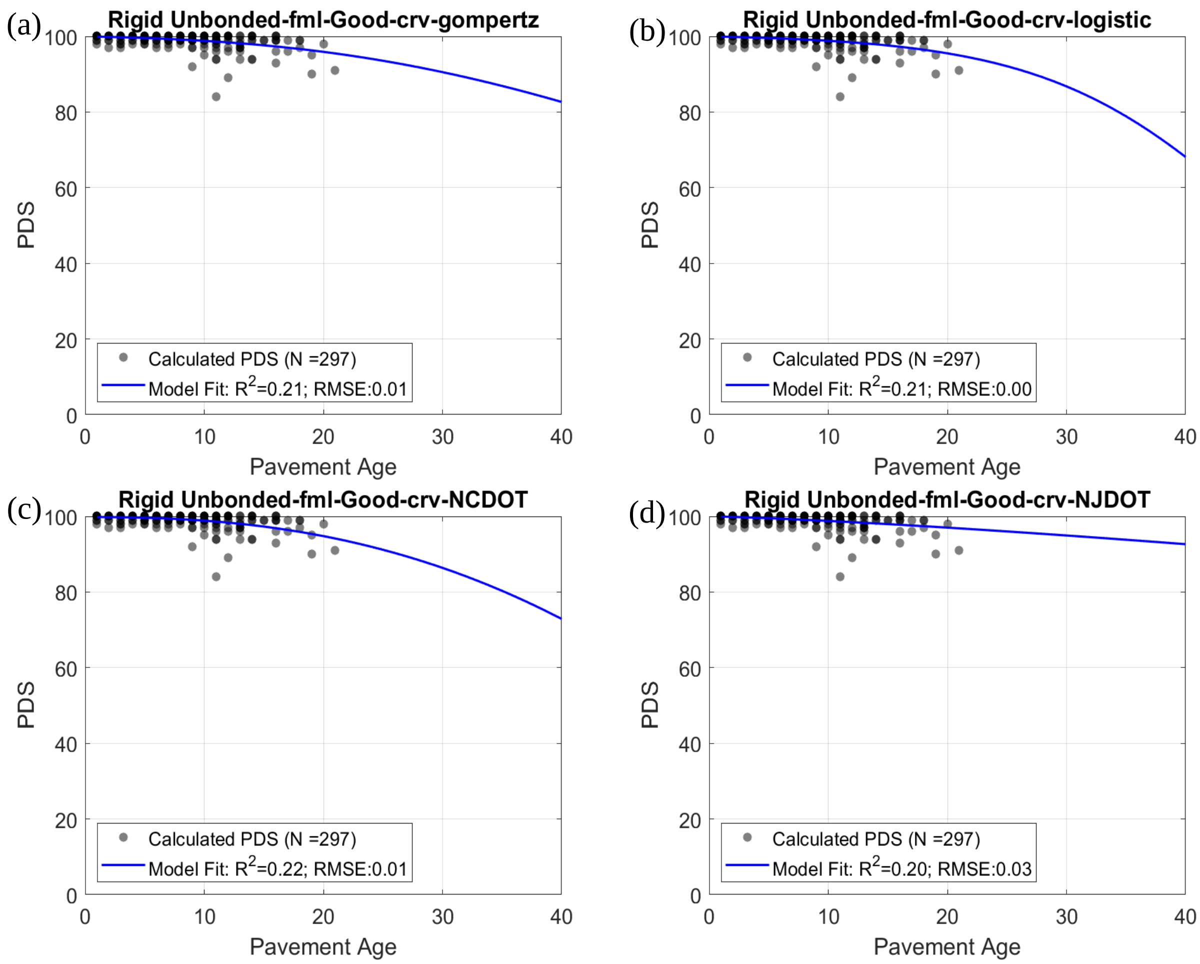


Figure 8.10 Rigid unbonded modeling for PDS with AvgL3 fair family using: (a) Gompertz, (b) Logistic, (c) NCDOT, and (d) NJDOT models

8.5 Fix Life Estimation for PDS with Avg$_{L3}$ Families

This section describes the fix life estimation for PDS with Avg$_{L3}$ families. Table 8.1 presents the total pavement section length for good, fair, and poor family groups for all asphalt and rigid pavement surface types.

In the previous section, it was demonstrated that the Avg$_{L3}$ method, NJDOT, and logistic growth model provide a good fit for all surface types and pavement families. Therefore, these models generated composite curves for all flexible pavement families. Figure 8.11 and Figure 8.12 depict the individual family curves and composite curves for crush and shape, reconstruction, 2-course overlay, and rubblize with the NJDOT and logistic growth model. Additionally, the fix life for each surface type is reported when the PDS composite curve reaches a threshold value of 50, and the calculation is based on the years since the pavement was opened to traffic.

Table 8.1 Total section length for the PDS-based Avg_{L3} families

Surface Type	**Asphalt Pavement Families**		
	Good (miles)	**Fair (miles)**	**Poor (miles)**
Crush and Shape	1105	174	62
Reconstruction	283	130	50
2-Course overlay	921	963	293
Rubblize	371	52	9
Surface Type	**Rigid Pavement Families**		
	Good (miles)	**Fair (miles)**	**Poor (miles)**
Reconstruction	1379	53	14
Unbonded	268	1.4	0

Likewise, the NCDOT and logistic growth model were suitable for all rigid surface types and pavement families. Consequently, composite curves were developed for all rigid pavement families using these models. The composite curve for rigid reconstruction and rigid unbonded with the NCDOT and logistic growth model is displayed alongside the curves for all rigid pavement families in Figure 8.13 and Figure 8.14. Table 8.2 presents the fix life of each surface type of flexible and rigid pavement calculated from the composite curves mentioned above. Moreover, in Table 8.2, MDOT's current fix life for these pavement types is reported as well. Compared to fix lives of asphalt pavements with MDOT families, it can be observed that PDS with the Avg_{L3} families provides lower fix-life values for NCDOT and NJDOT models. However, for logistic and Gompertz models, it is the opposite as with the Avg_{L3} method, PDS show higher fix lives than those with the MDOT families. One probable reason for this discrepancy could be the typical S-shape deterioration curves for logistic and Gompertz models. As these two performance curves approach the later life of a pavement, the deterioration curve looks fattened, which as a result, can take a longer time to reach the specified PDS threshold.

On the other hand, for rigid pavement, a similar observation can also be noticed that NCDOT and NJDOT models give significantly lower fix lives compared to those with logistic and Gompertz models.

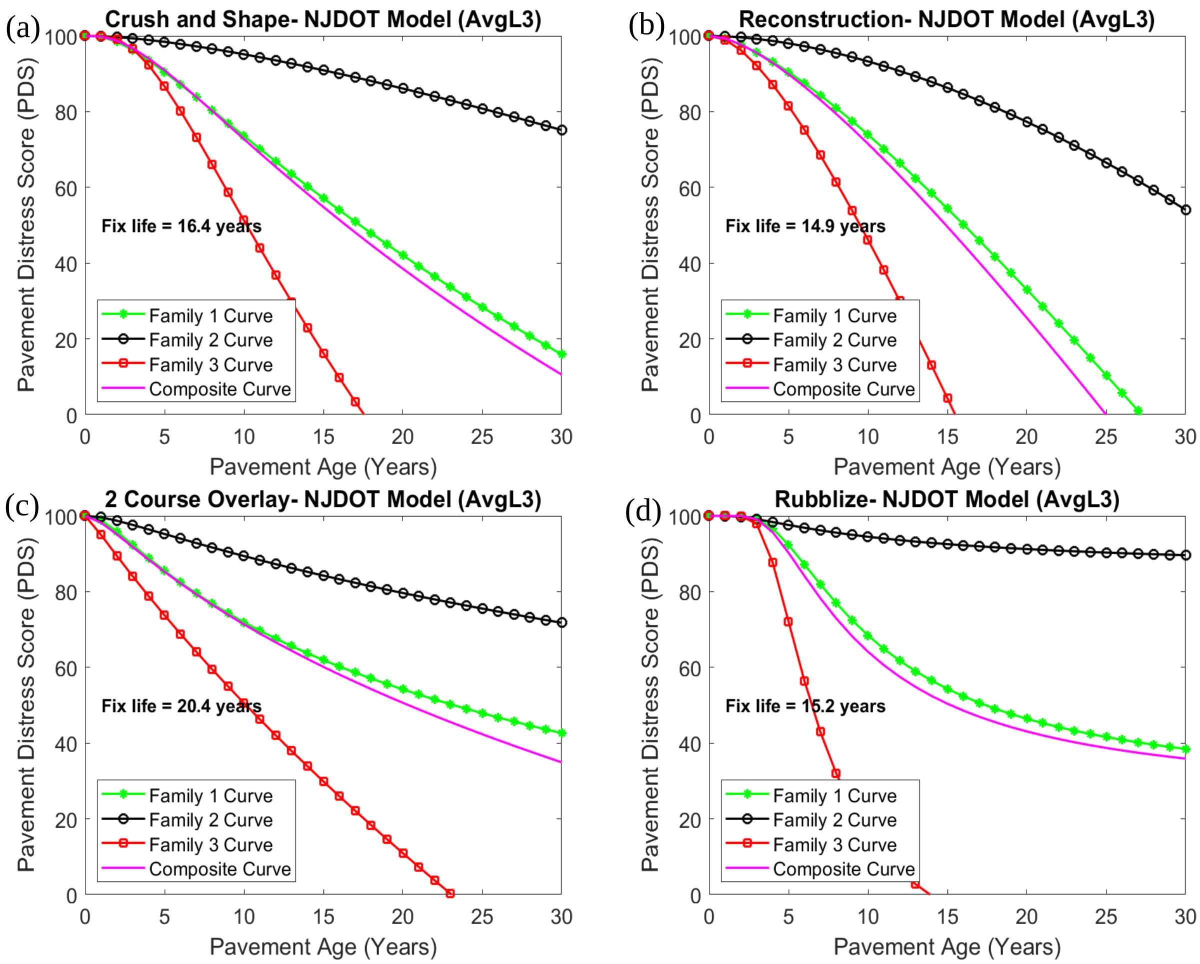


Figure 8.11 HMA PDS composite curves with Avg_{L3} families using the NJDOT growth model for (a) crush and shape, (b) reconstruction, (c) 2-course overlay, and (d) rubblize

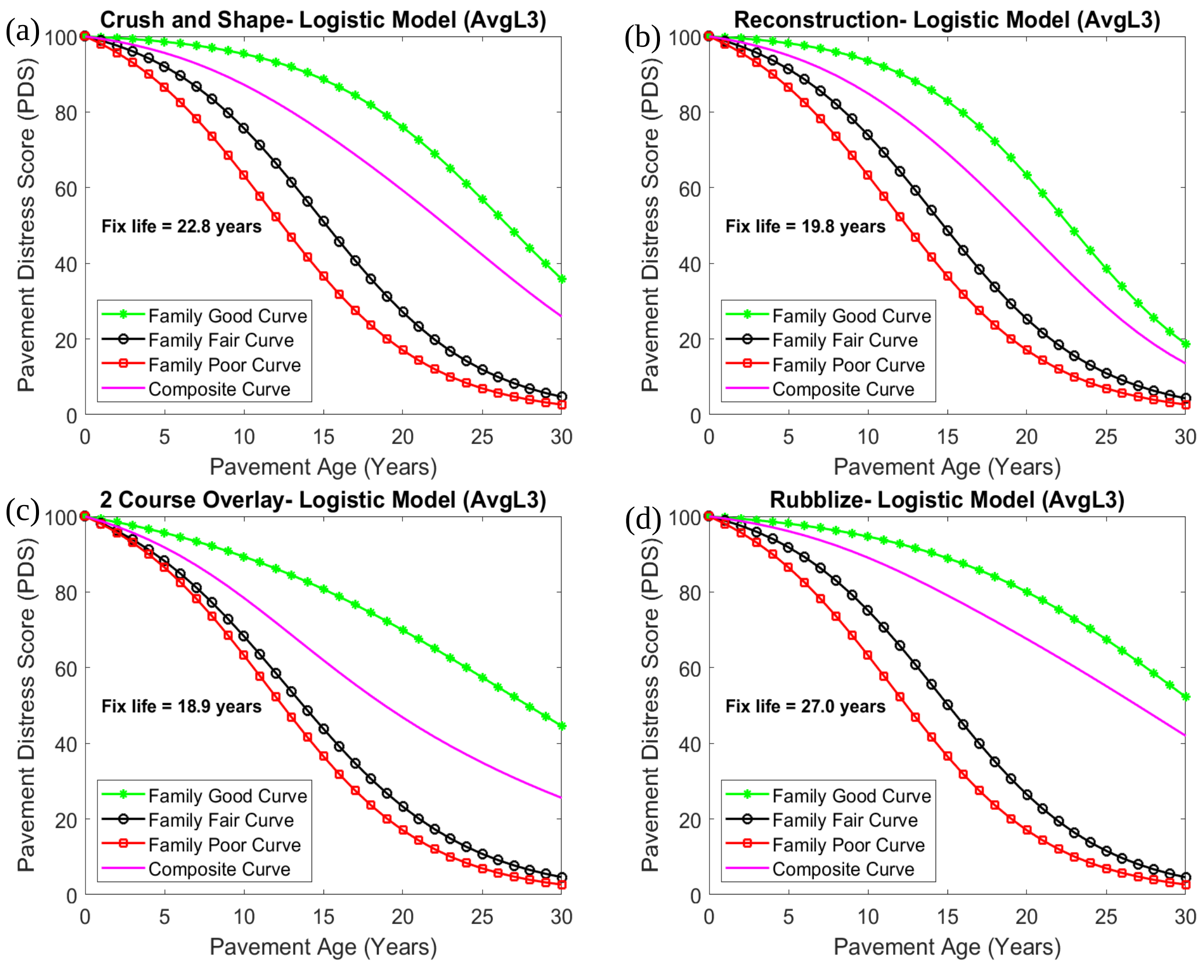


Figure 8.12 HMA PDS composite curves with Avg_{L3} families using the logistic growth model for (a) crush and shape, (b) reconstruction, (c) 2-course overlay, and (d) rubblize

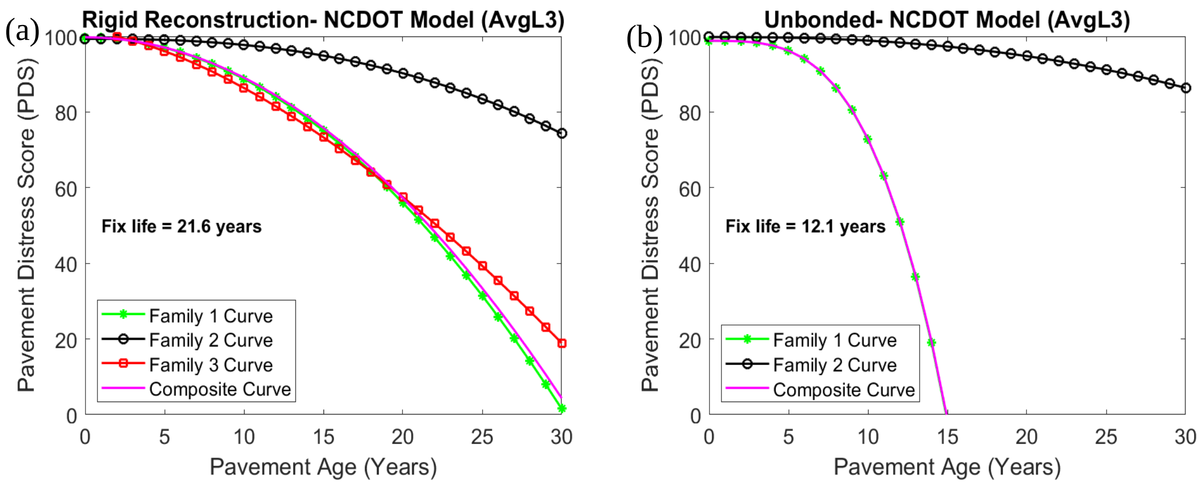


Figure 8.13 Rigid composite curves with Avg_{L3} families using the NCDOT growth model for (a) reconstruction and (b) unbonded

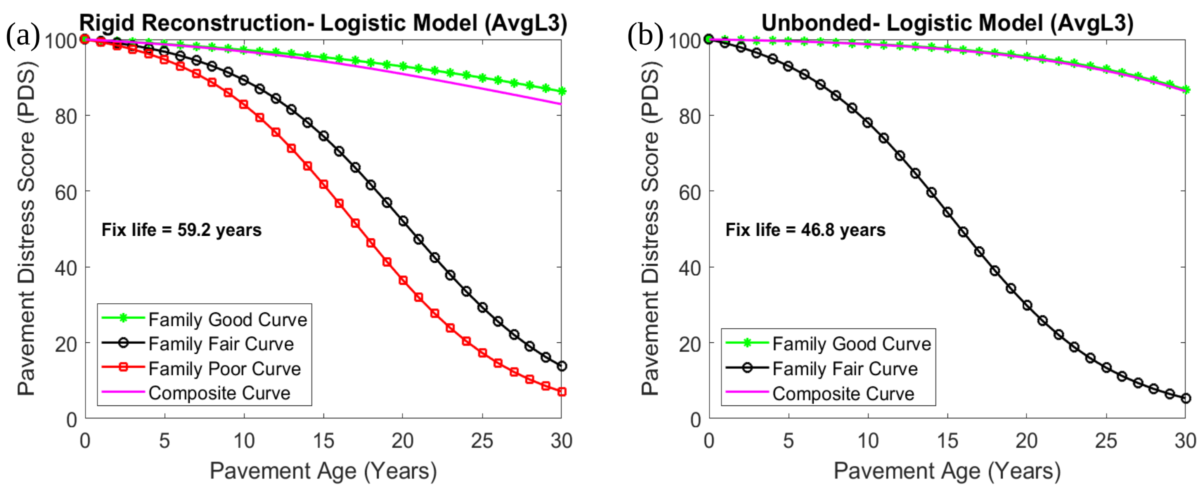


Figure 8.14 Rigid composite curves with Avg_{L3} families using the logistic growth model for (a) reconstruction and (b) unbonded

Table 8.2 Fix life using PDS composite curves with Avg_{L3} families

Models	**Asphalt Pavement**				**Rigid Pavement**	
	Crush & Shape	**HMA Recon**	**2-Course Overlay**	**Rubblize**	**Concrete Recon**	**Unbonded**
NJDOT	16	15	20	15	23	13
NCDOT	15	14	18	11	22	12
Logistic	23	20	19	27	59	47
Gompertz	25	21	20	29	80	71
MDOT Current (DI-based)	19	18	18	16	26	19

9. IRI PERFORMANCE MODELING

In this chapter, International Roughness Index (IRI) performance modeling and fix-life estimation are outlined. As noted before, PDS does not include sensor data (e.g., IRI, rutting). Therefore, these sensor data are analyzed separately to get their performance over time and calculate pavement fix life based on individual parameters. This will allow MDOT to make effective maintenance decisions by knowing the parameter which governs their fix life estimation.

In order to perform IRI modeling, raw IRI data was first cleaned by considering all 0.1-mile segments where there is no bridge or rail track, and the survey van did not stop maintaining its speed greater than 40 mph. Then average IRI for the whole section length was extracted for those MDOT-classified pavement families based on DI. It is important to note that sensor data is available from 1998 through 2019, whereas the PMS database is available from 1992. Therefore, in some pavement family groups, the not exact number of PDS data and IRI data are available.

Four different performance models were used to fit measured IRI data. Due to a lack of data sources related to past MDOT traffic, pavement structural parameters, soil parameters, and climatic conditions, only a few IRI models could be found in the literature, which is a function of pavement age only.

Maher et al. developed a sigmoidal increasing IRI model for the New Jersey Department of Transportation (NJDOT) [31]. The model is presented in Equation 9.1. Hereafter, this model is named as NJDOT IRI model. Suleiman et al. [40] developed an IRI model for the Dubai road network. Using this model, the researchers could get a reasonable correlation between the predicted and measured IRI data. This model, shown in Equation 9.2, is named as Dubai IRI model. Khattak et al. [60] proposed a performance model for pavement condition index as a function of pavement age. The original condition index model was modified and presented in Equation 9.3. The world bank used a simpler IRI power model in their HDM4 program. This model (Equation 9.4) was also slightly modified in this study by incorporating the initial IRI term. This model is called as IRI power model.

$$\mathrm{IRI}_{\mathrm{NJmodel}} = \mathrm{IRI}_0 + e^{(A - B \times C^{\ln(t)})} \qquad 9.1$$

$$IRI_{Dubaimodel} = A \times e^{(B \times t)} \quad 9.2$$

$$IRI_{rev.Louisiana} = IRI_0 + C \times e^{(\frac{B}{A} \times t^A)} \quad 9.3$$

$$IRI_{Powermodel} = IRI_0 + A \times t^B \quad 9.4$$

where,

IRI_0 = initial IRI at age zero (70 inch/mile),

t = pavement age since the last rehabilitation/construction activity, and

A, B, and C = model coefficients

It is to be noted that MATLAB's built-in function genetic algorithm (GA) was used to obtain IRI model coefficients. The genetic algorithm was used to minimize the absolute difference between the measured IRI and the predicted IRI for each model. In this process, at first, an initial set of coefficients were set, then with a large range of coefficient boundary, the genetic algorithm searched for the optimum coefficient set for each model and individual pavement families. It is worth to note in this GA application, population and generation were selected as 3000 and 500, respectively.

9.1 Performance modeling for HMA IRI with MDOT families

Similar to the PDS performance modeling approach, IRI performance curves were initially constructed with MDOT families. Figure 9.1 and Figure 9.2 show IRI performance model curves for reconstruction and crush & shape pavement type for all family groups. For brevity, 2-course overlay and rubblized surface-type pavement modeling with IRI data are shown in Appendix C. The coefficient of determination (R^2) was also reported for each model on these plots. It is noticed that measured IRI data does not follow an increasing trend; rather, it is scattered all over the plots. As MDOT classified their pavement families according to DI trends, these families are not represented well in terms of IRI data. Therefore, to get a better model, a new set of families should be established based on measured IRI data.

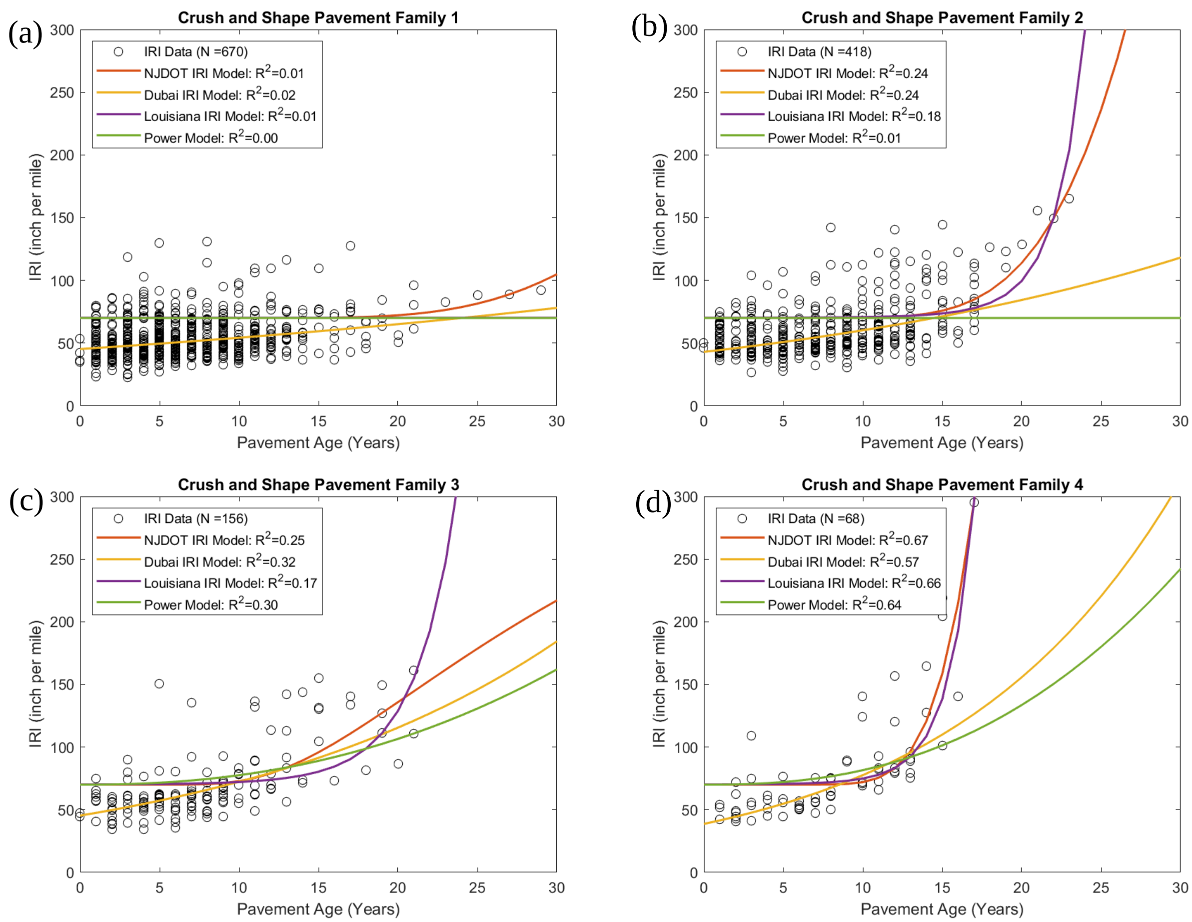


Figure 9.1 HMA crush and shape modeling for IRI data with MDOT families: (a) Family 1, (b) Family 2, (c) Family 3, and (d) Family 4

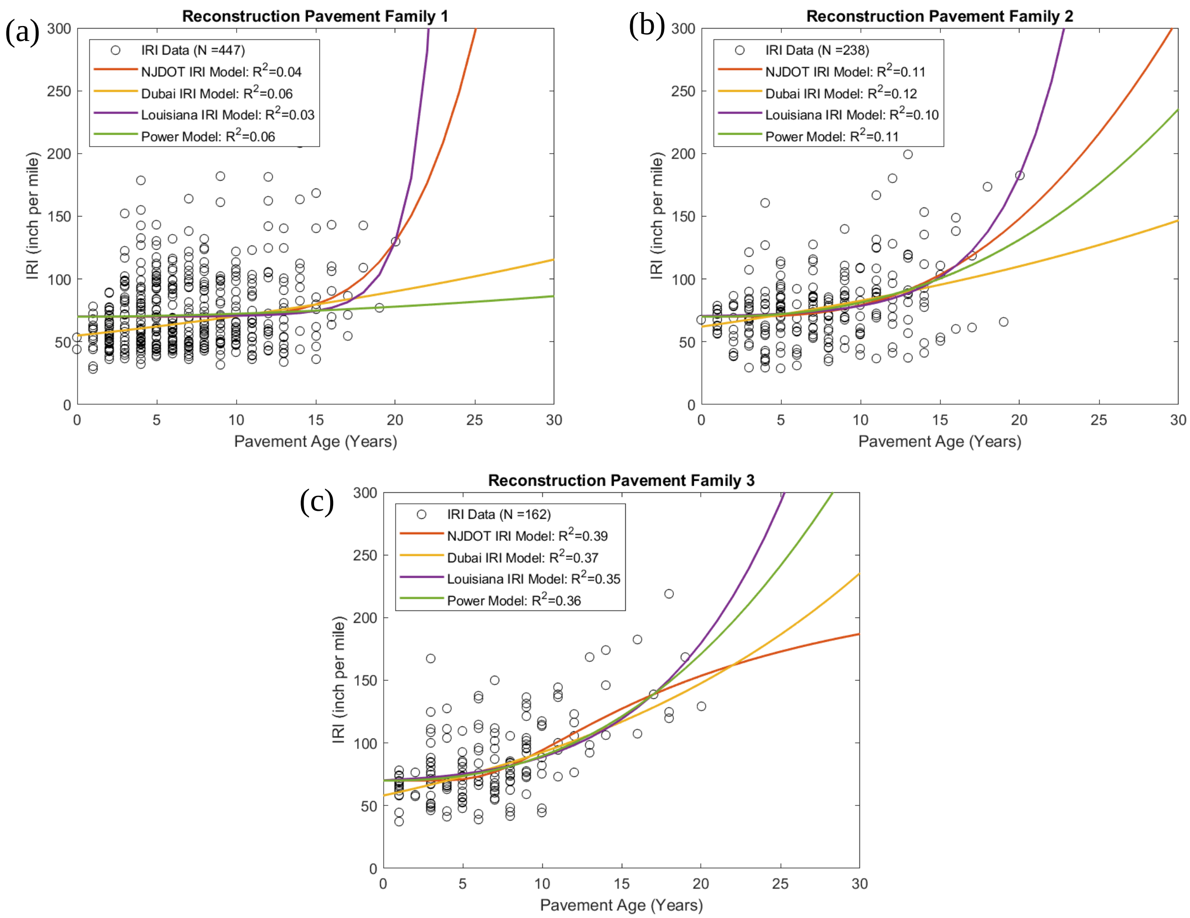


Figure 9.2 HMA reconstruction modeling for IRI data with MDOT families: (a) Family 1, (b) Family 2, and (c) Family 3

9.2 Performance modeling for rigid IRI with MDOT families

Figure 9.3 and Figure 9.4 present rigid IRI model fits for all four models for rigid reconstruction and unbonded PCC overlay, respectively. In rigid IRI modeling, a poor correlation between the measured IRI and predicted IRI was observed for each model. The need for new families based on IRI is also clear for rigid pavements.

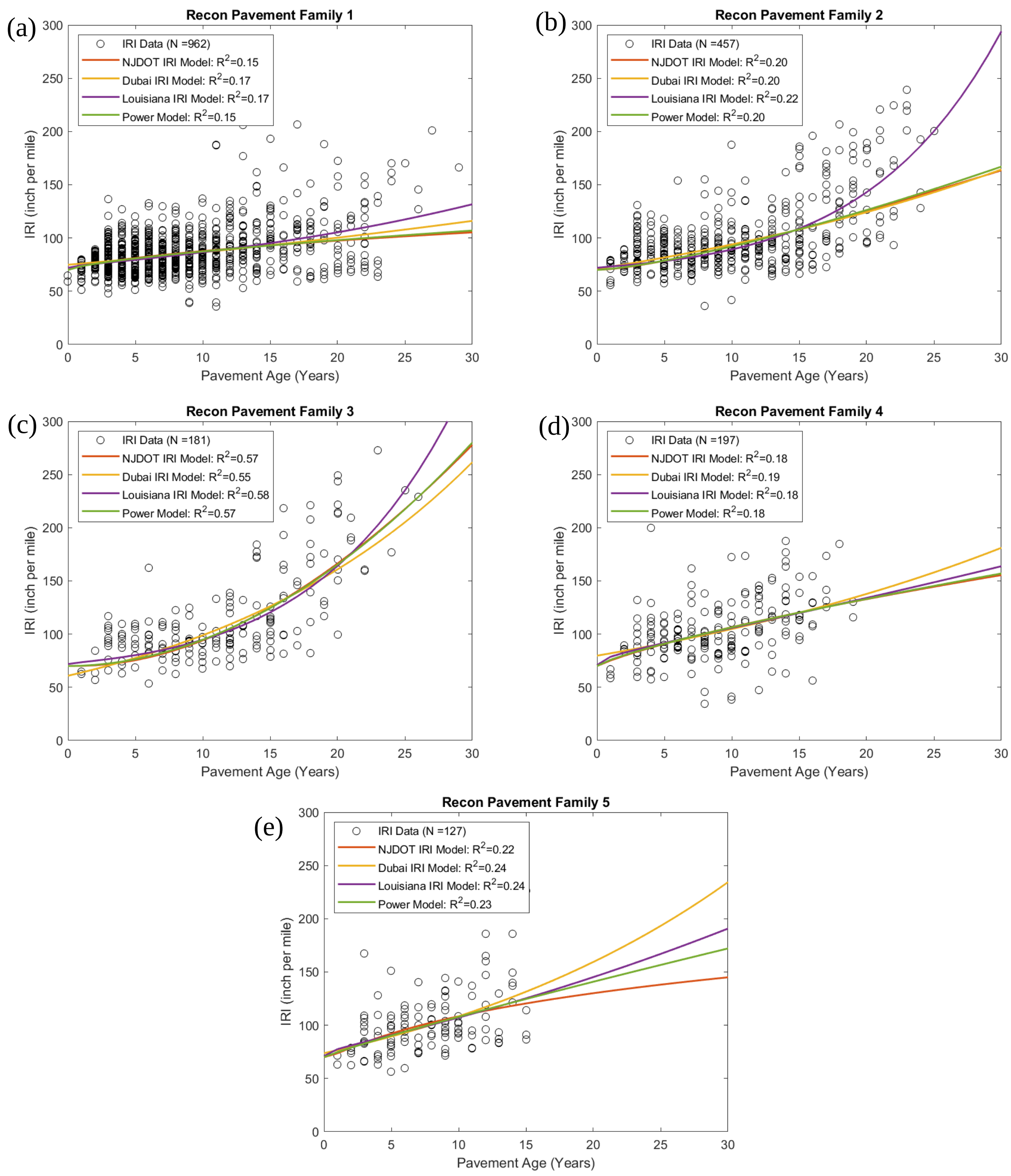


Figure 9.3 Rigid reconstruction modeling for IRI data with MDOT families: (a) Family 1, (b) Family 2, (c) Family 3, (d) Family 4, and (e) Family 5

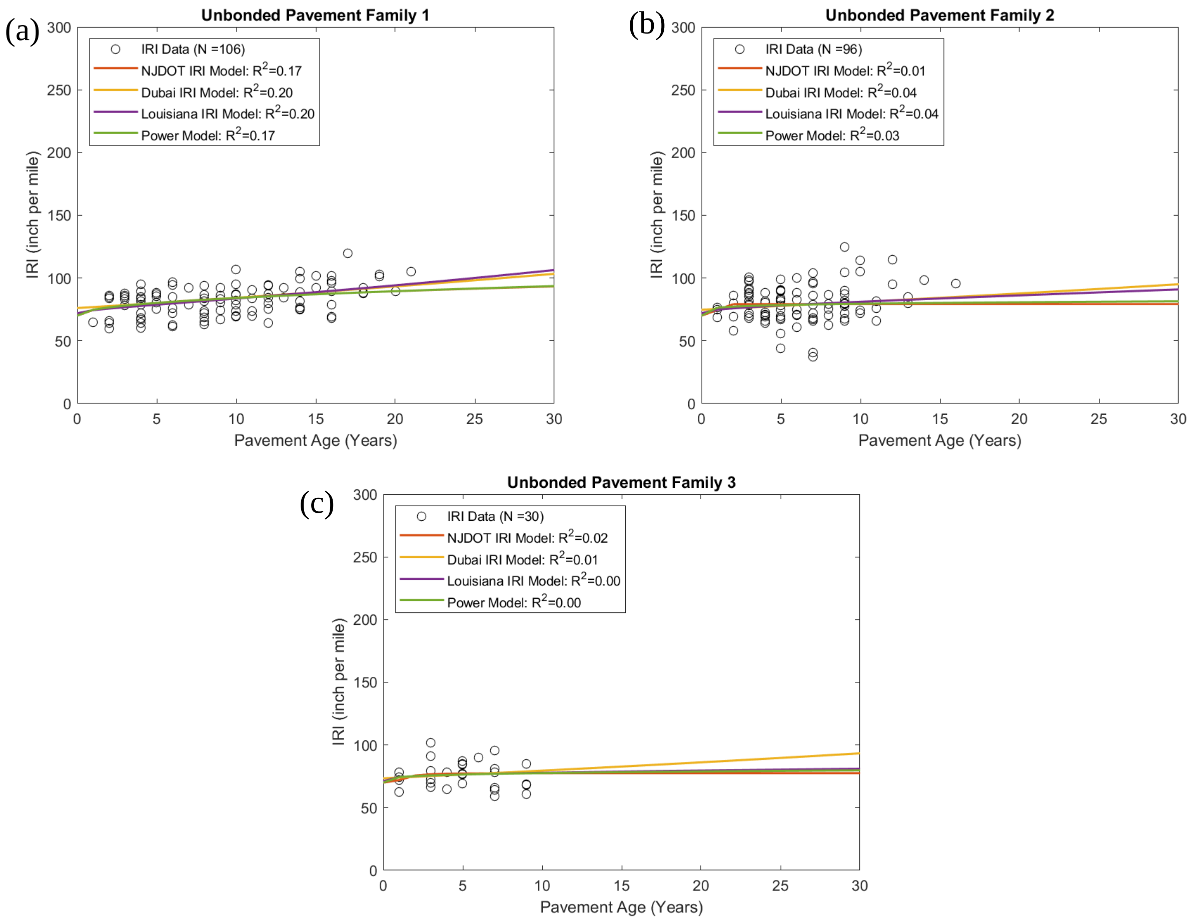
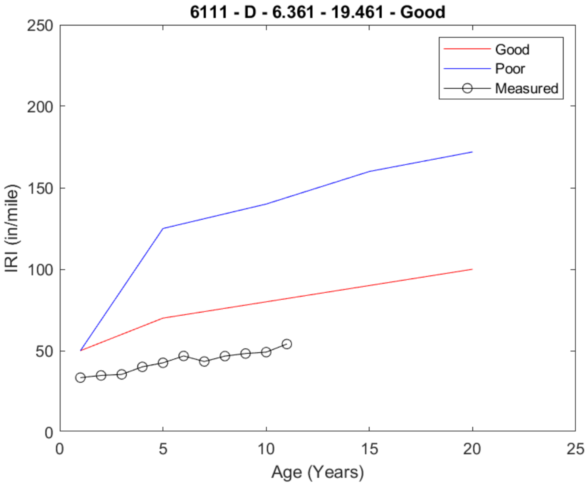


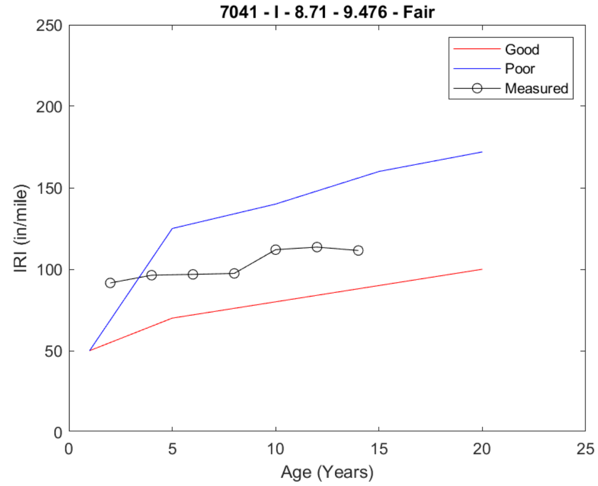
Figure 9.4 Rigid unbonded modeling for IRI data with MDOT families: (a) Family 1, (b) Family 2, and (c) Family 3

9.3 New families based on IRI for flexible pavements

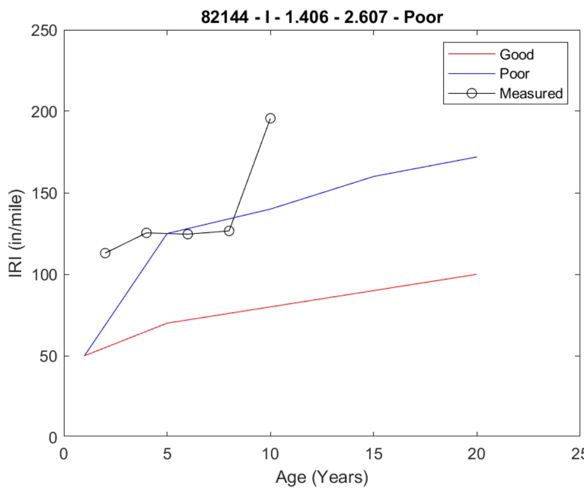
In this section, the FHWA criteria, as mentioned before in Chapter 8, have been utilized to group pavements based on IRI. The procedure involved plotting a time series trend for each section and comparing it with recommended reference lines. Based on the position of the measured IRI points, the sections were categorized as either good, fair, or poor. A section performing below the good line was classified as a good-performing section, while a section above the poor line was classified as a poor-performing section. Sections falling between the good and poor lines were classified as fair-performing sections. In cases where the performance trend passed through more than one category zone, the category with the maximum number of points was selected. Additionally, in situations where two different categories had an equal number of points, the low-performance category was selected. Figure 9.5 provides examples of good, fair, and poor categories for flexible sections.



Good performing section



Fair performing section



Poor performing section

Figure 9.5 Illustration of categorizing pavement sections based on IRI trends for flexible sections (FHWA criteria)

Once each section was categorized into good, fair, and poor sections, respectively, they were compared with the MDOT families. Figure 9.6 shows histograms of percentages of each category based on FHWA criteria and MDOT families. It can be observed that the distribution between the two histograms is comparable.

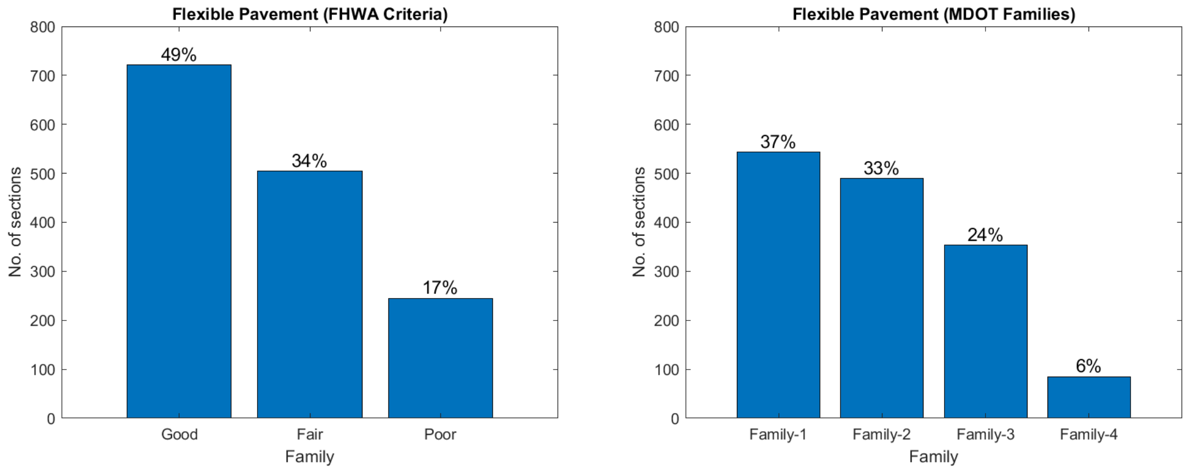
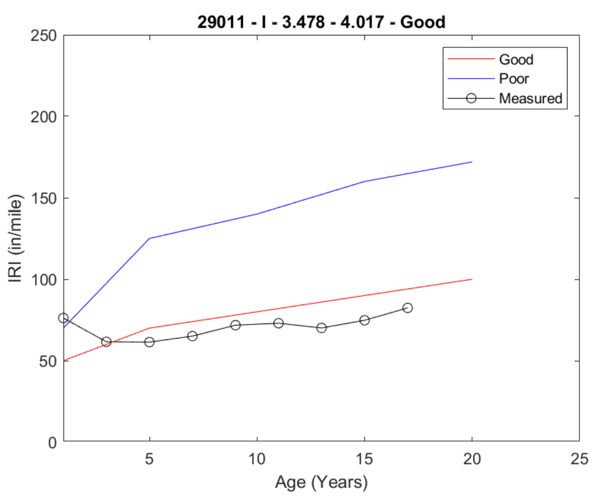


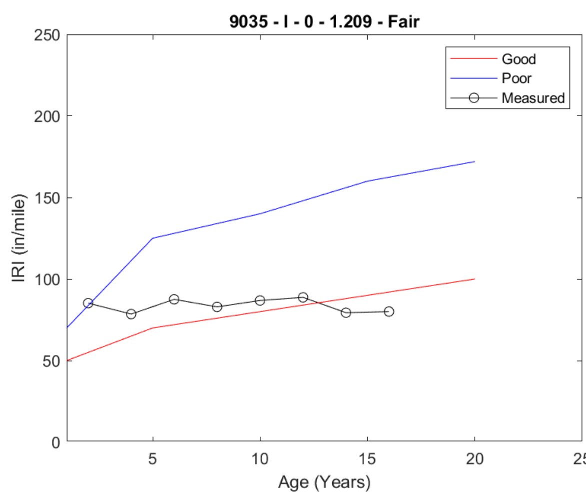
Figure 9.6 Histogram showing the distribution of different categories for flexible sections

9.4 New families based on IRI for rigid pavements

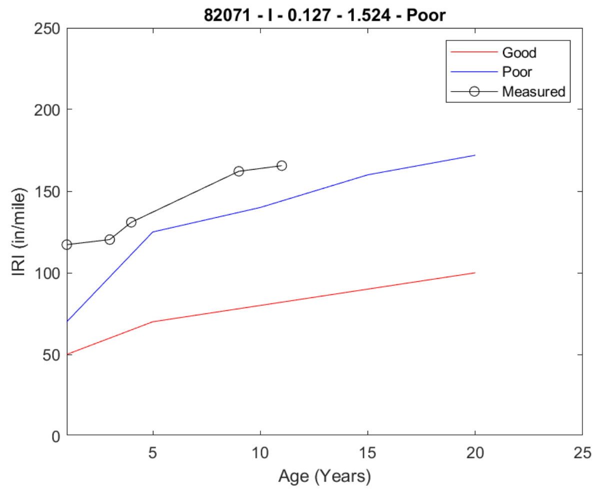
Similar to the flexible sections, rigid sections were also classified into good, fair, and poor categories based on IRI. Figure 9.7 shows example sections for good, fair, and poor categories for rigid sections.



(a) Good performing section



(b) Fair performing section



(c) Poor performing section

Figure 9.7 Illustration of categorizing pavement sections based on IRI trends for rigid sections (FHWA criteria)

Figure 9.8 shows histograms of percentages of each category based on FHWA criteria and MDOT families. Since the two criteria (FHWA and MDOT families) have a different number of categories, it is challenging to compare them. However, with the new family classification majority of pavements are classified as a fair category.

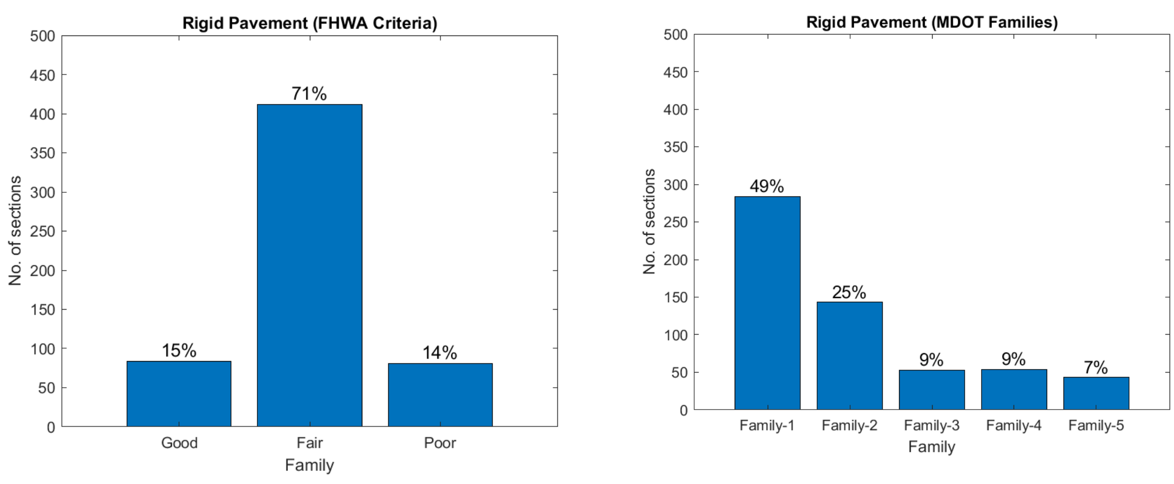


Figure 9.8 Histogram showing the distribution of different categories for rigid sections

9.5 *Performance modeling for HMA IRI data with new families*

Figure 9.9 and Figure 9.10 show IRI performance model curves for reconstruction and crush & shape pavement type for new family groups with the four models. 2-course overlay and rubblized surface-type pavement modeling with the new family are shown in Appendix C. It can be observed that the new family sets provide better IRI data trends with age, and each model could fit the trend better, especially for fair and poor-condition pavements. In the good pavement family, IRI values are clustered around the 40 to 70-inch/mile range, and over the years, IRI did not increase as observed in fair and poor family groups. Therefore, for the good family group, all four models could not predict better performance curves with reasonable R^2. Among the four models, the Dubai IRI model seems the best one with greater R^2.

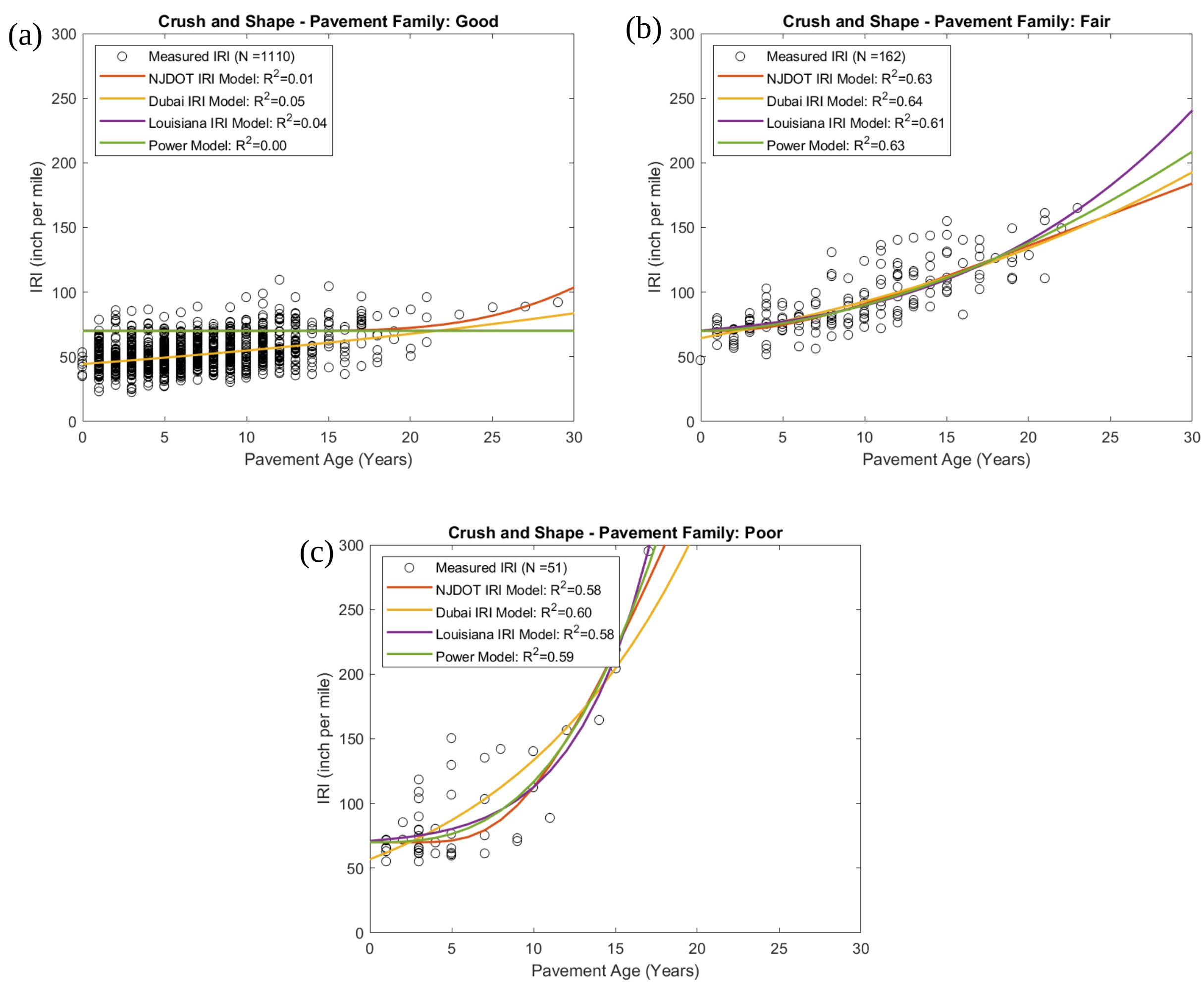


Figure 9.9 HMA crush and shape modeling for IRI data with new families: (a) good, (b) fair, and (c) poor

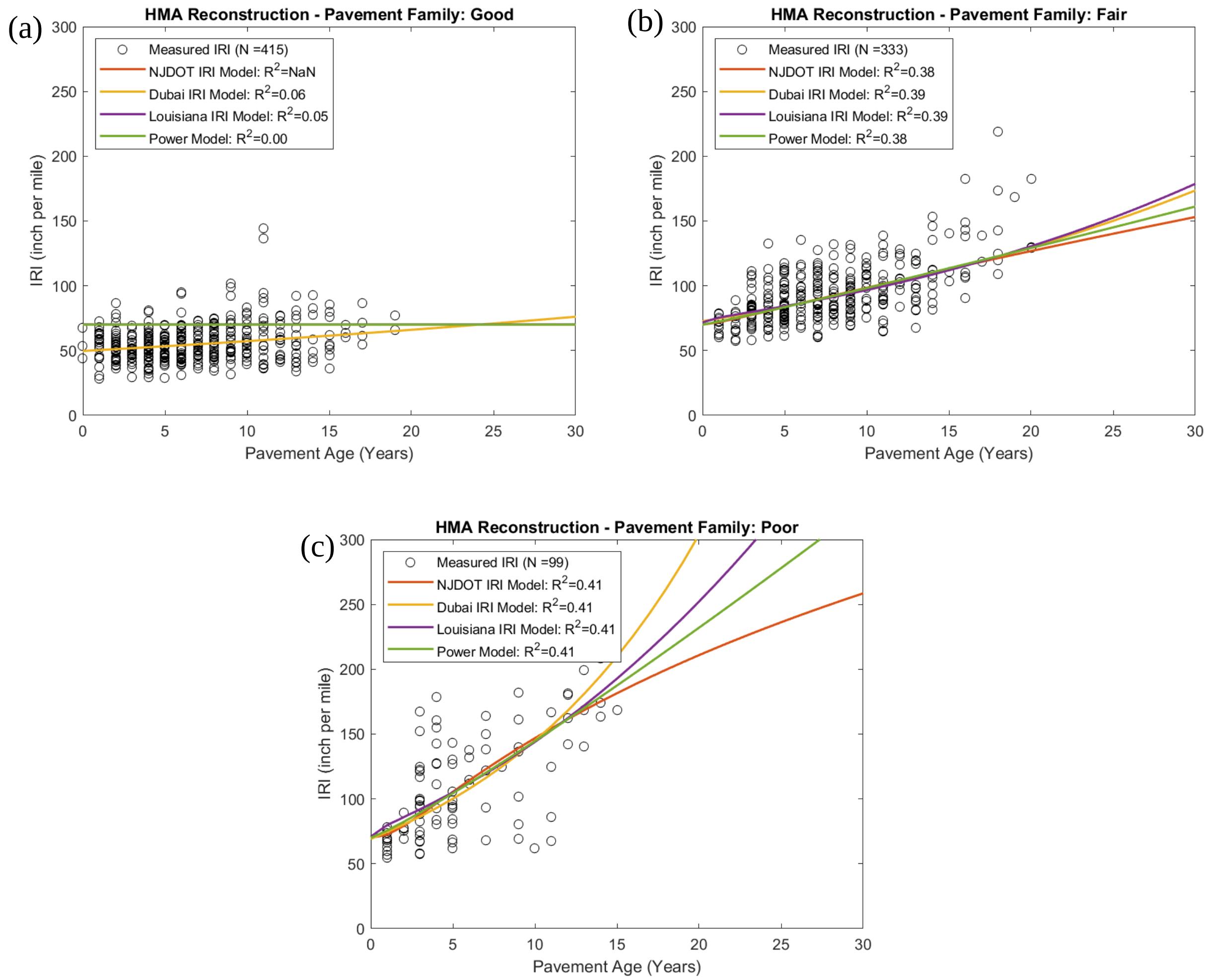


Figure 9.10 HMA reconstruction modeling for IRI data with new families: (a) good, (b) fair, and (c) poor

9.6 Performance modeling for rigid IRI data with new families

Figure 9.11 and Figure 9.12 show the IRI model curve fits for rigid reconstruction and rigid unbonded overlay with the new set of pavement families, respectively. Like flexible pavement, rigid good family groups also show a similar flat trend for all four performance models.

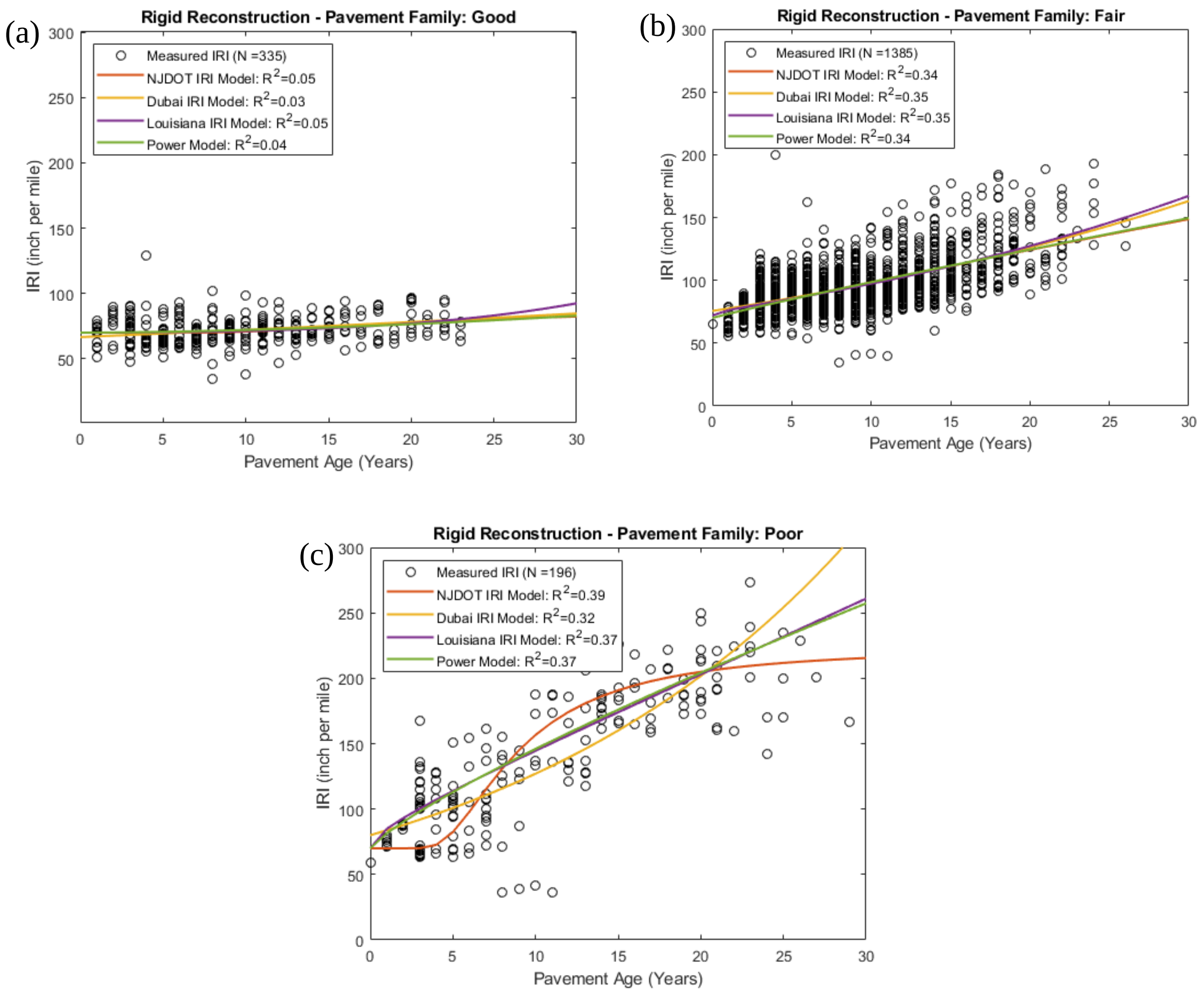


Figure 9.11 Rigid reconstruction modeling for IRI data with new families: (a) good, (b) fair, and (c) poor

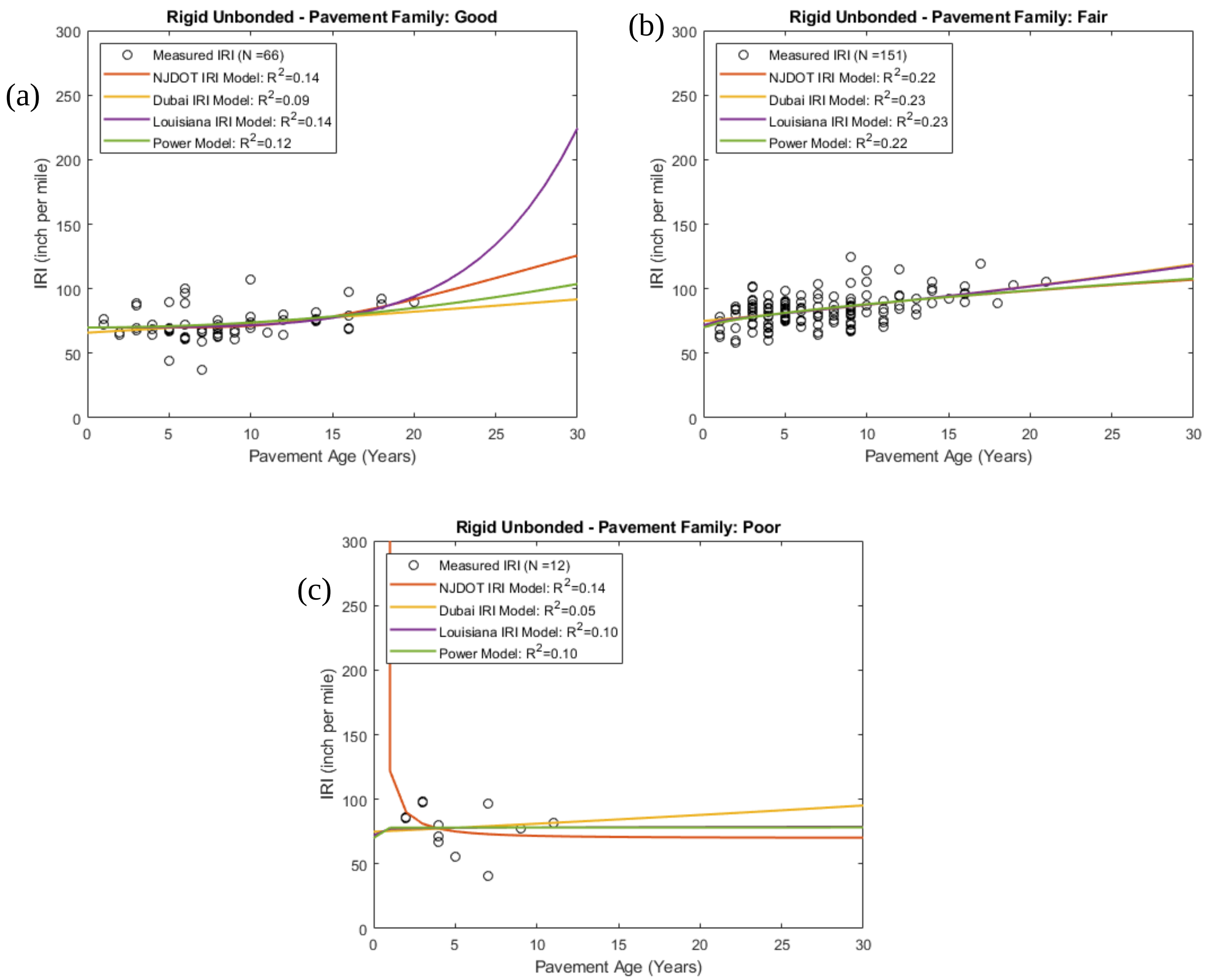


Figure 9.12 Rigid unbonded modeling for IRI data with new families: (a) good, (b) fair, and (c) poor

9.7 Fix Life Estimation for IRI with new families

To determine the fix life of different pavement types based on the International Roughness Index (IRI), a threshold must first be established to determine when major rehabilitation is necessary. To achieve this, maintenance boxplots for IRI were created for both HMA and rigid pavements, using IRI data collected just prior to light, medium, and major maintenance activities.

Figure 9.13 illustrates clear distinctions between the light, medium, and major maintenance groups. However, the magnitude of IRI in the rigid pavement boxplot was higher than in the flexible pavement boxplot for all three maintenance groups, indicating that MDOT's past maintenance decisions may have been influenced by IRI data.

Upon closer examination, it was found that for flexible pavement, around 25 percentiles of pavement had undergone major rehabilitation when the IRI data reached 140 inches/mile or higher. Conversely, for rigid pavement, the 50 percentile of pavement sections experienced major maintenance when IRI reached 150 inches/mile or higher. Thus, a threshold of 150 inches/mile may be suitable for calculating the IRI-based fix life of both rigid and HMA pavements.

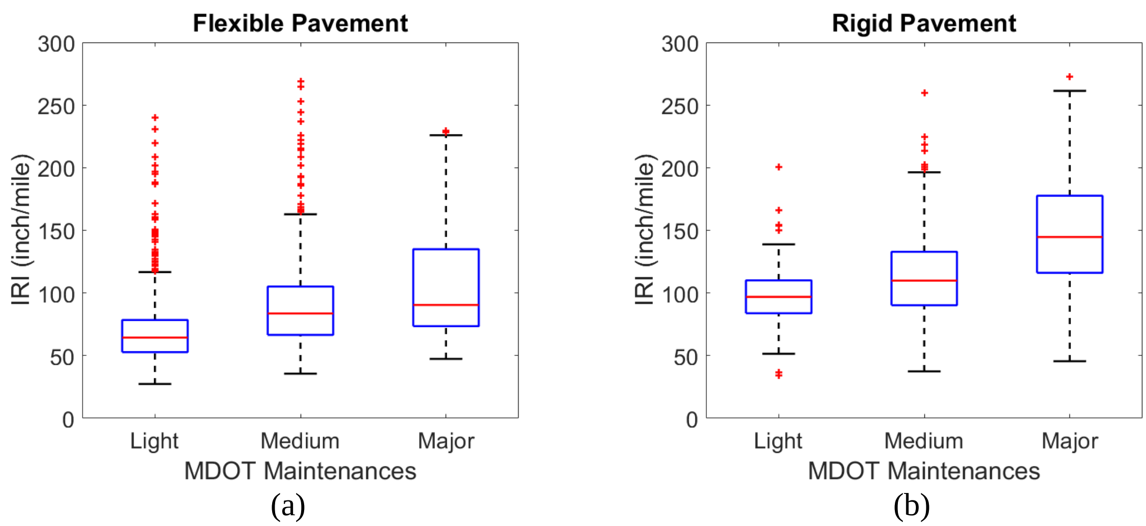


Figure 9.13 Box plots showing MDOT maintenance records with corresponding IRI for (a) flexible and (b) rigid sections

It is noted that based on new IRI families (i.e., good, fair, and poor), the total section length for each family case was recalculated, as shown in Table 9.1.

Table 9.1 Total section length for the new category of pavement families

Surface Type	**Asphalt Pavement Families**		
	Good (miles)	**Fair (miles)**	**Poor (miles)**
Crush and Shape	1104.8	173.8	62.2
Reconstruction	283.1	129.5	50.2
2-Course overlay	921.2	963.1	293.2
Rubblize	370.5	52	9.3
Surface Type	**Rigid Pavement Families**		
	Good (miles)	**Fair (miles)**	**Poor (miles)**
Reconstruction	216.8	982.0	164.8
Unbonded	46.0	185.4	22.8

Similar to PDS fix life estimation, composite curves were constructed to calculate fix lives for each surface type using different models. Fix life results are presented in Table 9.2. The IRI threshold was determined as 150 inches/mile. It can be observed that the Dubai IRI model predicts reasonable fix life, and it is comparable with MDOT's current DI-based fix life for different surface types. In general, the NJDOT IRI and the power IRI models gave unrealistic fix lives for both pavement types. Multiple models can give MDOT the flexibility to choose the optimum fix life they may think is reasonable.

For illustration purposes, in Figure 9.14 and Figure 9.15, composite curves alongside individual family curves with the Dubai IRI model are shown for different surface types of flexible and rigid pavement, respectively.

Table 9.2 Fix lives based on new families of IRI (threshold = 150 inch/mile)

Model	**Fix Life (years) - IRI**					
	Asphalt Pavement				**Rigid Pavement**	
	Crush & Shape	**HMA Recon**	**2-Course Overlay**	**Rubblize**	**Concrete Recon**	**Unbonded**
NJDOT IRI Model	32	70	85	200	191	53
Dubai IRI Model	34	28	23	25	37	67
Revised Louisiana Model	26	35	26	31	41	29
IRI Power Model	31	44	35	52	52	51
MDOT Proposed	19	18	18	16	26	19

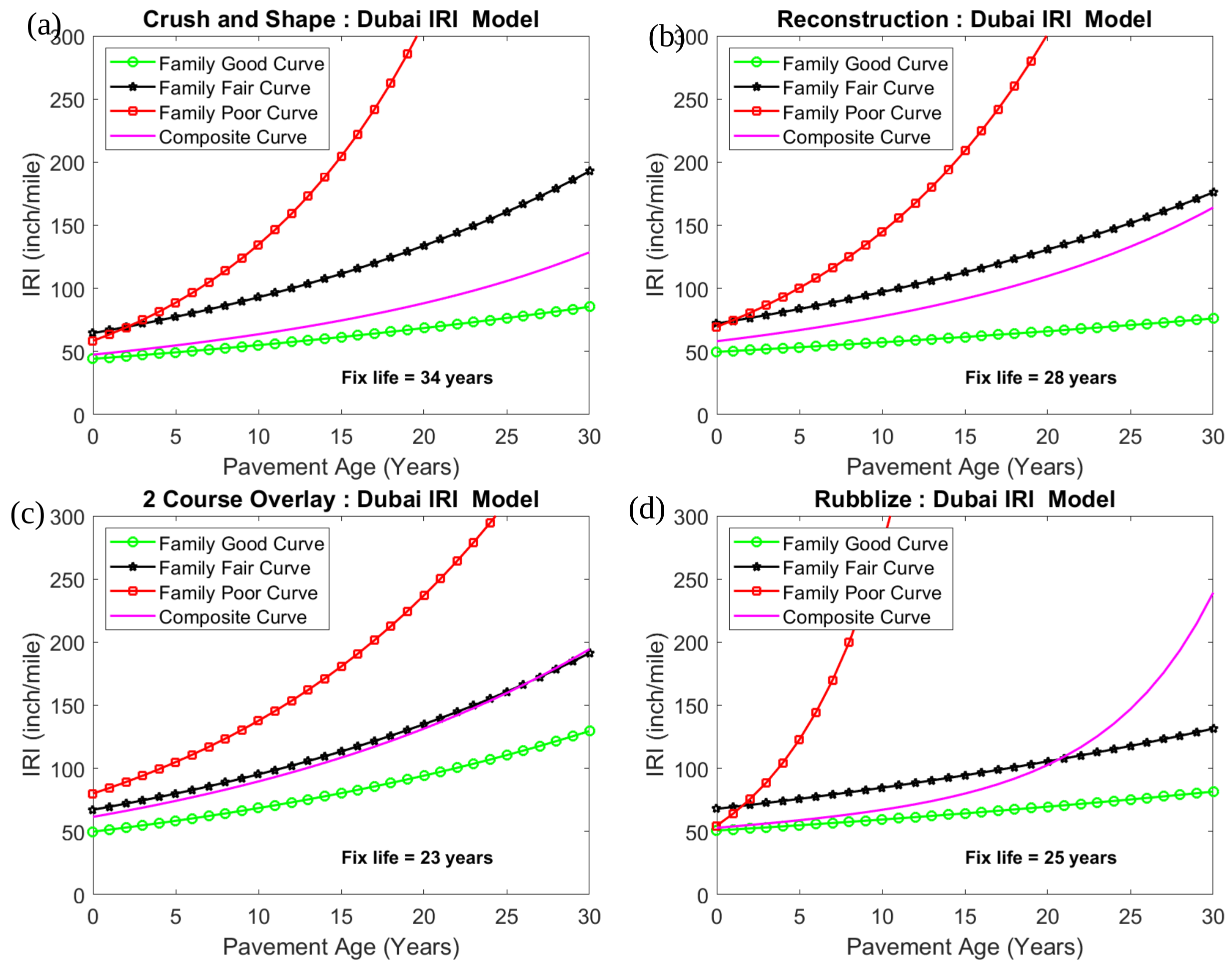


Figure 9.14 Rigid composite curves for IRI data with new families: (a) crush and shape, (b) reconstruction, (c) 2-course overlay, and (d) rubblize

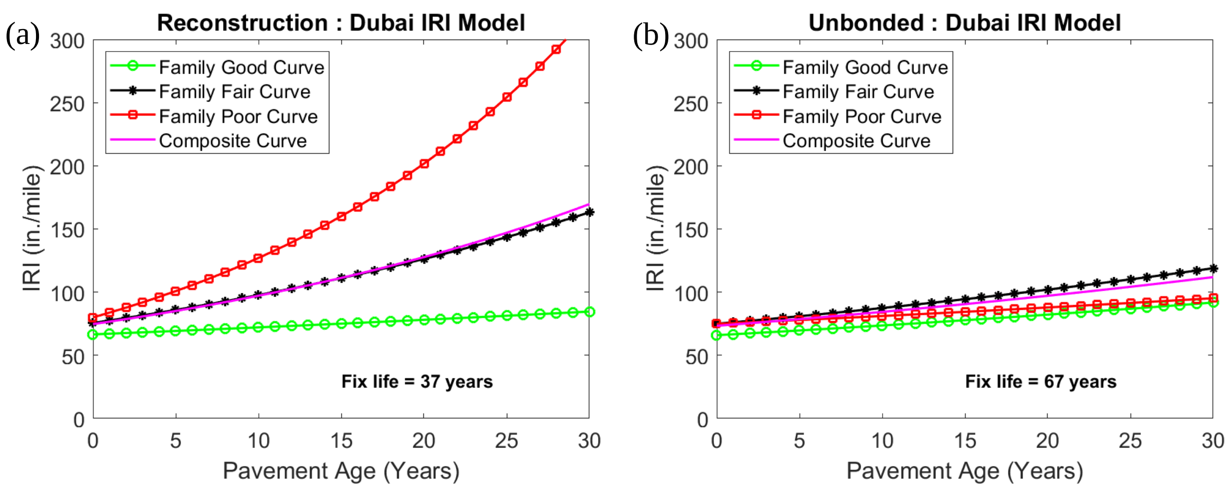


Figure 9.15 Rigid composite curves for IRI data with new families: (a) reconstruction, (b) unbonded

10. SUMMARY AND CONCLUSION

A condition index is a tool used to assess the condition of pavement surfaces under various traffic loads, environmental conditions, and material characteristics. This information is essential for states to allocate maintenance resources effectively. Due to unique challenges in distress data gathering and rating, Michigan DOT has decided to suspend its current Distress Index (DI). Therefore, the principal objective of this study was to develop an enhanced condition index for Michigan that would align more closely with national standards. The development of the new condition score was still based on MDOT’s historical pavement management data source. The comprehensive study was performed so that it would not cause drastic business changes to MDOT, yet a new pavement family classification and performance modeling approach was introduced. Proper communication with regional offices was tried to maintain in finalizing distress lists, weight factors, and rating scales. The findings of this study are:

- An extensive review of nationwide distresses and severity definitions is conducted to recommend concise and practical distress lists to MDOT for their future asphalt and rigid pavement survey. Seven different distresses are recommended for both asphalt and rigid pavements.
- Five condition indices were compared with Michigan DOT's Distress Index using MDOT's PMS database. By examining time series plots of pavement sections and comparing them to Michigan DOT’s Distress Index (DI), it was found that Minnesota DOT’s SR and Louisiana DOT’s PCI were promising for both asphalt and rigid pavements. In this comparison process, it was acknowledged that discrepancies between DI and other condition indices could be attributed to various factors, including differences in the number of distress inputs, their units, severity levels, deduct points and mathematical formulas.
- MDOT's past maintenance records were analyzed with the box plot representation for each index. The analysis revealed that MDOT's Distress Index (DI) could distinguish between light, moderate, and significant maintenance levels. Similarly, Minnesota's SR box plot effectively differentiated between different types of repairs and reduced variability within a single box plot for both asphalt and rigid pavement. On the other hand, Oregon's OCI was the worst in representing MDOT's past maintenance due to the high magnitudes and variability in individual box plots.

- A qualitative approach was also taken in this study to see which condition index satisfies a few essential criteria that agencies look for while choosing a condition index. Through that analysis, it was also observed that Minnesota's SR was the most appropriate index that can be used as a starting point. Therefore, it was recommended that MDOT adopt a condition index similar to Minnesota's SR, adjusting weight factors to better differentiate past maintenance activities. The rating scale should also be changed to 100-0, where 100 represents the perfect condition, to align with other state DOTs.
- This study's new pavement condition index was named "Pavement Condition Score (PDS)."
- This study highlighted the detailed conversion of MDOT's current PMS data to percentages considering various AD matrices to define severity levels. This would help MDOT to direct their future vendors on how the raw data be processed so that minimal effort needs for MDOTs in-house in calculating PDS.
- Default weight factors of Minnesota's SR were optimized carefully so that calculated PDS reflected Michigan DOT's past maintenance records reasonably. MDOT's region engineers further validated the estimated PDS numbers by visually inspecting many road segments.
- After finalizing the weight factors, network-level pavement performance modeling with MDOT pavement families for both asphalt and rigid pavement was performed using four different models. From the performance curve fits it was observed that for asphalt pavements, the NJDOT and logistic growth model showed a better fit with low RMSE. The NCDOT and logistic growth model showed a reasonable fit for rigid pavements. Later, based on a threshold of PDS equal to 50, fix life estimation was also found reasonable for these mentioned models compared to MDOT's current practice of fix life for different pavement types.
- As MDOT's past pavement families were based upon historical DI values, this study developed a new group of families (good, fair, and poor) using the newly developed condition index, PDS. The new family method provided better distribution of calculated PDS with better curve fits.
- One of the probable reasons for high rigid PDS values or fix lives could be missing patching as a distress input. MDOT was reluctant to include patching as it creates a burden in their

quality assurance effort. However, from other states' practices and MDOT's region engineers' comments, it is known that engineers usually do major rehabilitation on patched roads. Therefore, including patching with proper quality assurance may lower the rigid PDS fix lives.

- Another innovative aspect of this study is that International Roughness Index (IRI) data were analyzed for performance modeling, and consequently, fix life was estimated. Similar to PDS, a new family method of pavement condition grouping was developed based on IRI. Four different IRI performance models were utilized. The performance curves fit and fix life results revealed that the Dubai IRI model performed the best with reasonable fix life for all surface types. However, IRI-based fix lives were higher for all performance models compared to PDS.

In summary, this research study has yielded a new pavement condition parameter that MDOT can readily implement in the near future. The new parameter has been chosen to ensure compatibility with previous systems. The required pavement distresses can be collected accurately and quickly by the vendor responsible for pavement data collection. Nevertheless, this study can also guide other state agencies if they want to review their routine condition index. The following framework can help in creating a reliable condition index for infrastructure assets:

Review other condition indices practice nationwide: It is important to review and understand the best practices and condition indices used in other regions or areas. This will provide a benchmark for developing the condition index.

Analyze past maintenance records with all condition indices: The next step is to analyze the past maintenance records of the infrastructure assets with all the condition indices. This analysis will help in identifying the best condition index suitable for the assets.

Adjust in the distress list and severity assumptions: After selecting the appropriate condition index, the next step is to adjust the distress list and severity assumptions based on the local condition of the infrastructure assets.

Calibrate distress weight factors to satisfy current condition observations: Once the adjustments are made, it is essential to calibrate the distress weight factors to satisfy current condition observations. This step helps in ensuring that the condition index reflects the current condition of the infrastructure assets accurately.

By following this framework, one can develop a reliable condition index for infrastructure assets. This index will help in effectively managing the assets and maintaining them in good condition.

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APPENDIX A: PDS MODEL FITS WITH MDOT FAMILIES

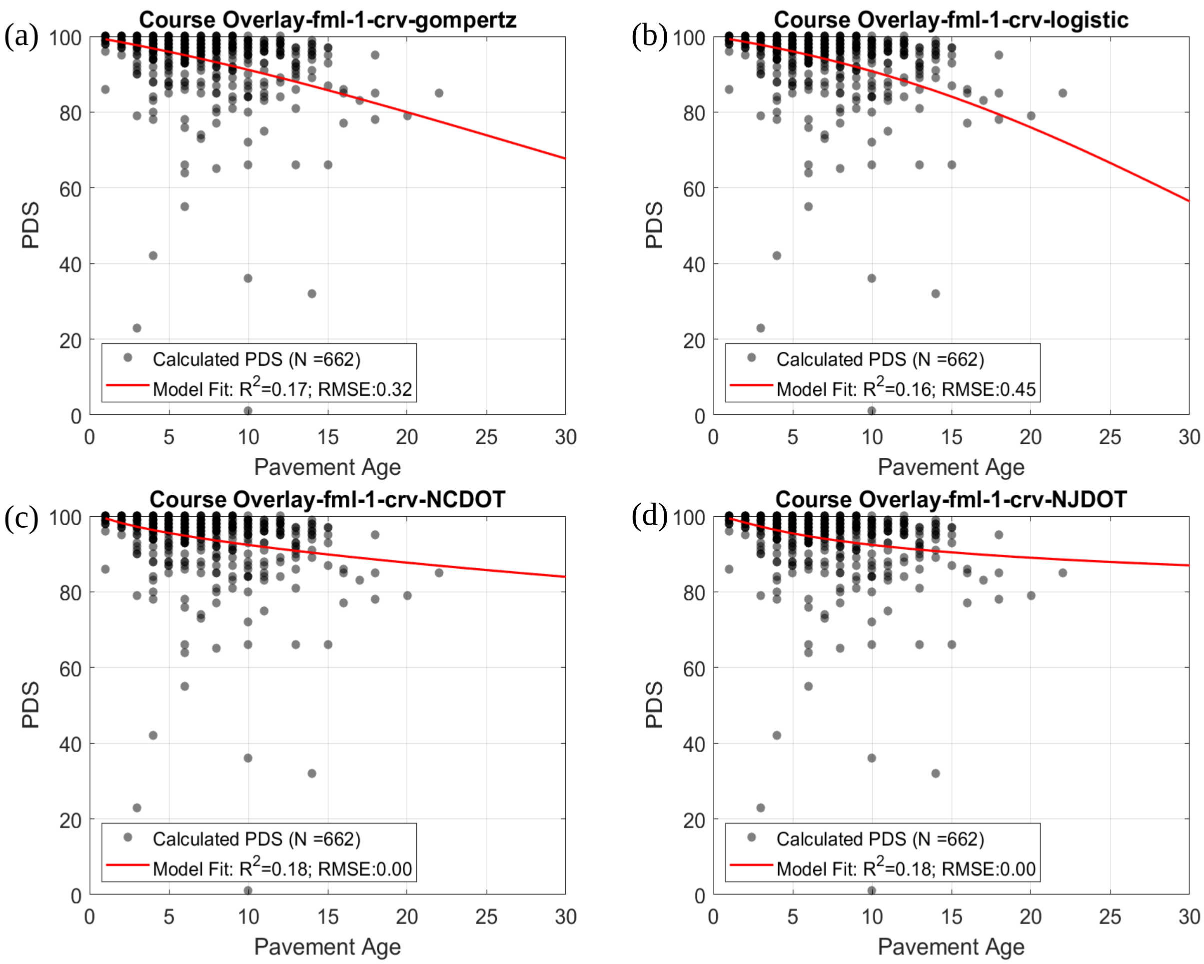

Figure A.1 HMA 2-course overlay modeling for PDS with MDOT Family 1 using: (a) Gompertz, (b) Logistic, (c) NCDOT and (d) NJDOT models

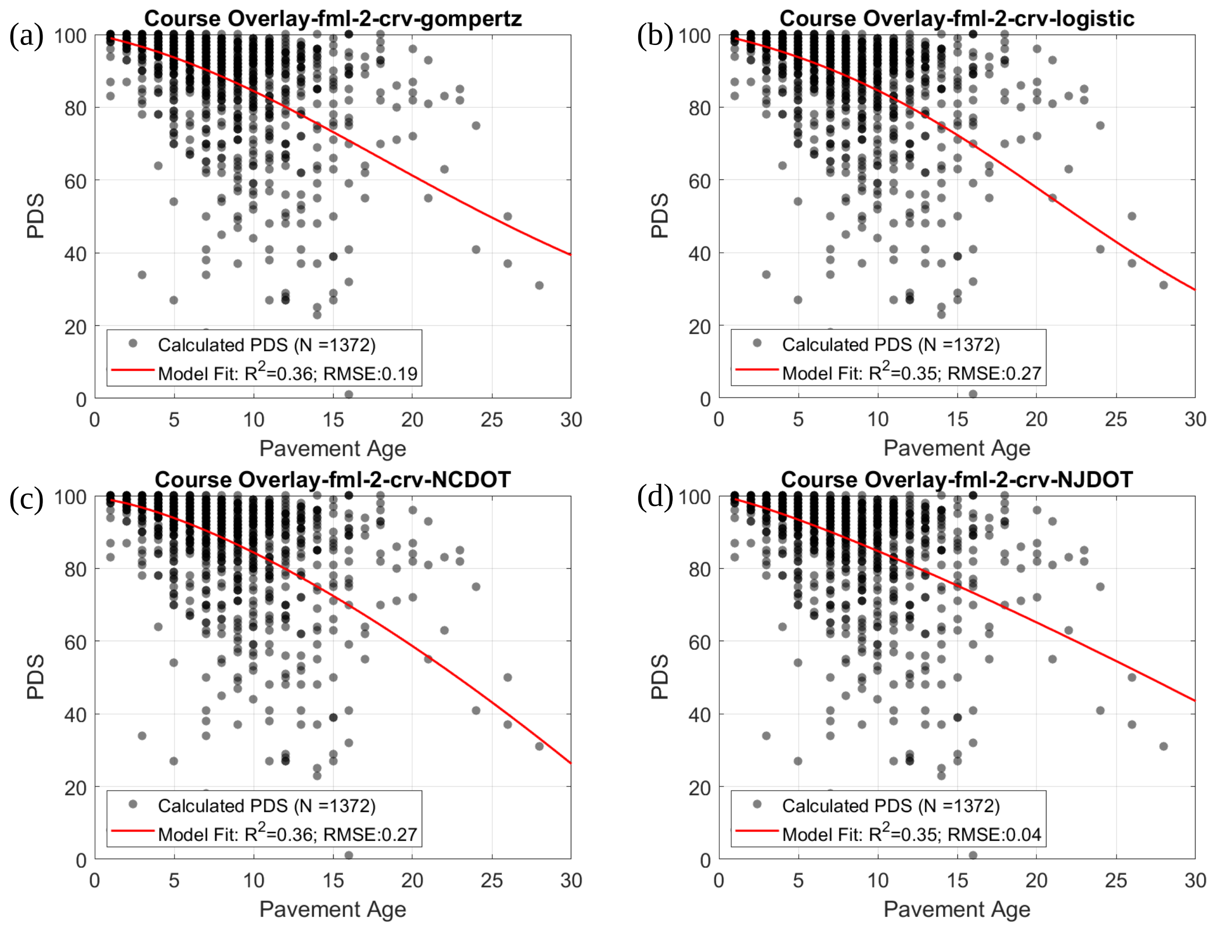

Figure A.2 HMA 2-course overlay modeling for PDS with MDOT Family 2 using: (a) Gompertz, (b) Logistic, (c) NCDOT and (d) NJDOT models

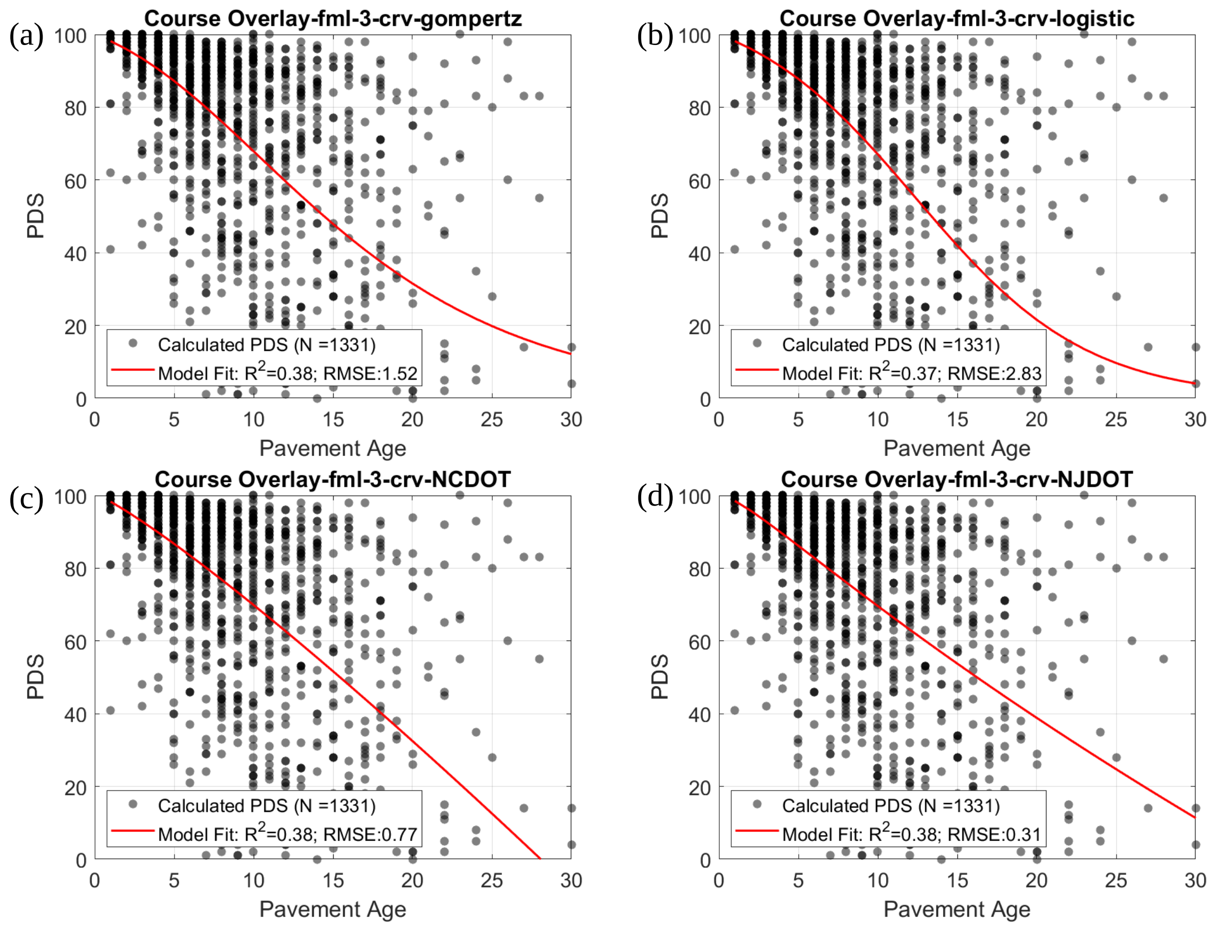

Figure A.3 HMA 2-course overlay modeling for PDS with MDOT Family 3 using: (a) Gompertz, (b) Logistic, (c) NCDOT and (d) NJDOT models

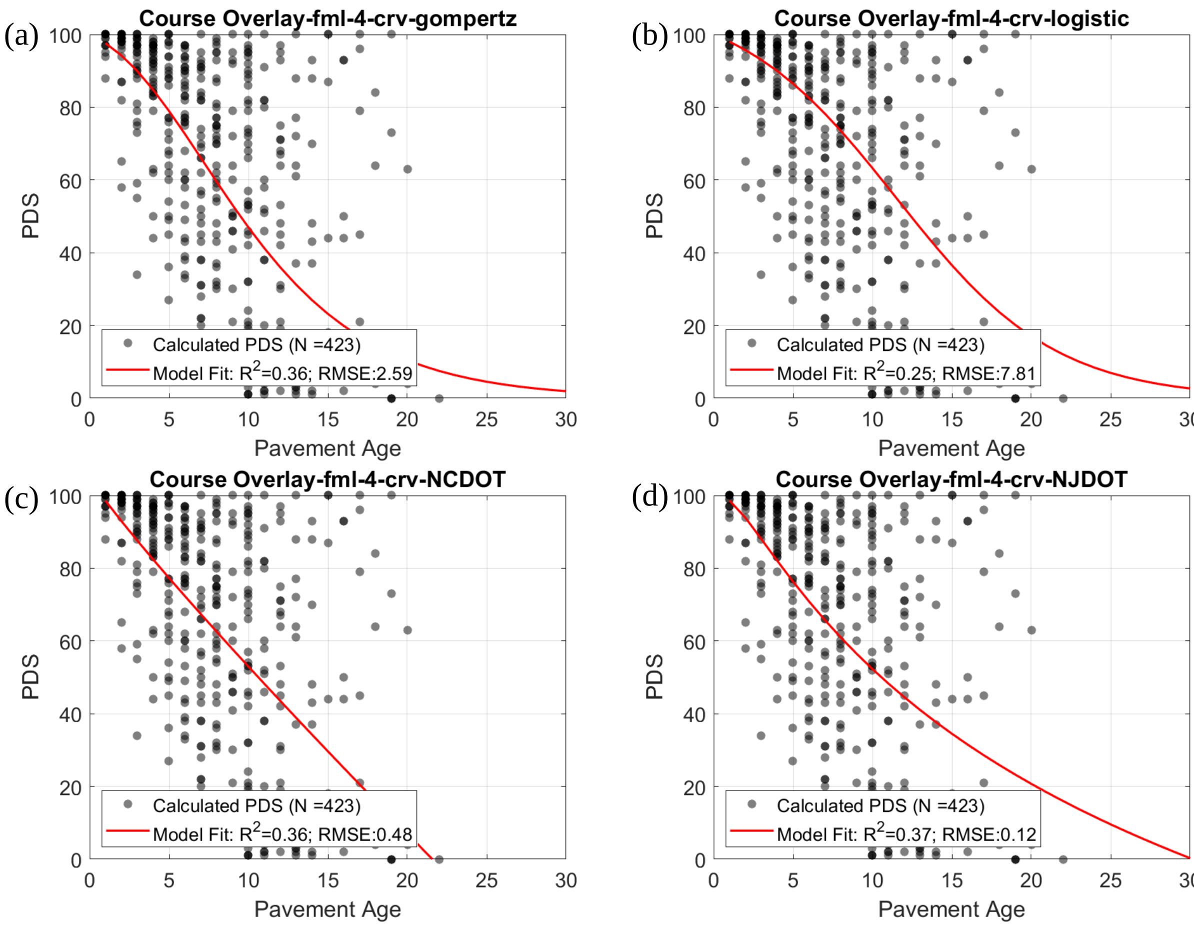

Figure A.4 HMA 2-course overlay modeling for PDS with MDOT Family 4 using: (a) Gompertz, (b) Logistic, (c) NCDOT and (d) NJDOT models

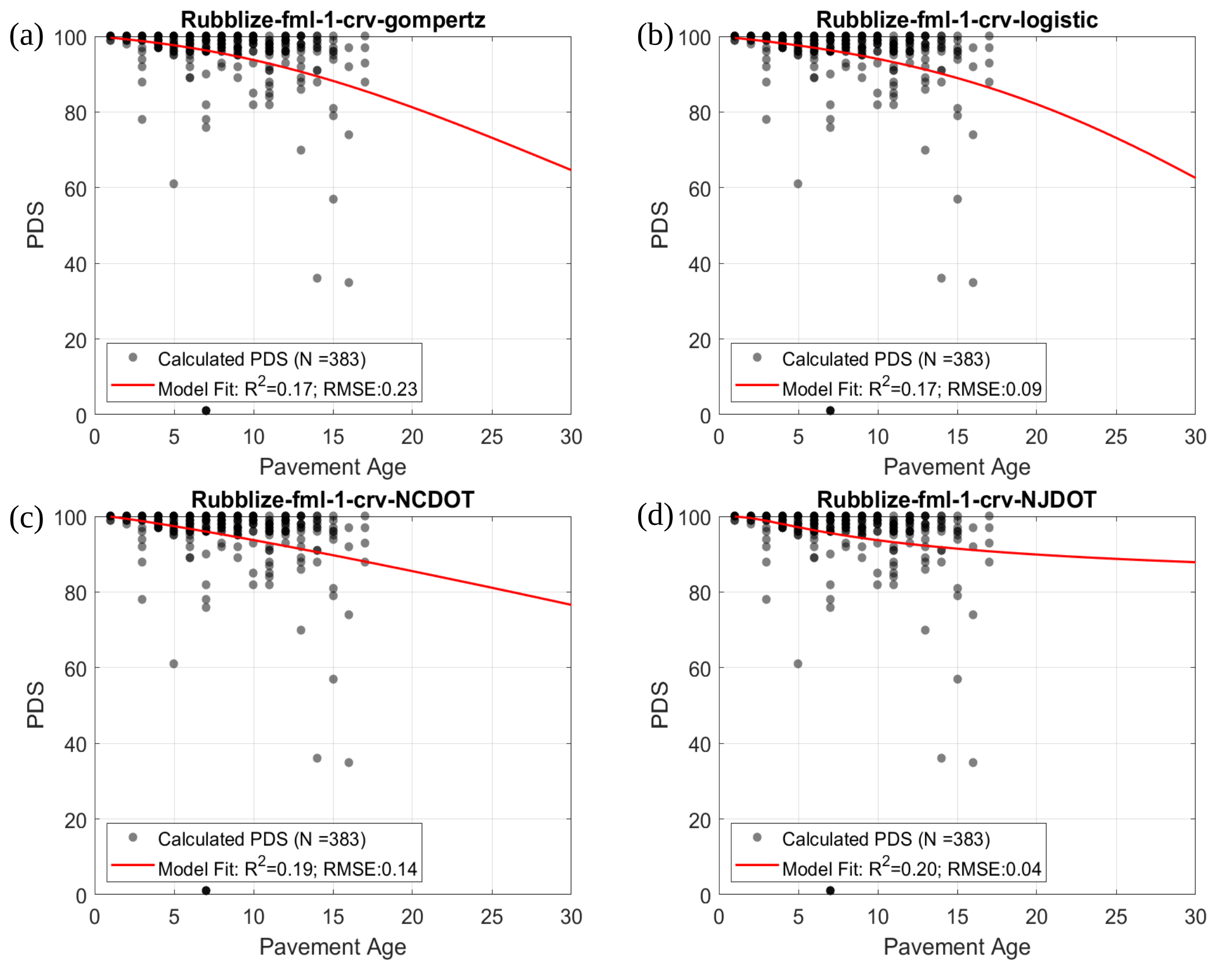

Figure A.5 HMA rubblize modeling for PDS with MDOT Family 1 using: (a) Gompertz, (b) Logistic, (c) NCDOT and (d) NJDOT models

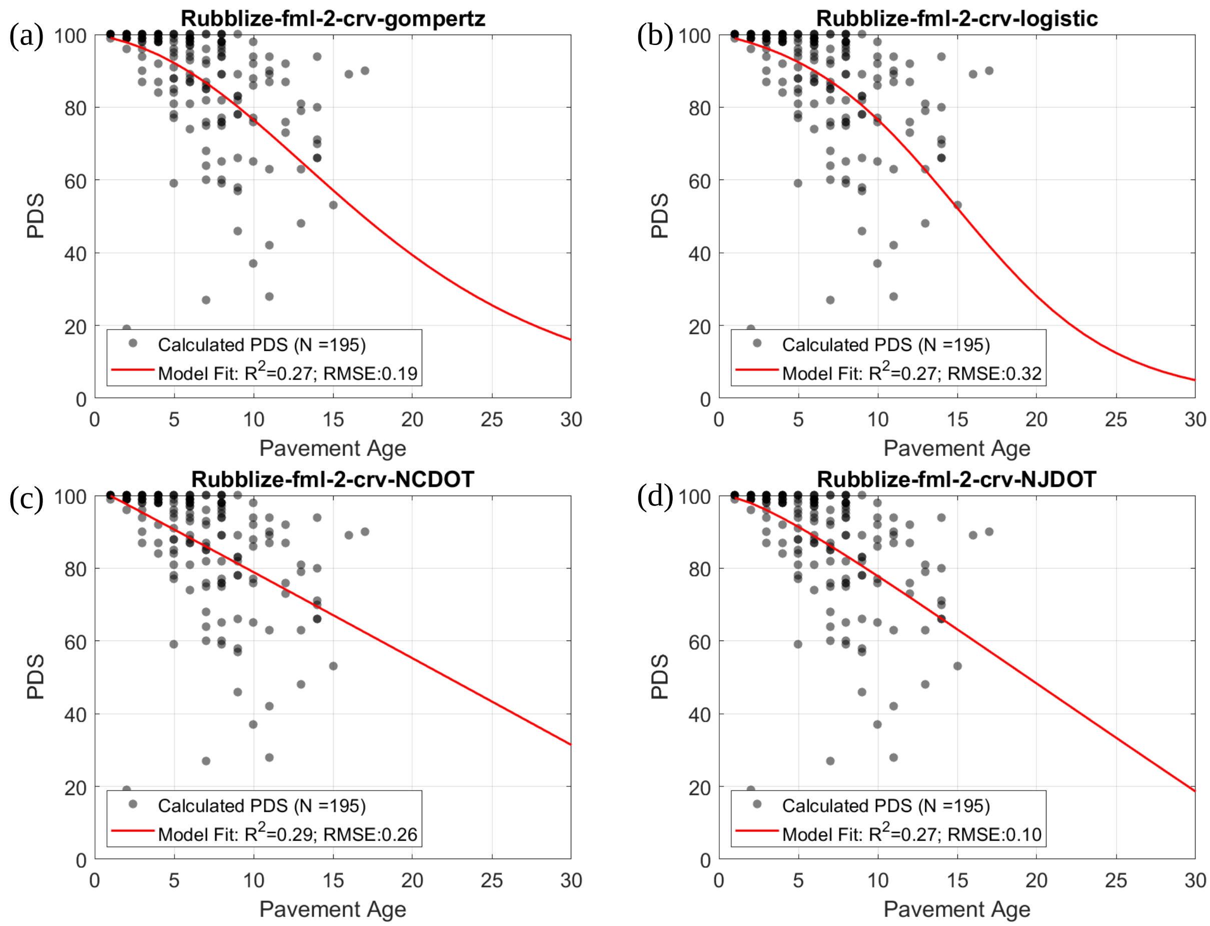

Figure A.6 HMA rubblize modeling for PDS with MDOT Family 2 using: (a) Gompertz, (b) Logistic, (c) NCDOT and (d) NJDOT models

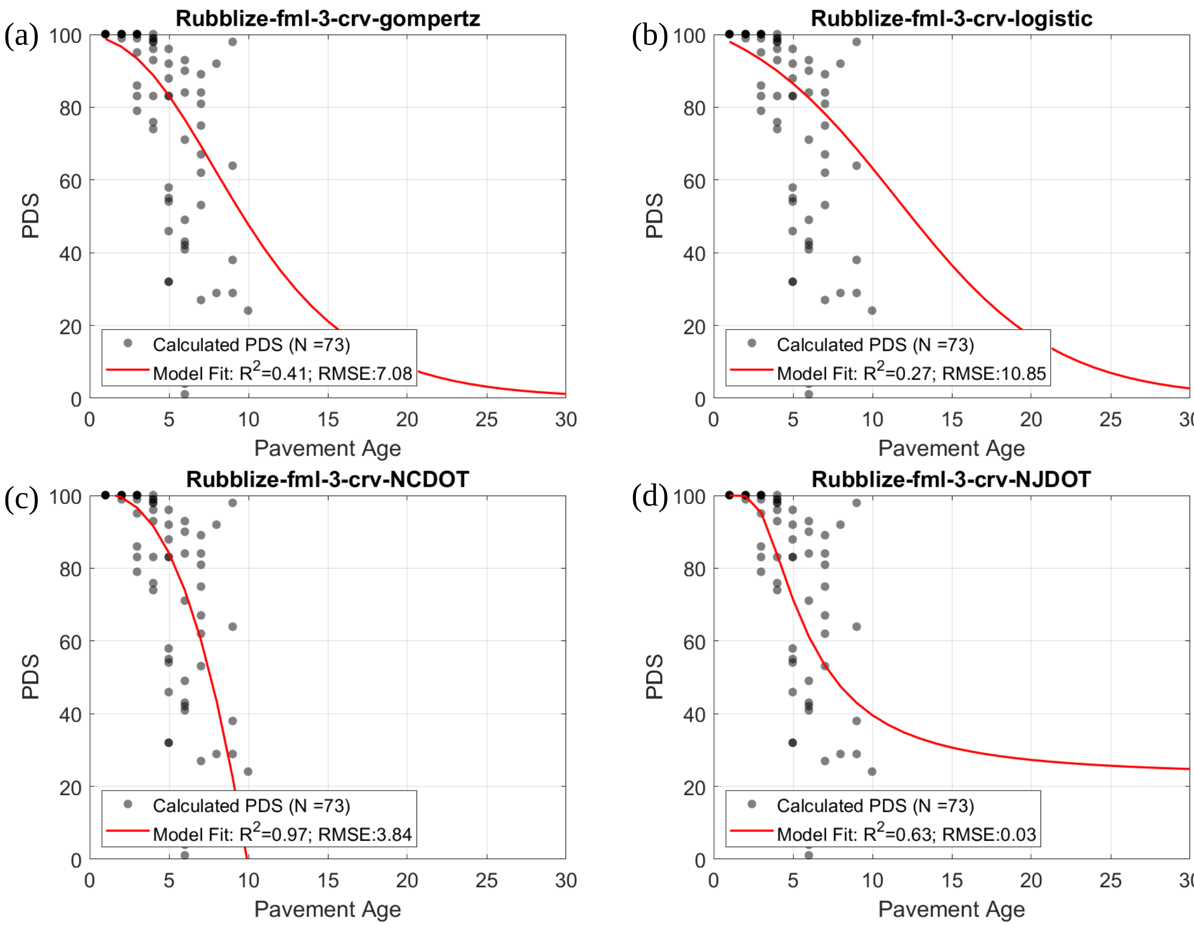

Figure A.7 HMA rubblize modeling for PDS with MDOT Family 3 using: (a) Gompertz, (b) Logistic, (c) NCDOT and (d) NJDOT models

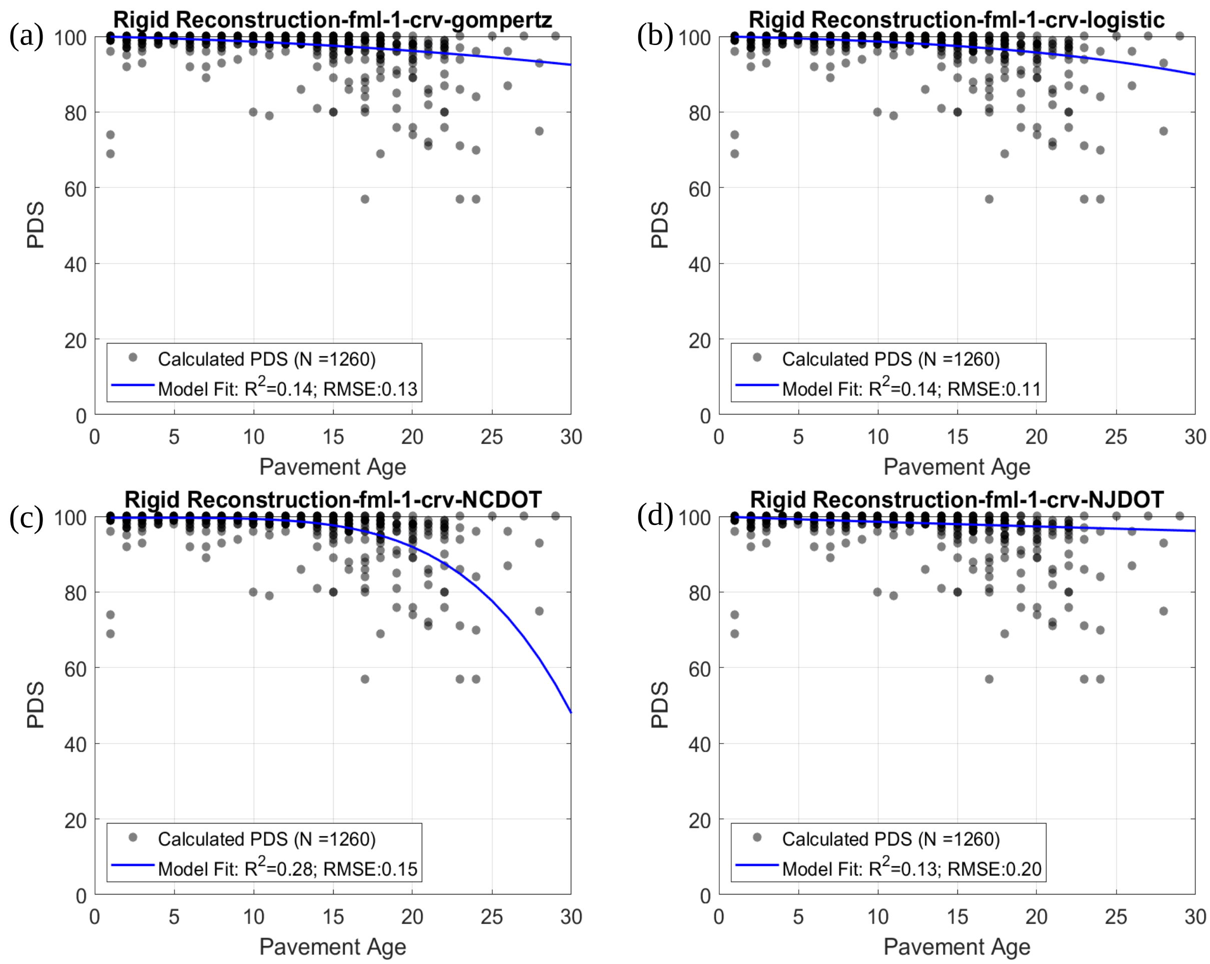

Figure A.8 Rigid reconstruction modeling for PDS with MDOT Family 1 using: (a) Gompertz, (b) Logistic, (c) NCDOT and (d) NJDOT models

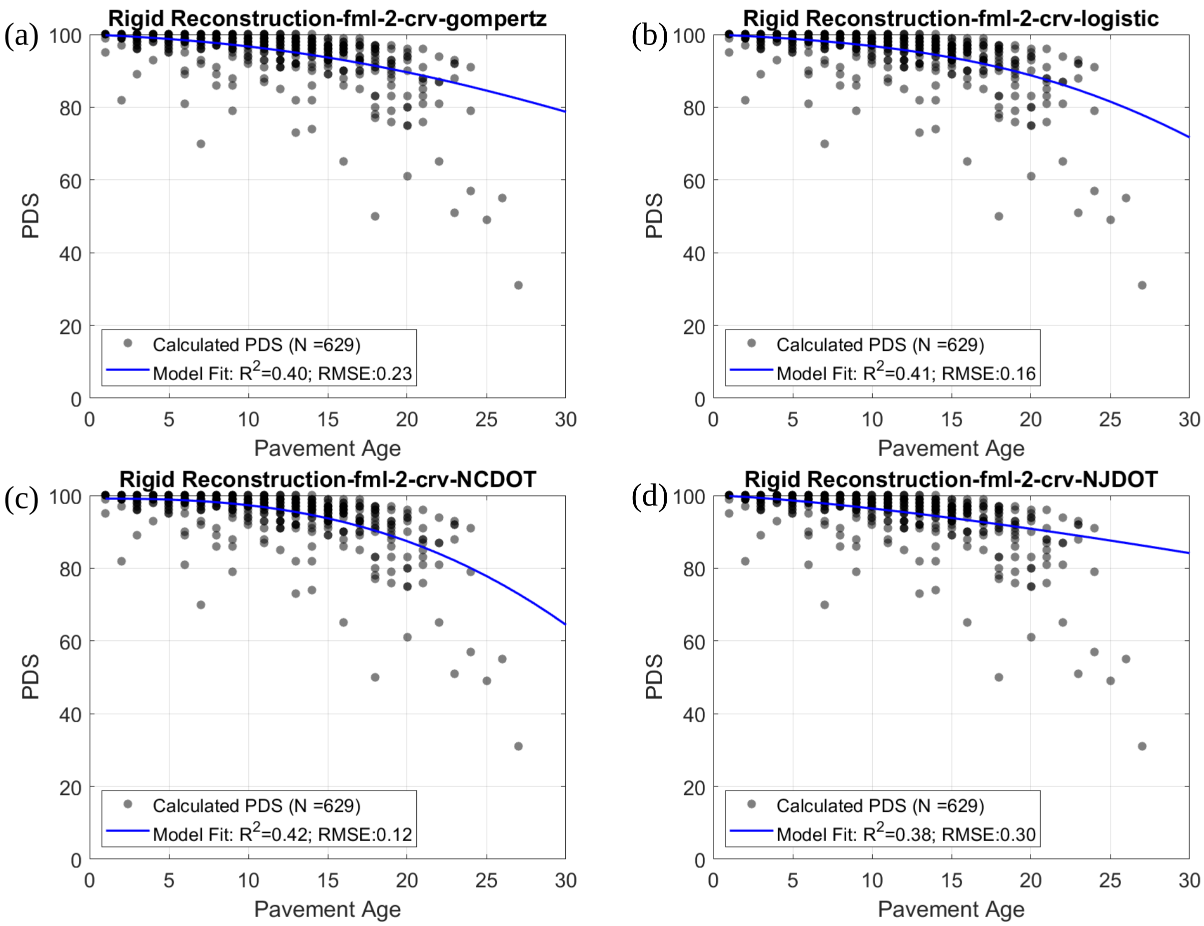

Figure A.9 Rigid reconstruction modeling for PDS with MDOT Family 2 using: (a) Gompertz, (b) Logistic, (c) NCDOT and (d) NJDOT models

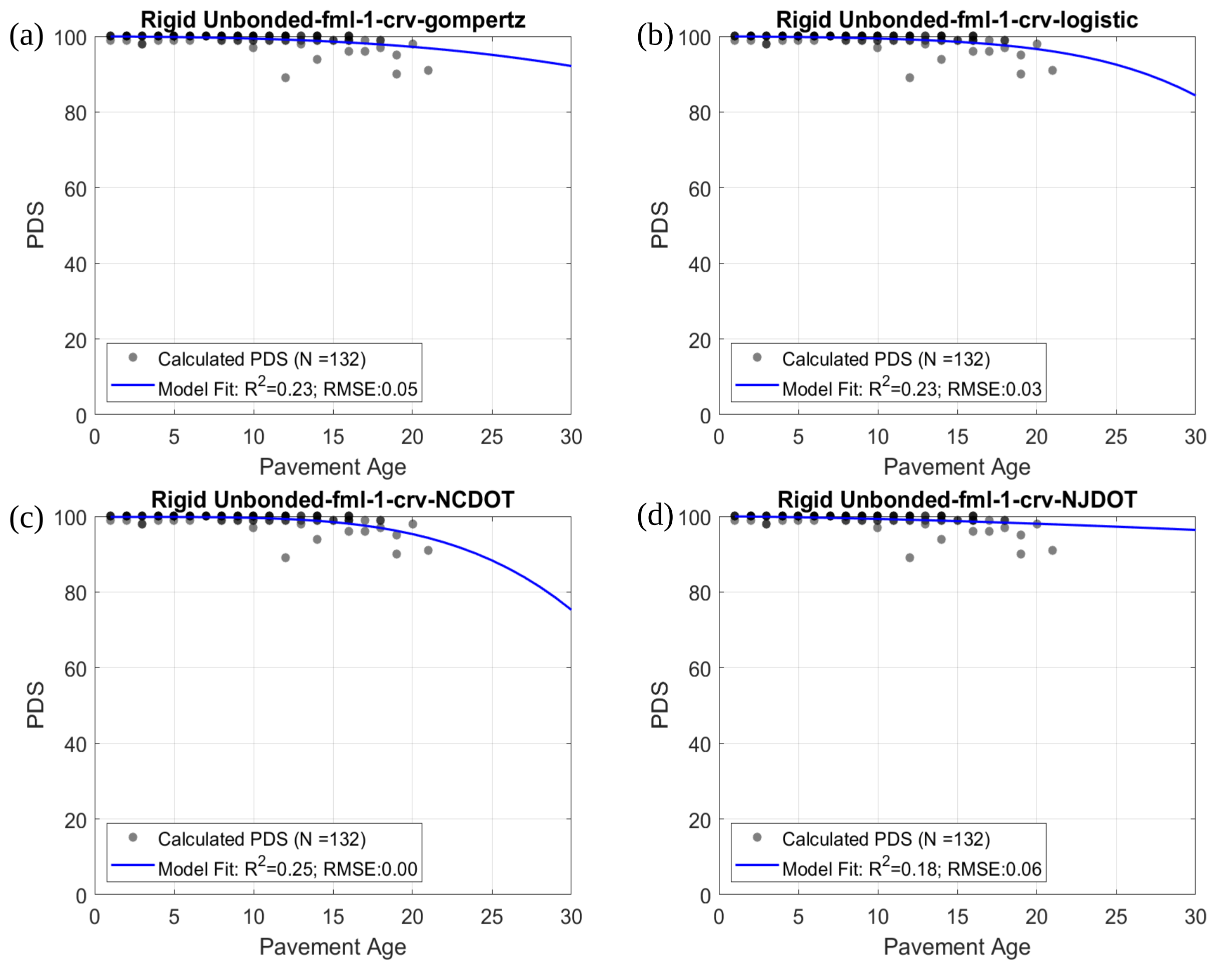

Figure A.10 Rigid unbonded modeling for PDS with MDOT Family 1 using: (a) Gompertz, (b) Logistic, (c) NCDOT and (d) NJDOT models

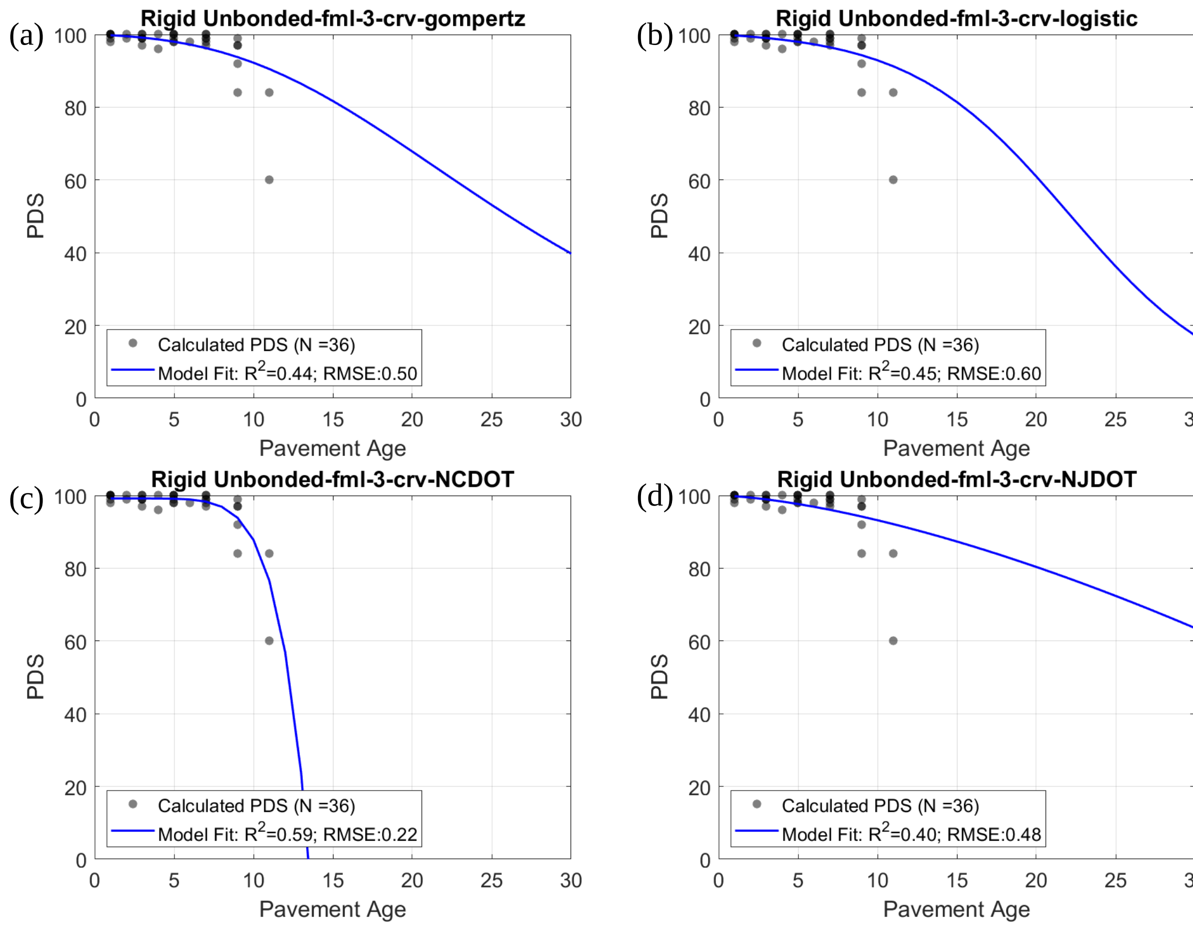

Figure A.11 Rigid unbonded modeling for PDS with MDOT Family 3 using: (a) Gompertz, (b) Logistic, (c) NCDOT and (d) NJDOT models

APPENDIX B: PDS MODEL FITS WITH AVGL3 FAMILIES

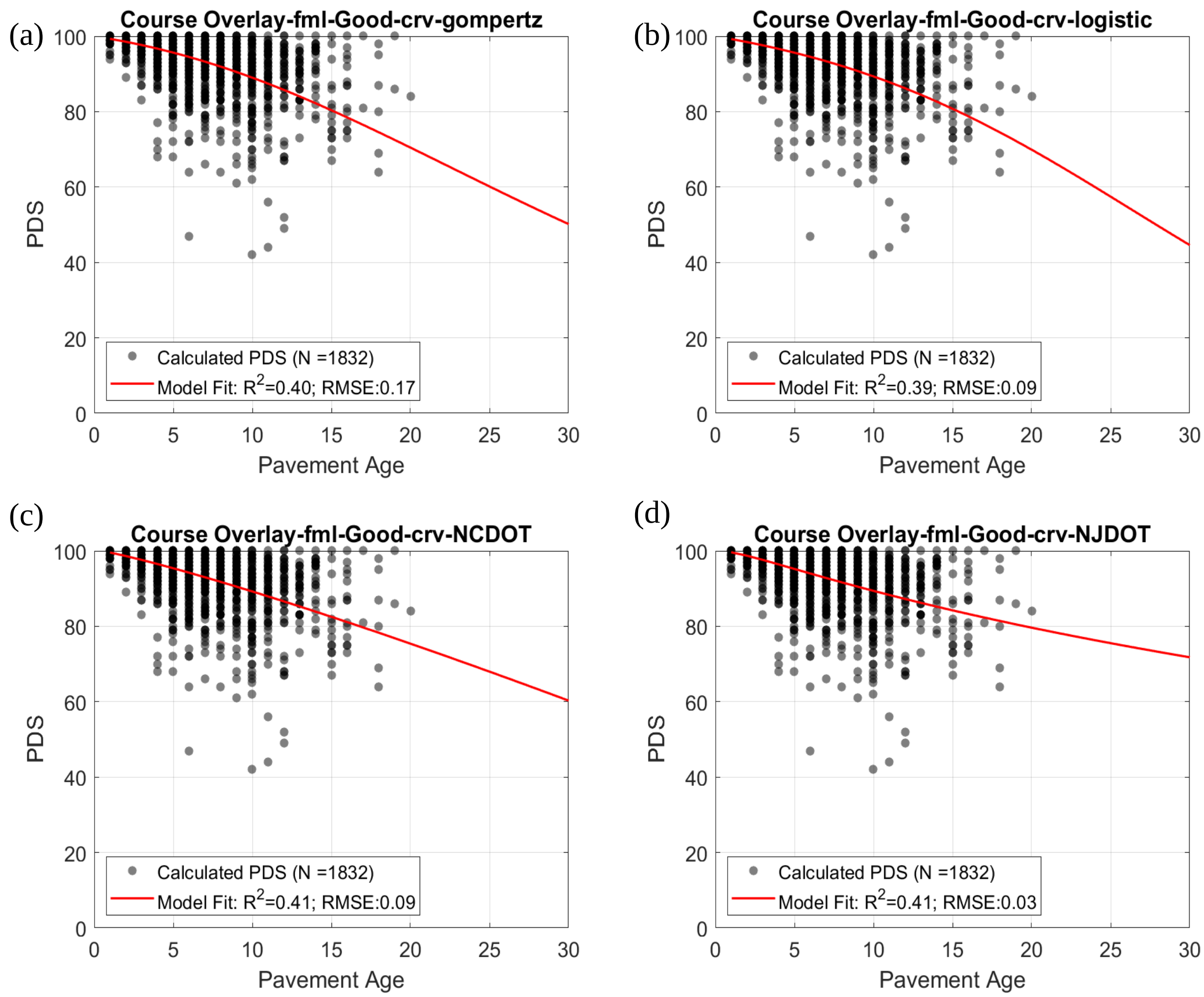

Figure B.1 HMA 2-course overlay modeling for PDS with Avg_{L3} good family using: (a) Gompertz, (b) Logistic, (c) NCDOT and (d) NJDOT models

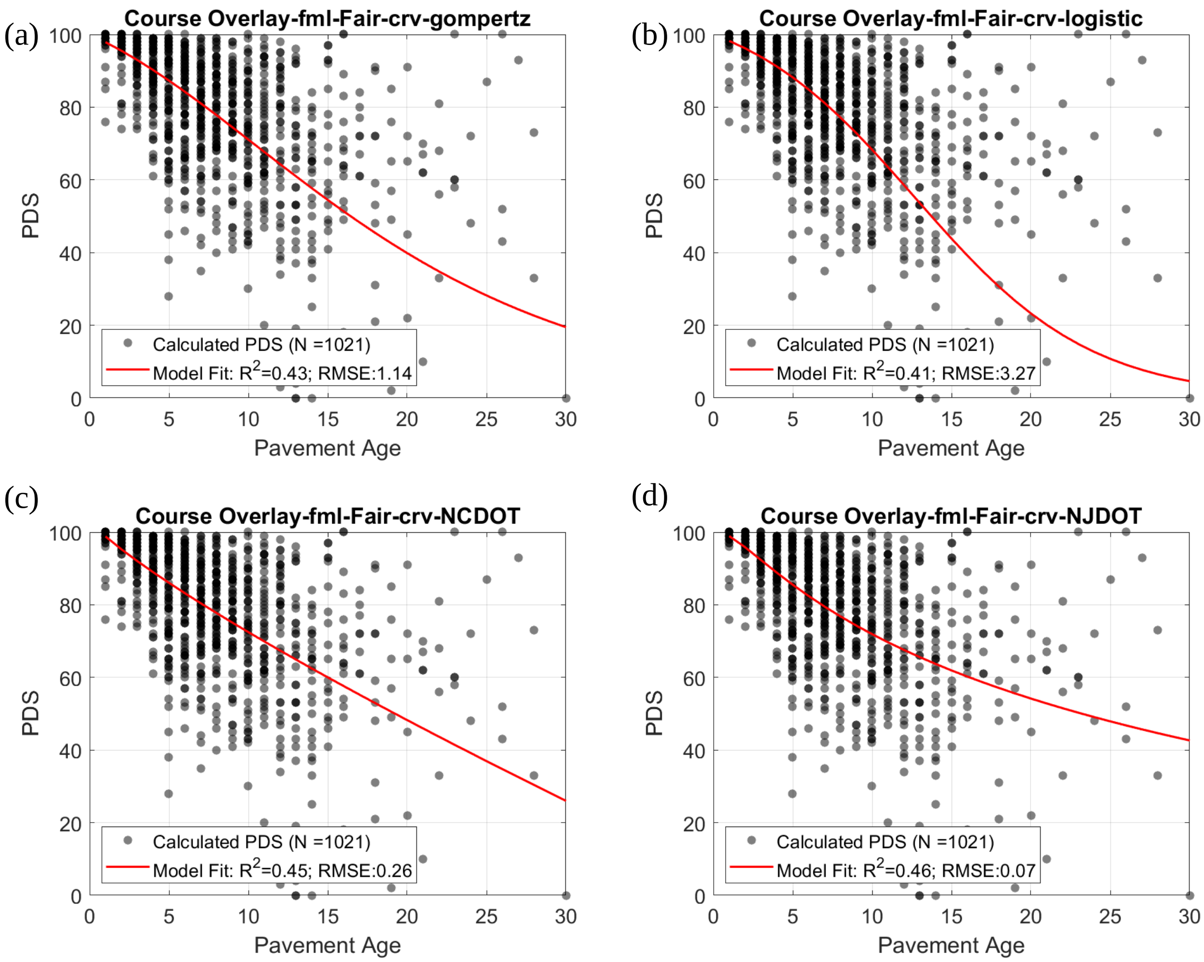

Figure B.2 HMA 2-course overlay modeling for PDS with Avg_{L3} fair family using: (a) Gompertz, (b) Logistic, (c) NCDOT and (d) NJDOT models

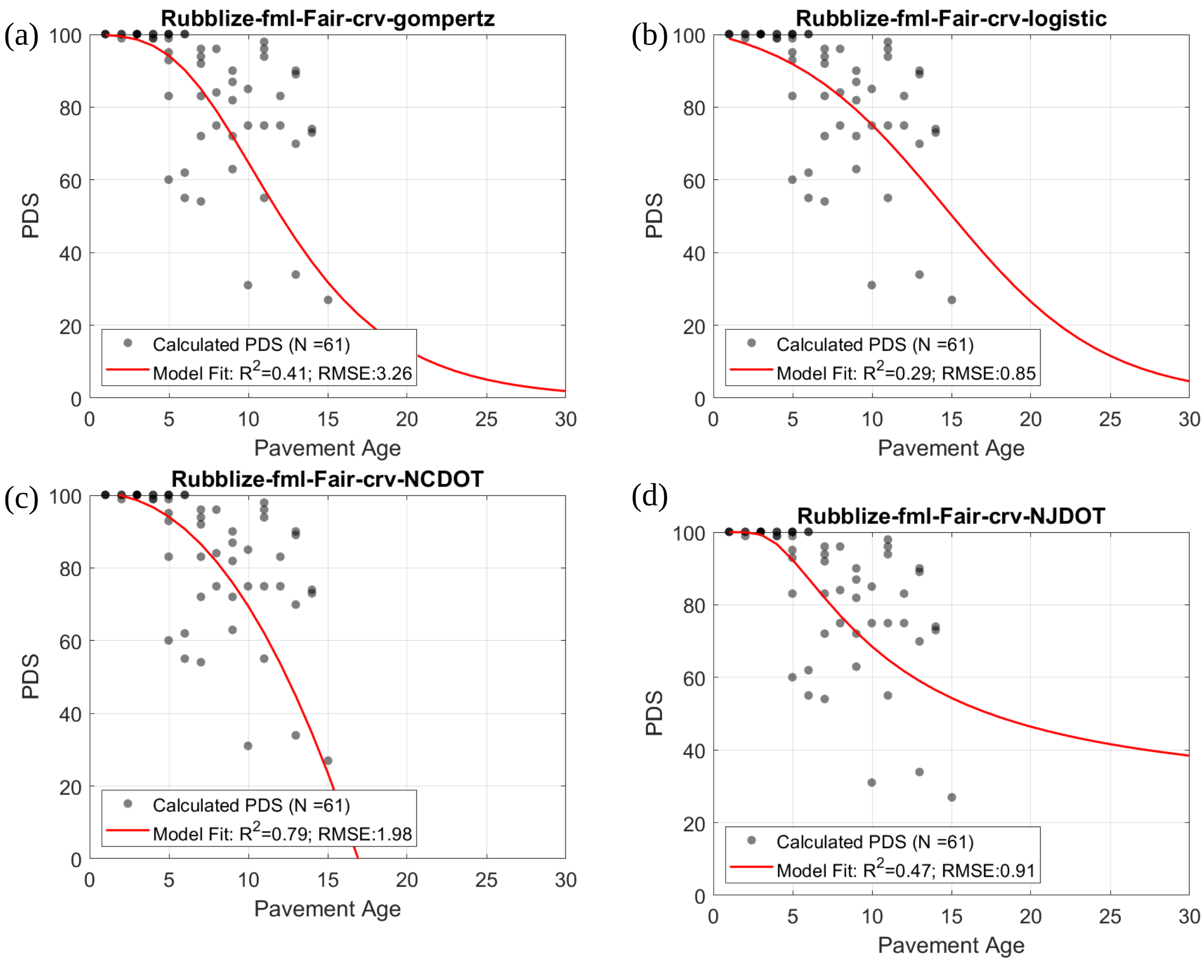

Figure B.3 HMA rubblize modeling for PDS with Avg_{L3} fair family using: (a) Gompertz, (b) Logistic, (c) NCDOT and (d) NJDOT models

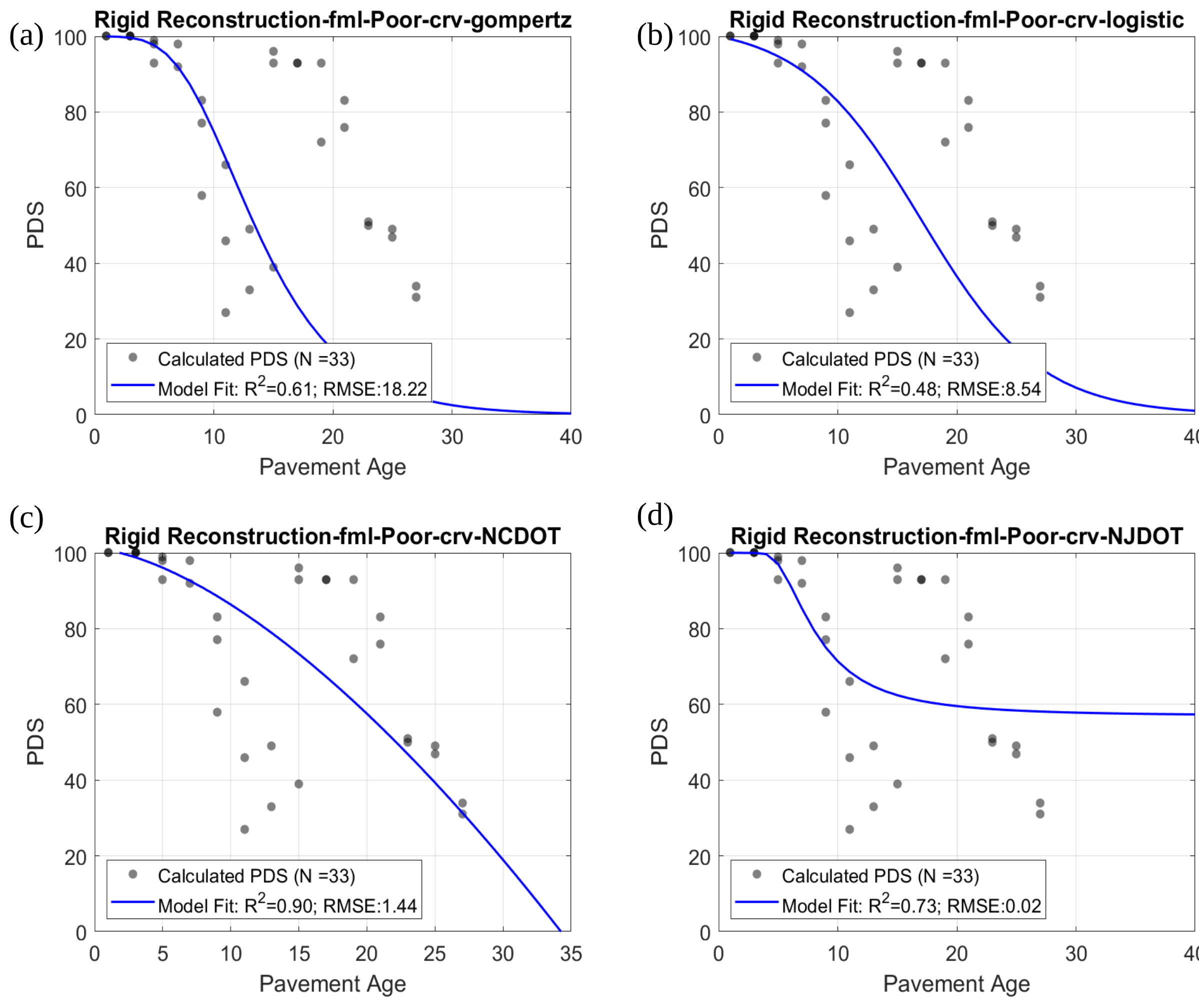

Figure B.4 Rigid reconstruction modeling for PDS with Avg_{L3} poor family using: (a) Gompertz, (b) Logistic, (c) NCDOT and (d) NJDOT models

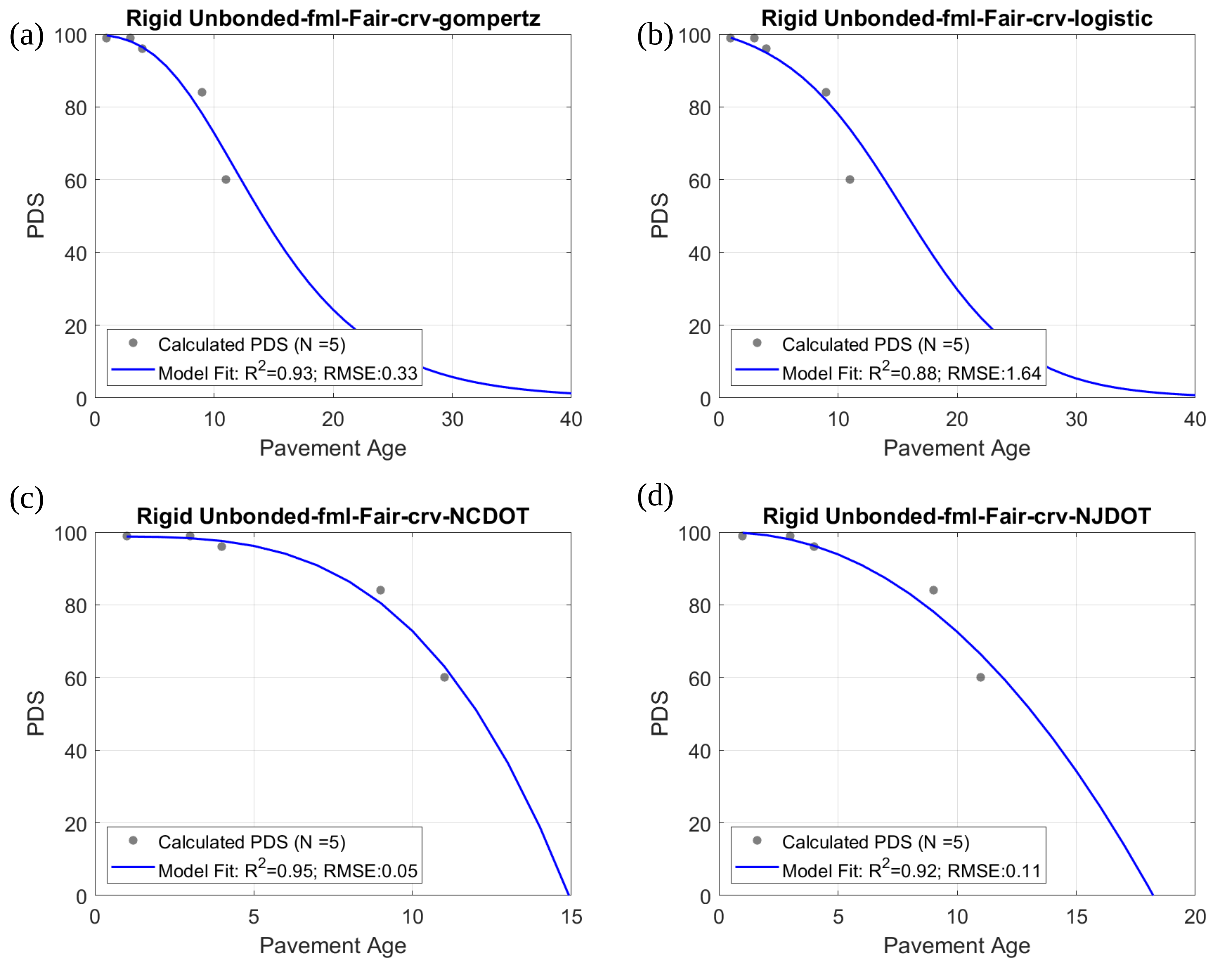

Figure B.5 Rigid unbonded modeling for PDS with Avg_{L3} fair family using: (a) Gompertz, (b) Logistic, (c) NCDOT and (d) NJDOT models

APPENDIX C: IRI MODEL FITS

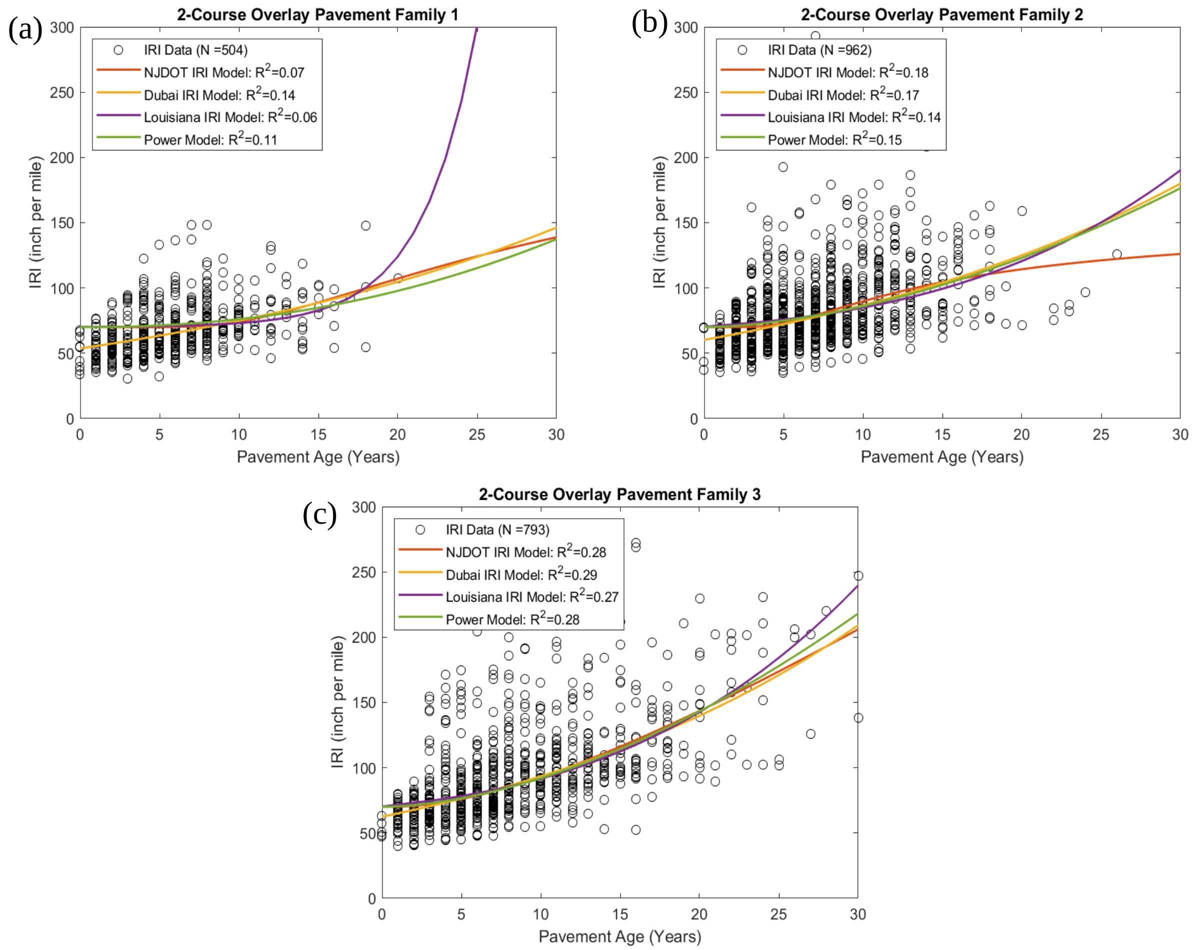

Figure C.1 HMA 2-course overlay modeling for IRI data with MDOT families: (a) family1, (b) family2, and (c) family3

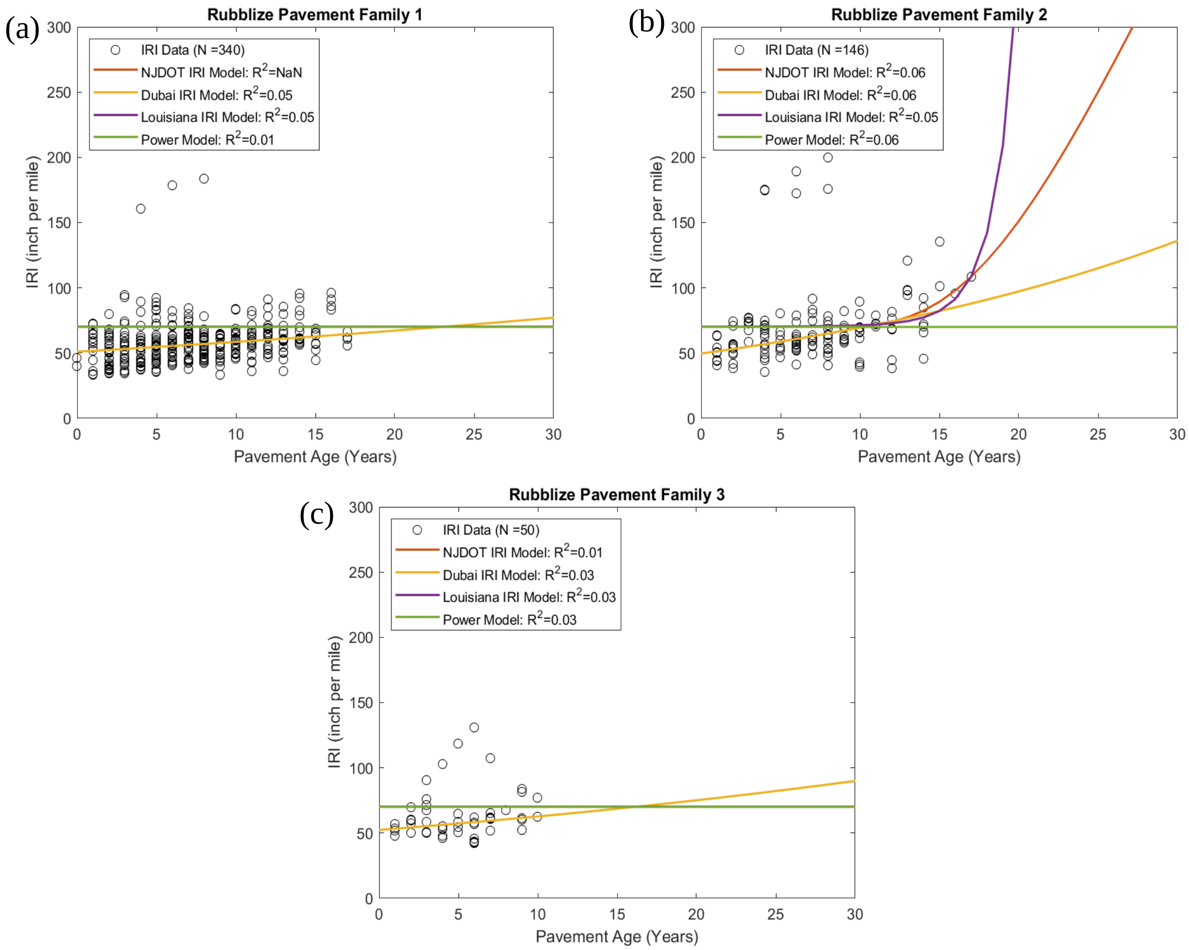

Figure C.2 HMA rubblize modeling for IRI data with MDOT families: (a) family1, (b) family2, and (c) family3

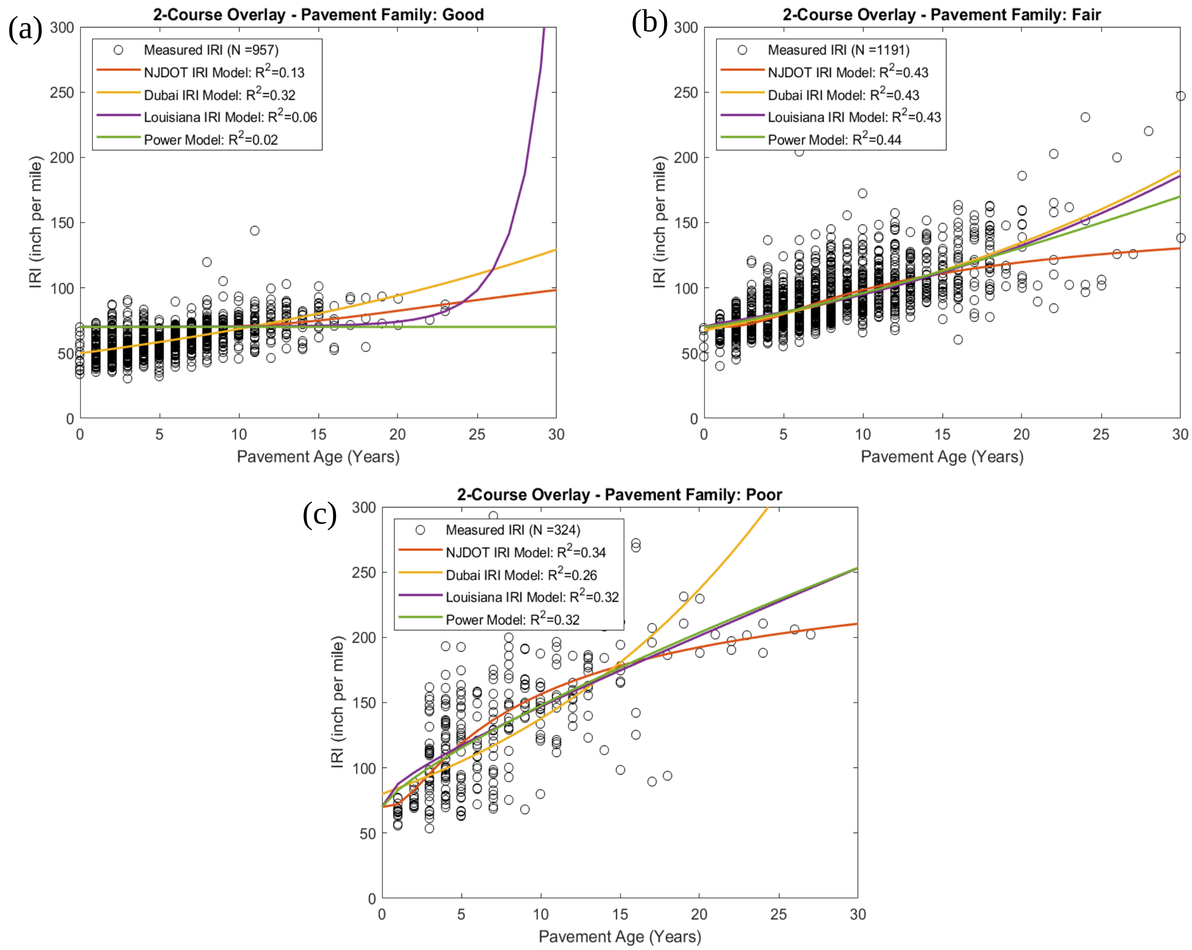

Figure C.3 HMA 2-course overlay modeling for IRI data with new families: (a) good, (b) fair, and (c) poor

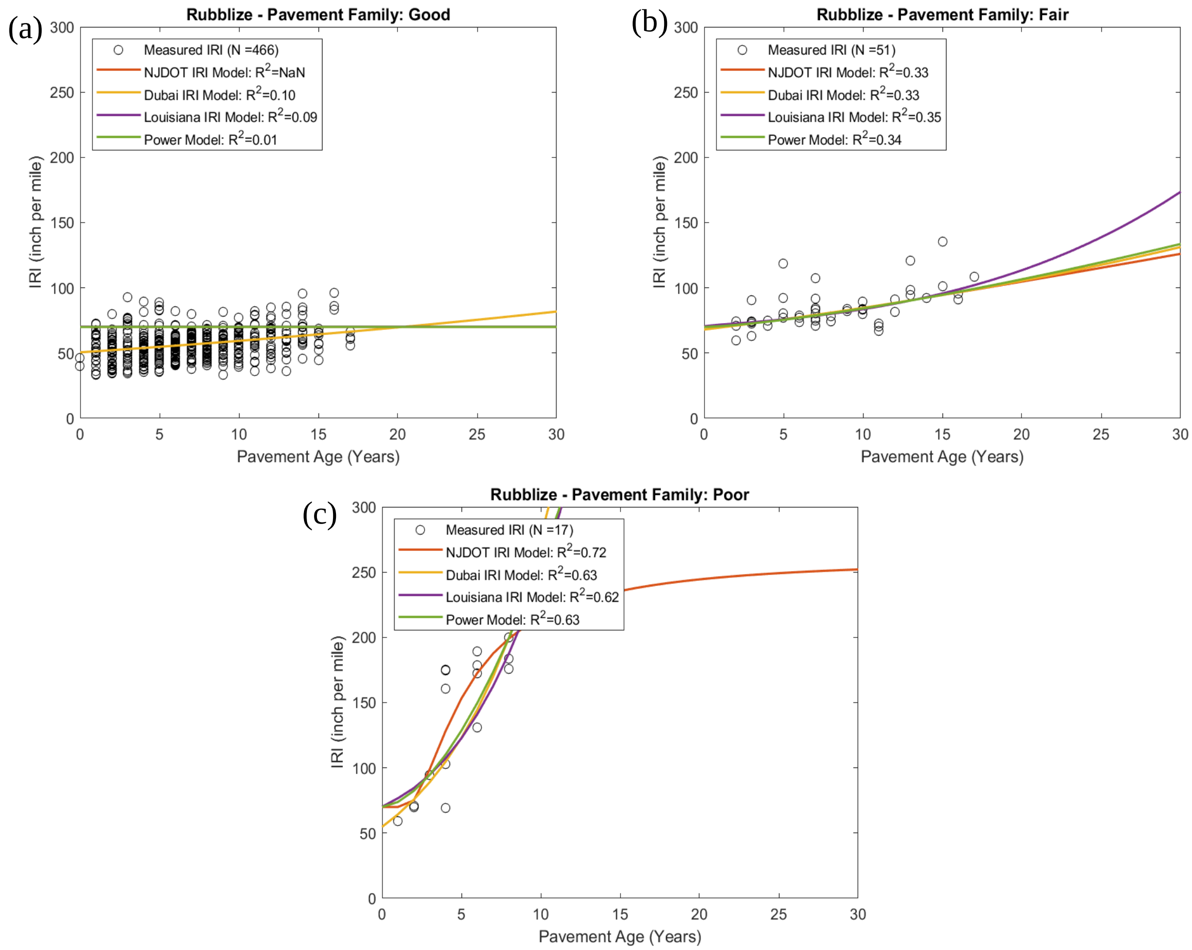

Figure C.4 HMA rubblize modeling for IRI data with new families: (a) good, (b) fair, and (c) poor