CURRENT PRACTICES IN PAVEMENT PERFORMANCE MODELING

PROJECT 08-03 (C07)

Task 4 Report

Final Summary of Findings

Prepared For:

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Submitted: February 26, 2010

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA-PA-2010-007-080307		

4. Title and Subtitle	5. Report Date
Research of Current Practices in Pavement Performance Modeling	02-26-2010
	6. Performing Organization Code
7. Author(s)	**8. Performing Organization Report No.**
Angela S. Wolters and Kathryn A. Zimmerman	
9. Performing Organization Name and Address	**10. Work Unit No. (TRAIS)**
Applied Pavement Technology, Inc. (APTech) 115 West Main Street, Suite 400 Urbana, IL 61801	**11. Contract or Grant No.** **355I01**
12. Sponsoring Agency Name and Address	**13. Type of Report and Period Covered**
The Pennsylvania Department of Transportation Bureau of Planning and Research Commonwealth Keystone Building 400 North Street, 6th Floor Harrisburg, PA 17120-0064	Final Report July 2009 – February 2010 **14. Sponsoring Agency Code**

15. Supplementary Notes

PennDOT Technical Liaisons: Clint H. Beck and John E. Van Sickle

16. Abstract

In anticipation of developing pavement performance models as part of a proposed pavement management system, the Pennsylvania Department of Transportation (PennDOT) initiated a study in 2009 to investigate performance modeling activities and condition information used by other state highway agencies (SHAs), and to obtain recommendations on how to proceed with their own modeling efforts.

A survey of state practice was conducted and the practices of other states were summarized. The findings from the survey were then used to develop three pavement performance modeling options for PennDOT. A final recommendation of how PennDOT should proceed with pavement performance modeling was created and is detailed in this *Final Report.*

17. Key Words	18. Distribution Statement
Pavement management, pavement performance models, performance model development, model assessment, pavement condition information	No restrictions. This document is available from the National Technical Information Service, Springfield, VA 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	294	

Form DOT F 1700.7 **(8-72)** **Reproduction of completed page authorized**

EXECUTIVE SUMMARY

Introduction

Within pavement management systems (PMSs), pavement performance models are used for the following activities:

- Estimating future pavement conditions.
- Identifying the appropriate timing for pavement maintenance and rehabilitation actions.
- Identifying the most cost-effective treatment strategy for pavements in the network.
- Estimating statewide pavement needs required to address agency-specified goals, objectives, and constraints.
- Demonstrating the consequences of different pavement investment strategies.

Therefore, it is important that the performance models are reliable and represent the actual deterioration trends as closely as possible. The closer the performance models reflect agency-specific deterioration patterns, the less likely the system is to misrepresent future condition levels or the impacts of various construction programs.

In anticipation of developing pavement performance models, the Pennsylvania Department of Transportation (PennDOT) initiated a study in 2009 to investigate performance modeling activities and condition information used by other state highway agencies (SHAs), and to obtain recommendations on how to proceed with their own modeling efforts. The findings and recommendations of the study are detailed in the *Final Report* of the project and the considerations and recommendations are highlighted in this *Executive Summary*.

Considerations

Several performance modeling objectives and key considerations were outlined prior to the development of model recommendations. The following objectives for pavement performance modeling were identified:

1. Provide a methodology for predicting future funding needs.

   One reason for developing pavement performance models is to predict future conditions and, based upon the predicted condition, determine treatment recommendations and corresponding funding needs. Being able to conduct "what-if" funding scenarios is a high priority for PennDOT; this need is a major impetus for the implementation of a pavement management system.

2. Provide practical and implementable predictions that can be explained to decision makers.

   Many agencies would like transparent pavement management recommendations based on reliable data and on performance models that reflect actual conditions. Likewise, PennDOT wants its pavement performance models to be based on reliable and obtainable data. In addition, PennDOT prefers a transparent process that can be easily explained to all stakeholders.

3. Select models that may be easily incorporated into pavement management software.

   It is important that the models PennDOT uses can be easily incorporated into the pavement management system it is preparing to select and implement. Therefore, a probabilistic approach was not considered, as many software programs do not easily accommodate probabilistic models without requiring extensive software modifications or a conversion of the probabilistic models to a deterministic format.

4. Utilize existing data collection procedures and historical data as much as possible.

   PennDOT would like to be able to implement its models without having to dramatically change its current data collection practices. Therefore, the use of existing data collection procedures and historical data collected by the Roadway Management Division of the Bureau of Maintenance and Operations was be a priority in developing recommendations.

In addition to adhering to the objectives just discussed, there are several key considerations that were weighed when determining the feasibility of potential modeling approaches for PennDOT's use. These considerations include the following:

- What will the model predict?

  When developing models, consideration must be given to whether the models are going to predict distresses, individual indices (e.g., cracking index, rutting index, etc.), or an overall index. The prediction of individual distresses is a more complicated approach than the development of predictions of either individual indices or an overall index.

- How will an overall index be calculated?

  The overall index can be calculated using deduct values based solely upon distress or a combination of both distress and ride. Depending upon the needs of the agency, either option is a viable approach.

- What rating scale will be used?

  A variety of rating scales are used by various agencies. The most prominent scale is a 100-point scale. However, a scale can be based on any value desired by the agency.

- Should models be developed for pavement families or should individual models be developed?

  Performance models can be created for groups of pavements, known as "families," or for each individual pavement section. Many agencies focus on the development of family models, as this is a simpler method that results in the development of a smaller number of equations. The family modeling approach is also sometimes easier to incorporate into a pavement management system than individual models.

- What type of model will be used?

  The majority of agencies use deterministic models, because their form makes them easier to explain to users and they are often easier to incorporate into the pavement management system. Nevertheless, there are agencies that utilize other forms, including probabilistic or expert models.

- What variables will be considered in the model?

  Pavement performance models can contain a variety of variables. However, the majority of models include the incorporation of age as the primary predictor of condition. Some agencies do expand their models to consider additional factors such as traffic, layer thicknesses, and so on. However, the effort to incorporate additional variables can be significant.

- Who will develop the models?

  Models can be developed by an agency or through the use of consultants or software vendors. The choice often depends upon the skills of available staff within the agency.

- What pavement management software will be used?

  The development of models is also dependent upon the pavement management software that the agency will use. For example, some systems incorporate individual pavement models more readily than others.

- What level of effort is required to develop the models?

  The level of effort needed to develop models is another major consideration when moving forward with model development. For example, the development of distress models for individual sections requires a more significant effort than the development family models.

Recommendations

A preferred pavement performance modeling approach for PennDOT was developed. In addition, in case the preferred approach should fail to provide the desired modeling results, two alternative approaches were created.

The recommended option (option 2 as described in the final report) is to use the current treatment selection matrix for determining short-term treatment recommendations and to develop pavement performance models that can be used to determine longer-term treatment recommendations A summary of the recommendations relative to option 2 are provided below:

- The pavement performance models will predict overall pavement condition.
- The overall index will be calculated using distress and ride.
- A 100-point rating scale will be used for the overall index.
- Pavement family models will be developed for the prediction of the overall index. These will be in accordance with the categories in the treatment selection matrix.
- The model form will be deterministic.
- The pavement performance models will use surface age as the independent variable used to predict pavement age.
- The models will be developed in-house with the use of consultants or University personnel if help is needed.
- The model development will begin before the selection of a pavement management system, as the implementation of pavement management software is at least a year away.

It should be noted that the proposed recommendations present a moderate level of effort for PennDOT if the agency moves forward with development in-house. Given the modeling recommendations, a final summary of the overall steps needed to develop the performance models according to the proposed option are summarized below:

- Develop the overall condition index.
- Calculate overall index and surface age for all historical condition survey data.
- Develop pavement performance family models using proposed option.
- Assess models for reliability.
- Implement final models.
- Update models (initially every 2 years with new data collection).

As PennDOT moves forward with the proposed performance modeling approach, the details outlined in the *Final Report* can guide the process. As evidenced in the report, the process for developing performance models is somewhat dictated by the data available. In the past, initial attempts by PennDOT to model individual distress types did not show significant promise. However, the use of other modeling options, or the use of age as a predictor, may prove to have better predictive capabilities than were available through past efforts. Therefore, although option 2 is the recommended modeling approach, if data issues arise that complicate the development of models in the prescribed manner, it may be more advantageous to further examine a different modeling option, such as option 3. Modeling is not a clear-cut, step-by-step process, and the details of the individual options may need to be adapted to allow the most robust models to be developed.

TABLE OF CONTENTS

EXECUTIVE SUMMARY I

CHAPTER 1 – CURRENT PAVEMENT PERFORMANCE MODELING PRACTICES 1

1.1 Introduction.. 1

1.2 Literature Review 1

1.2.1 Performance Modeling Overview 1

1.2.1.1 Individual versus Family Models... 2

1.2.2 Criteria for the Development of Pavement Performance Models 3

1.2.2.1 Adequate Functional Form of the Model.................................... 3

1.2.2.2 Inclusion of Significant Variables 10

1.2.2.3 Adequate Database 13

1.2.2.4 Satisfaction of the Statistical Criteria Concerning the Precision of the Model.. 15

1.2.2.5 Summary 16

1.3 State-of-the-Practice: Other State Agencies 16

1.3.1 Survey Results 17

1.3.2 Survey Summary... 25

1.4 Summary of Featured Practice 27

1.4.1 Minnesota.. 27

1.4.1.1 Survey Procedure 28

1.4.1.2 Performance Modeling Practices... 28

1.4.1.3 Steps Taken to Advance Modeling Efforts................................. 30

1.4.2 North Dakota 30

1.4.2.1 Survey Procedure 30

1.4.2.2 Performance Modeling Practices... 32

1.4.2.3 Steps Taken to Advance Modeling Efforts................................. 33

1.4.3 Oklahoma.. 33

1.4.3.1 Survey Procedure 33

1.4.3.2 Performance Modeling Practices... 34

1.4.3.3 Steps Taken to Advance Modeling Efforts.................................. 35

1.4.4 Oregon 35

1.4.4.1 Survey Procedure 35

1.4.4.2 Performance Modeling Practices ... *37*

1.4.4.3 Steps Taken to Advance Modeling Efforts ... *38*

1.4.5 Washington ... 38

1.4.5.1 Survey Procedure ... *38*

1.4.5.2 Performance Modeling Practices ... *39*

1.4.5.3 Steps Taken to Advance Modeling Efforts ... *40*

1.4.5.4 Case Study State Summary ... *40*

CHAPTER 2 – PRACTICE COMPARISON ... 42

2.1 Introduction ... 42

2.2 Summary of PennDOT Current Data Collection Activities and Past Performance Modeling Practices ... 42

2.2.1 Pavement Condition Data Collection Methods ... 42

2.2.1.1 Profile Data ... *42*

2.2.1.2 Rut Data ... *43*

2.2.1.3 Pavement Distress Data ... *43*

2.2.2 Past Pavement Performance Modeling Efforts ... 46

2.2.2.1 Concrete Pavement Models ... *47*

2.2.2.2 Bituminous-Surfaced Pavement Models ... *48*

2.3 Comparison of PennDOT Practices to Other SHAs ... 49

2.3.1 Data Collection Methods ... 49

2.3.2 Modeling Practices ... 60

2.4 Summary ... 64

CHAPTER 3 – PROPOSED MODELING OPTIONS ... 65

3.1 Objectives for the Proposed Modeling Approaches ... 65

3.2 Proposed Modeling Approaches ... 67

3.2.1 Option 1: Maintain Current Treatment Selection Matrix and Develop Supporting Distress Performance Models ... 67

3.2.1.1 Determine Modeling Approach ... *68*

3.2.1.2. Option I: Select Family Models ... *70*

3.2.1.3 Option II: Select Individual Models ... *70*

3.2.1.4 Create List of Model Forms ... *70*

3.2.1.5 Develop Models ... *71*

3.2.1.6 Evaluate Results for Sufficient Data, Erroneous Data, and Logical Models ... *71*

3.2.1.7 Create Listing of Final Models for Consideration 72

3.2.1.8 Select Final Models by Analysis of R-squared and Visual Fit of Data 72

3.2.2 Option 2: Maintain Existing Treatment Selection Matrix for Current Needs and Develop an Overall Index to Model Future Needs 72

3.2.2.1 Determine Rating Scale for the Overall Index 73

3.2.2.2 Develop Calculation Procedure for the Overall Index 73

3.2.2.3 Calculate Values Needed for Modeling 73

3.2.2.4 Determine Modeling Approach 74

3.2.2.5 Create List of Model Forms 74

3.2.2.6 Develop Models 76

3.2.2.7 Evaluate Results for Sufficient Data, Erroneous Data, and Logical Models 76

3.2.2.8 Create Listing of Final Models for Consideration 76

3.2.2.9 Select Final Models by Analysis of R-squared and Visual Fit of Data 76

3.2.3 Option 3: Compress Current Treatment Selection Matrix and Develop Performance Models for Individual Indices 76

3.2.3.1 Determine Type of Pavement Distress Indices to Develop 78

3.2.3.2 Determine Rating Scale 78

3.2.3.3 Develop Individual Index 78

3.2.3.4 Determine Overall Index 83

3.2.4 Assessing Model Reliability 83

3.3 Recommendations 86

3.4 Summary 88

APPENDIX A – PERFORMANCE MODELING SURVEY
APPENDIX B – PERFORMANCE MODELING SURVEY RESULTS
APPENDIX C – COMPARISON OF DISTRESS TYPES
APPENDIX D – MN/DOT SURVEY PROCEDURE AND CALCULATION OF SR
APPENDIX E – NDDOT DEDUCT VALUES
APPENDIX F – OKDOT DEDUCT VALUES AND PAVEMENT CONDITION INDICES
APPENDIX G – ODOT PROCEDURE FOR CALCULATING PAVEMENT CONDITION INDICES
APPENDIX H – WSDOT PROCEDURE FOR USING DISTRESSES TO DETERMINE DEDUCTS
APPENDIX I – PENNDOT PERFORMANCE MODELING EFFORTS
APPENDIX J – STATE PERFORMANCE MODELING PRACTICES

LIST OF FIGURES

Figure 1-1. Example model forms. 5
Figure 1-2. Distress levels used by KDOT to develop condition ratings (KDOT 2009).......... 8
Figure 1-3. Comparison of expert and percentile performance curves.......... 9
Figure 1-4. Essential Data in PMS (Saadatmand 2008). 11
Figure 1-5. Example residual plot.......... 16
Figure 1-6. Percent of SHAs collecting HMA distresses. 17
Figure 1-7. Number of SHAs collecting JCPC distresses.......... 17
Figure 1-8. Number of SHAs collecting CRCP distresses. 18
Figure 1-9. SHAs use of LTPP Distress Identification Manual.......... 18
Figure 1-10. SHAs use of individual indices. 20
Figure 1-11. SHAs use of overall indices. 20
Figure 1-12. Calculation method for the overall index. 21
Figure 1-13. Condition data collected and stored in the pavement management database or other location.......... 22
Figure 1-14. Preventive maintenance (PM) and rehabilitation data collected and stored in the pavement management database or other location. 22
Figure 1-15. Design and construction data collected and stored in the pavement management database or other location. 23
Figure 1-16. Condition data collected and used in pavement performance modeling.......... 23
Figure 1-17. Preventive maintenance (PM) and rehabilitation data collected and used in pavement performance modeling.......... 24
Figure 1-18. Design and construction data collected and used in pavement performance modeling. 24
Figure 1-19. Example RQI performance model (Lukanen 1986).......... 29
Figure 1-20. Distress percentages based upon age and "k" value (Lukanen 1986).......... 30
Figure 1-21. Example IRI performance model (NDDOT 2009). 33
Figure 1-22. Structural index performance model for HMA pavements with medium-high traffic volumes (OKDOT 2009). 35
Figure 1-23. Index calculation example from ODOT (ODOT 2008).......... 37
Figure 1-24. Model RSL used by ODOT.......... 38
Figure 1-25. Example PSC power models (WSDOT 1993).......... 39
Figure 1-26. Regression process used in WSPMS to predict PSC (WSDOT 1993). 40
Figure 2-1. PennDOT trial performance model (PennDOT 2009).......... 48
Figure 3-1. Option 1 model development workflow. 69
Figure 3.2. Option 2 model development workflow.......... 73
Figure 3-3. Option 3 model development workflow. 77
Figure 3-4. PennDOT treatment selection matrix for transverse cracking on bituminous pavements. 80
Figure 3-5. Example of PennDOT treatment selection matrix modified to include distress index scale.......... 84
Figure 3-6. Assessment of models workflow. 85

LIST OF TABLES

Table 1-1. Example Markov transition probability matrix. 7
Table 1-2. Continuous data to be considered in model development (Deighton 2004). 12
Table 1-3. Categorical data to be considered in model development (Deighton 2004). 13
Table 1-4. Performance modeling update schedule. 25
Table 1-5. Comparison of HMA distresses collected by States to those collected by PennDOT. 26
Table 1-6. Comparison of JPCP distresses collected by States to those collected by PennDOT. 26
Table 1-7. Comparison of CRCP distresses collected by States to those collected by PennDOT. 27
Table 1-8. Alligator Cracking deducts used by NDDOT (NDDOT 2009). 31
Table 1-9. Bleeding deducts used by NDDOT (NDDOT 2009). 32
Table 1-10. Summary of practice for case study States. 41
Table 2-1. Rating (conversion) values based upon distress extents and severities. 47
Table 2-2. Comparison of bituminous-surfaced pavement distresses collected by PennDOT to the other SHAs. 50
Table 2-3. Comparison of rigid pavement distresses collected by PennDOT to the other SHAs. 52
Table 2-4. Summary of practice for case study States. 55
Table 2-5. Review of PennDOT's use of HPMS data specifications. 56
Table 2-6. Review of PennDOT's use of MEPDG "Analysis Parameter" inputs. 58
Table 2-7. Summary of agencies that develop performance models and the level at which they are created. 60
Table 2-8. Summary of practice for case study States. 62
Table 3-1. Key modeling considerations for the case study states. 67
Table 3-2. Family groupings for the development of the Overall Index models. 75
Table 3-3. PennDOT pavement distress treatments and treatment groups. 79
Table 3-4. PennDOT pavement distress treatment combinations matrix. 79
Table 3-5. Example of ascending pavement condition scale correlated to PennDOT treatments. 81
Table 3-6. Ability of proposed modeling approaches to meet desired goals. 87

CHAPTER 1 – CURRENT PAVEMENT PERFORMANCE MODELING PRACTICES

1.1 Introduction

Within pavement management systems (PMSs), performance models are used to predict future pavement performance. Therefore, it is important that the performance models are reliable and represent the actual deterioration trends exhibited by the agency's pavements as much as possible. Pavement prediction models are important to pavement management for the following activities:

- Estimating future pavement conditions.
- Identifying the appropriate timing for pavement maintenance and rehabilitation actions.
- Identifying the most cost-effective treatment strategy for pavements in the network.
- Estimating statewide pavement needs required to address agency-specified goals, objectives, and constraints.
- Demonstrating the consequences of different pavement investment strategies.

It should be clear from the role of the pavement performance models in a PMS that the closer the performance models reflect agency-specific deterioration patterns, the less likely the system is to misrepresent future condition levels or the impacts of various construction programs. Accuracy in the models is also required to prevent agencies from incorrectly estimating the year in which rehabilitation is needed, or incorrectly reporting the pavement rehabilitation needs.

In anticipation of the development of pavement performance models using historical pavement condition information, PennDOT initiated a study to investigate the performance modeling activities and condition information used by other state highway agencies (SHAs) in 2009. This report summarizes the findings of the study and recommends options for PennDOT to consider when developing performance models.

1.2 Literature Review

Many State highway agencies around the country have undergone the development of pavement performance models or are in the process of doing so. Under this project, a literature review of sources documenting pavement performance modeling practices was conducted. The reviewed documents served as the foundation for an overview of performance modeling practices and the detailing of criteria needed to develop reliable models as presented in the next two sections.

1.2.1 Performance Modeling Overview

Pavement performance modeling is a portion of the overall pavement management process used by agency personnel to help make informed decisions regarding the maintenance and rehabilitation of a pavement network. The level of sophistication and types of data required for modeling (along with all other components of the pavement management process) vary depending on the needs of the user. Therefore, agencies differ in the types of data used in developing their pavement performance models. Many of these differences stem from dissimilarities in the pavement condition survey procedures followed. For example, some agencies elect to use the pavement condition data in its raw form while others use the raw data to calculate one or more condition indexes. Data can then be modeled in different forms for individual pavement sections or for groups of pavements with similar characteristics (referred to as families) using a variety of data elements to categorize the pavement sections correctly. The combinations of various attributes create a variety of modeling options.

A summary of SHA practices in pavement performance modeling and the use of the models in pavement management are discussed in more detail in the following sections. It is interesting to note that a recent survey of the status of pavement management applications in the United States by Saadatmand (2008) indicates that 76 percent of respondents were using their PMS to forecast pavement conditions, and that 65 percent of respondents were using their PMS to track pavement performance.

1.2.1.1 Individual versus Family Models

When developing pavement performance models for a pavement network, an agency may use individual section models or family models within its PMS. An individual model is based on the use of historical data from that particular piece of pavement. Individual models require a minimum of two data points to create a linear deterioration model, but most agencies will not use an individual model unless they have 3 to 5 data points that show a reasonable deterioration trend. The Minnesota DOT, for example, requires the recording of 3 years of performance data before they will use a section-specific performance model.

When insufficient data exist for an individual pavement section to allow it to be modeled based upon its own performance, its condition data can be combined with data from other pavement sections that have similar performance characteristics to develop a model. The resulting grouping is called a family, which is defined in pavement management as a group of similar pavement sections that are expected to perform in a similar manner. A pavement family might be a group of pavements with the same surface type, underlying pavement layers, and traffic levels. Performance models are created for a given pavement family by first plotting the condition of the sections versus the age of each corresponding section for each inspection. Regression techniques are then applied to predict the behavior of the data based upon the age of the pavement.

The Colorado Department of Transportation uses both individual and family models. Currently, they use raw distress data (IRI, rut, fatigue cracking, block cracking, transverse cracking, longitudinal cracking, and corner breaks) to create index values on a 1 to 100 scale for each distress type. Site-specific deterministic performance curves are then created for a project section if at least 5 years of performance data is available since last rehabilitation, the data has a standard deviation less than 10, and if a minimum coefficient of regression ($R^2 = 0.50$) is obtained. If a site-specific curve cannot be developed for a project section, the next option is the development of a family curve followed by the use of a default curve.

When the development of family curves is a necessity, curves are created using the criteria of pavement type (asphalt, asphalt over concrete, concrete, and concrete over asphalt), traffic (low, medium, high, very high, and very very high), climate (very cool, cool, moderate, and hot), and pavement thickness (Asphalt: 0 to 4 inches, 4 to 6 inches, and greater than 6 inches; Concrete: less than 8 inches and greater than 8 inches). When less than 9 data points exist for a given family curve, a default curve developed on expert opinion is used (Keleman, Henry, and Farrokhyar 2003).

The Louisiana Department of Transportation and Development (LADOTD) also utilizes a family modeling approach for its performance models. Their models are separated into four pavement families for the purpose of pavement condition analysis: interstate highway system (IHS), national highway system (NHS), State highway system (SHS) and regional highway system (RHS). The pavement families are based on the pavement type (composite, asphalt, jointed? concrete and continuously reinforced concrete) and the highway classification system (IHS, NHS, SHS and RHS) (Khattak et al. 2008).

Other agencies, such as the Maryland State Highway Administration (MDSHA), also use pavement families to develop performance models. In terms of pavement performance modeling, Maryland utilizes 36 models, which are a combination of 3 traffic levels (low, medium, and high), 3 pavement types (flexible, rigid, and composite), and four last major treatment levels (15 years, 12 years, 8 years, and 5 years). These major treatment levels define the life expectancy if a treatment is applied to the pavement section. Using these three criteria to group the pavement sections, matrices that define the probability of deterioration for each pavement group are developed (Stephanos et al. 2002).

1.2.2 Criteria for the Development of Pavement Performance Models

Early in the history of pavement management, a study outlined basic criteria that should be followed to develop reliable pavements performance models at any level within a transportation agency. The four highlighted items were (Darter 1980):

- An adequate functional form of the model.
- The inclusion of all significant variables that affect performance.
- An adequate database.
- The satisfaction of the statistical criteria concerning the precision of the model.

The literature also emphasized the importance of understanding the principles behind each of the models so that the proper model type and form can be selected. It is important that the data needed to develop the models are available and that they continue to be updated as changes occur. It is also imperative that the limitations of each model be understood so that they are not used outside the intended range. Over time, these recommendations are the basis for the development of reliable performance models and each of these needs are discussed in more detail in the following sections.

1.2.2.1 Adequate Functional Form of the Model

It is important that the models be used appropriately, so the limitations of each model must be considered. This relates directly to the selection of the appropriate form of the equation so that all physical and mathematical boundary conditions are satisfied.

There are several different model forms that are used in pavement management, including linear, polynomial, and power functions. In addition, there are four broad categories of pavement performance models: deterministic, probabilistic, expert or knowledge-based, and biologically-inspired models. A discussion of the typical model forms used within each model category is presented.

The way a model will be used influences the selection of model type. The most common approaches used for network-level pavement management include deterministic and probabilistic models. In the following sections, each type of model is discussed, and information is presented regarding the various forms that can be used for each modeling type (Zimmerman 1996).

1.2.2.1.1 Deterministic Models

Deterministic models most often predict a single dependent value (such as the condition of a pavement) from one or more independent variables (such as the age of the pavement, past cumulative traffic, environment, and pavement construction characteristics). Most deterministic pavement performance models are based on regression analysis, which uses two or more variables in a mathematical equation to predict the dependent variable (performance measure) as a function of the independent variable. The coefficients of the equations are estimated to minimize the difference between the regression line and actual data through least squares regression. The linear least squares regression involves estimating coefficients by minimizing the sum of the squared deviations between the observed and predicted values to determine the model with the best fit to the data. For proper predictions in the PMS, the deterministic model forms must be constrained so that conditions consistently degrade as time and/or traffic increase.

The simplest regression form is linear. The general form of the equation is shown in equation 1-1. In a linear regression model, the behavior of the independent variable is used to explain the behavior of a dependent variable.

$$y = b_0 + b_1 x \qquad (1\text{-}1)$$

where:
- y = dependent variable
- x = independent variable
- b_0 and b_1 = coefficients

Often the regression equation is based upon an S-shaped deterioration curve. Higher order (polynomial) regressions yield curvilinear relationships between the independent and dependent variable and are represented by equation 1-2.

$$y = b_0 + b_1 x + \ldots + b_n x^n \qquad (1\text{-}2)$$

where:
- y = dependent variable
- x = independent variable
- $b_0, b_1, \ldots b_n$ = coefficients

The main differences between the two regression methods are the increased complexity of the form of the equation that the multiple variable regression model can take and the fact that the coefficients are no longer linear.

Another typical deterministic equation form used for pavement management is a power function such as the equation form used by the Washington State Department of Transportation. An example of the power form of the equation is shown in equation 1-3.

$$y = b_0 - b_1 x_1^{b2} \qquad (1\text{-}3)$$

where:
- y = dependent variable

x_1 = independent variable
b_0, b_1, b_2 = coefficients

For equations 1-1 through 1-3, the linear least squares regression technique is used to determine the best fit of the model through variable coefficients that represent the smallest sum of the squared differences between the observed and predicted values. Figure 1-1 provides an example pictorial representation of how these three model forms (linear, polynomial, and power) could predict the condition of the pavement versus the age.

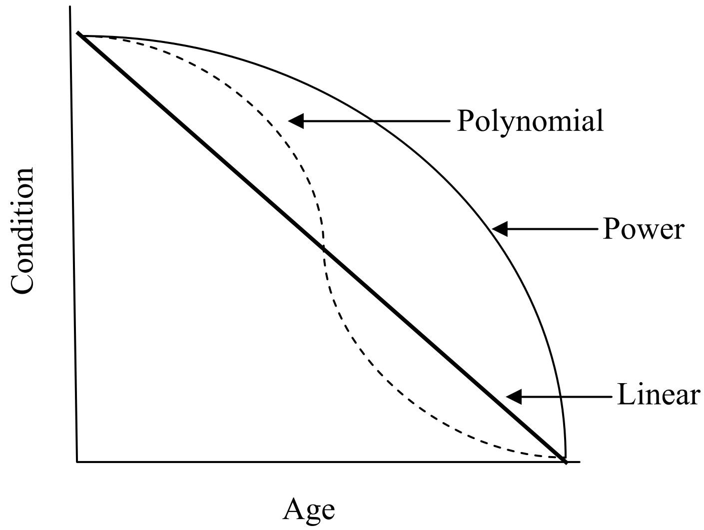

Figure 1-1. Example model forms.

In addition to the development of regression equations created from a single variable, some agencies consider the use of multiple variables. In a multiple regression model, the behaviors of several independent variables are used to estimate the performance of a dependent variable. The general form of the equation, which is an expanded version of the linear least squared regression equation, is shown in equation 1-4.

$$y = b_0 + b_1x_1 + b_2x_2 + \ldots b_nx_n \qquad (1\text{-}4)$$

where:
y = dependent variable
x_1, x_2, …x_n = independent variables
b_0, b_1, b_2, …b_n = coefficients

Since there are multiple independent variables, agencies may be interested in determining the interactions between some of the variables. Along with including these variables independently, the interactions between the terms can be evaluated by creating variables that combine two independent variables. For example, if traffic and pavement thickness are both included as independent variables in the equation, each may be included as a variable represented as x_1 and x_2 in the equation while the product of the two variables might also be included in the equation and would be added as another term (x_1*x_2) in equation 1-4. Inclusion of these types of interactions further complicates the regression analysis because it adds to the number of variables included in the analysis. Multiple regression can be a somewhat time consuming process because the variables included in the final multiple regression equation must be determined through a step-wise addition and deletion process or the use of statistical software to automate this process. However, the use of multiple variables (rather than a single variable) has the potential of better estimating the performance of an individual section because of the number of variables specific to the section. If a single variable such as age is used, two sections from the same family will have identical performance predicted if they have the same starting condition. On the other hand, if a variable is used to predict performance, you must have confidence in its value. If it's only used to separate pavement sections into families, the specific value is less important. Therefore, agencies should only use multiple variables if they have confidence in both.

Deterministic and probabilistic models (discussed in the next section) are the most commonly used models within pavement management. The majority of SHAs utilize deterministic models. For example, the Arizona Department of Transportation (ADOT) has developed deterministic pavement performance models using non-linear regression analysis that are based on polynomial functions that produce an S-shaped curve. ADOT utilizes two broad categories of pavement performance models – one based on the Pavement Serviceability Rating (PSR), which is a function of the International Roughness Index (IRI), and another based on the extent of cracking at a given age. ADOT uses a family-based approach wherein pavements with similar characteristics are grouped into one category. The following categories are considered for the development of the family classifications: last rehabilitation activity, pavement type, environmental conditions, traffic, subgrade conditions, and structural thickness (Li et al. 2006).

As discussed earlier, LADOTD also utilizes deterministic performance models that are linear, polynomial or exponential functions relating the pavement age to the roughness index, rutting index and other distress indices (Khattak et al. 2008). These examples show agencies that have developed single variable regression models. While these models are easy to develop and understand, because only one variable is used to predict performance, their accuracy can be limited. Therefore, some agencies, such as the Kansas Department of Transportation (KDOT), have developed very sophisticated performance prediction equations dependent upon a variety of variables. For example, the impact of the change in IRI due to a structural action has the predictive equation shown in equation 1-5. The models developed by Kansas are integral in determining performance of the pavement sections. KDOT uses the predicted change in IRI along with other distress types to determine a distress index. The index is then used in probabilistic models to predict overall condition.

$$\begin{aligned}\Delta IRI = -35.1 + 0.688 * IRI_{prior} - 5.16 * Composite \\ - 2.64 * EqThick + 0.0467 * IRI_{prior} * EqThick\end{aligned} \qquad (1\text{-}5)$$

where:

IRI_{prior} = IRI before the action

Composite = Composite index

Eq Thick = equivalent thickness (inches) of the planned action

1.2.2.1.2 Probabilistic Models

Unlike deterministic models, probabilistic models predict a range of values, such as the likelihood that a pavement will change from one condition state to the next in a single reporting cycle. Probabilistic models include survivor curves, Markov, and semi-Markov transition processes that estimate the likelihood of pavement sections changing from one condition State to another.

An example Markov transition probability matrix is shown in table 1-1. In pavement management, the Markovian theory assumes that the current condition state of the pavement is only dependent on the preceding pavement state. So for each predefined condition state, probabilities are assigned to estimate what percentage of pavement sections will stay in the same condition or move to another condition state.

Table 1-1. Example Markov transition probability matrix.

Condition State	**State 1 (100 – 81)**	**State 2 (80 – 61)**	**State 3 (60 – 41)**	**State 4 (40 – 0)**	**State 5 (20 – 0)**
State 1 (100 – 81)	0.90	0.10			
State 2 (80 – 61)	0.05	0.65	0.30		
State 3 (60 – 41)		0.05	0.50	0.35	0.10
State 4 (40 – 20)			0.05	0.75	0.20
State 5 (20 – 0)				0.05	0.95

Probabilistic models provide an opportunity to accommodate uncertainty and to predict performance when no historical database is available. However, since the models only depend on the current condition state, there is no opportunity to include other variables (such as traffic loading) that often contribute to performance and that are often changing over time. Since the Markov models do not allow for changing conditions over time, Semi-Markov models can be used. These models allow transition probability matrixes to be created and used together to provide piecewise increments of time.

As mentioned previously, KDOT utilizes Markov prediction modeling, using combinations of severity and extent to map levels of distress. For example, they use the descriptions in figure 1-2 to set distress levels for concrete pavements. Based upon the distress levels for each distress type, they create a three digit distress state (111 – 333). The resulting index is used in the Markov modeling process to predict future performance. They also use a distress predictor called “Index to First Distress” which is a 1 to 4 value assigned to indicate the level of the last treatment. For example, a value of 1 indicates that the last action was light and is not expected to provide a long life; a value of 4 would indicate a heavy action. This “Index to First Distress” provides a way of incorporating memory into the Markov prediction process.

ATTACHMENT I -- Distress Levels per 100 foot Sample Location

Distress Type	Level 1 (Acceptable)	Level 2 (Tolerable)	Level 3 (Unacceptable)
Joint Distress (Up to four codes per sample location) joints.	Any number of Code 1 joints and less than three Code 2 joints but no Code 3 or 4 4 joints.	Any number of Code 1 joints and three or more Code 2 joints and/or five or less Code 3 joints but no Code	Any number of Code 1 and Code 2 joints and more than five Code 3 joints and/or some Code 4 joints.
Faulting (One code per sample location)	Most frequent fault height less than 0.25".	Most frequent fault height from 0.25" to 0.5".	Most frequent fault height greater than 0.5".
Transverse Cracking (Up to three codes per sample location)	Less than three Code 1 cracks, and no Code 2 or Code 3 cracks.	Three or more Code 1 cracks, and/or some but less than three Code 2 cracks, and/or some but less than two Code 3 cracks.	Any number of Code 1 cracks, and three or more Code 2 cracks, and/or two or more Code 3 cracks.

Figure 1-2. Distress levels used by KDOT to develop condition ratings (KDOT 2009).

The Iowa Department of Transportation utilizes a combination of probabilistic and deterministic performance modeling to characterize the behavior of their interstate and primary road sections within its pavement network. They utilize deterministic models for prediction of pavement performance for use in project selection and conduct the network analysis by utilizing full optimization through the use of linear programming and probabilistic performance forecasting.

At the project selection level, a multi-year prioritization is conducted based upon an incremental benefit cost analysis using the deterministic performance models. The process allows the development of recommended treatments for projects by year. The network analysis utilizes probabilistic forecasting to explain the probability of a pavement section in a specific condition state moving to a different condition state in a given year. The analysis results in a determination of budget needs along with treatment, cost, and condition distribution for the network (Smadi).

1.2.2.1.3 Expert/Knowledge-Based Models

Another type of model, expert or knowledge-based, is developed based on the collective experience and knowledge of agency personnel. Expert models are typically used when historical data are not available, when there are gaps in the data, or when a new design is being used. Many agencies use expert models when they are first implementing a pavement management system or when they modify their approach to collecting pavement condition information.

For example, in 2000, the Oklahoma Department of Transportation (OkDOT) was mandated by their legislature to implement a pavement management system. They quickly moved forward with the creation of the pavement management system (prior to any data collection and subsequent performance model development) and created performance curves based upon expert opinion.

The original expert equations, which were developed based upon a family modeling approach for various individual indices, were utilized for the initial pavement management analysis. Then, once pavement condition data had been collected around the State, the pavement performance models were updated to see how they compared to the expert curves.

The modeling approach using actual pavement condition data utilized the least squares curve-fitting approach from a regression analysis to produce pavement performance models. A total of four functional modeling forms were evaluated: linear, cubic, quadratic, and the power model (also referred to as the Washington State model). For each model form, 25th, 50th, and 75th quantile curves are also defined to provide a more complete evaluation of the data sets. The three quantiles are defined as follows (Freund and Simon 1995):

- The first quantile, the 25th quantile, is the median of all the values to the left of the median position for the whole set of data.
- The second quantile, the 50th quantile, is the median.
- The third quantile, the 75th quantile, is the median of all the values to the right of the median position for the whole data set.

A comparison of the expert curve to the percentile curves is shown in figure 1-3.

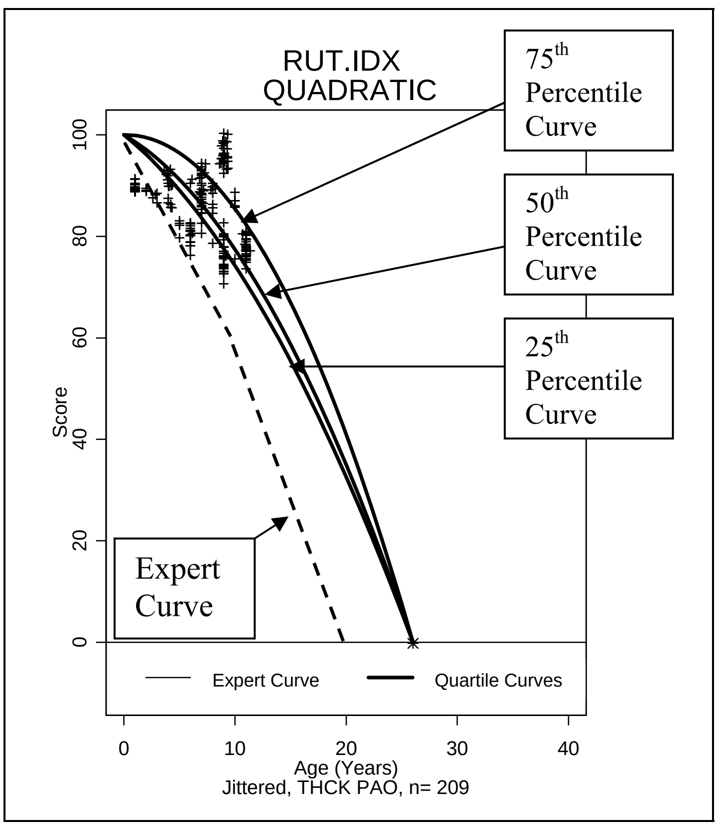

Figure 1-3. Comparison of expert and percentile performance curves.

As shown in figure 1-3, the use of actual data resulted in performance curves that predicted significantly better performance compared to the expert curve.

1.2.2.1.3 Biologically-Inspired Models

Biologically-inspired models are a relatively new category of performance models that have been investigated often in research. Genetic algorithms (GA) and artificial neural network (ANN) based models are typical models in this category. The GA models are based on the theory of evolution. The evolution is achieved in a process similar to that of biological evolution. The fitness of the individuals in the population is evaluated, followed by the creation of a new population using three key operations: reproduction, crossover and mutation of the individuals in the original population. These kinds of models are iterative models. Research had indicated that the GA-based models can be successfully implemented when the available data is scarce and time-consuming to obtain.

ANN-based models are another important class of biologically-inspired models. ANN-based models can be regarded to be highly simplified models of the human brain system. The capabilities of the human brain – learning, generalization and abstraction – are simulated by these kinds of models. Several ANN-based models have been used to model pavement performance (FDOT 2003) for research purposes, but have not been often used within pavement management systems.

1.2.2.1.4 Additional Modeling Approaches

Similar to the use of GA and ANNs, additional modeling efforts have been examined that utilize complex regression and statistical analysis. The modeling efforts which are beyond the use of empirical regression have been documented in the literature as an effective way of predicting performance of pavement infrastructure (Prozzi and Hong 2008) even at the network-level using mechanistic-empirical methods (Ullidtz 1999). However, these efforts, while proven extremely effective at predicting performance, have found little use in fully implemented pavement management systems, as many available pavement management systems do not accommodate them.

1.2.2.2 Inclusion of Significant Variables

Similar to the importance of the form, performance models must also focus on including variables that are significant to pavement performance. Data requirements for performance models vary depending on the type of model being developed. At the most basic level, inventory and monitoring information are the significant variables used to develop the models. Inventory data include any network data that do not change with time or traffic, such as geographic location and section length. Monitoring data are influenced by time and traffic and the future changes in monitoring data are most commonly calculated by the performance models. Examples of monitoring data include pavement condition, crack quantities, pavement roughness, and pavement rutting.

Pavement performance models can be developed with little more than pavement age, surface type, and condition data. However, the reliability of the models is generally improved when additional significant variables that influence pavement performance are considered, such as traffic loads, environmental factors, and pavement structure.

The literature search results indicate that agencies are using a variety of data to develop their performance models. The study by Saadatmand provides details on the essential pavement management data elements used a PMS some of which are then used in developing performance models (2008). The results are shown in figure 1-4.

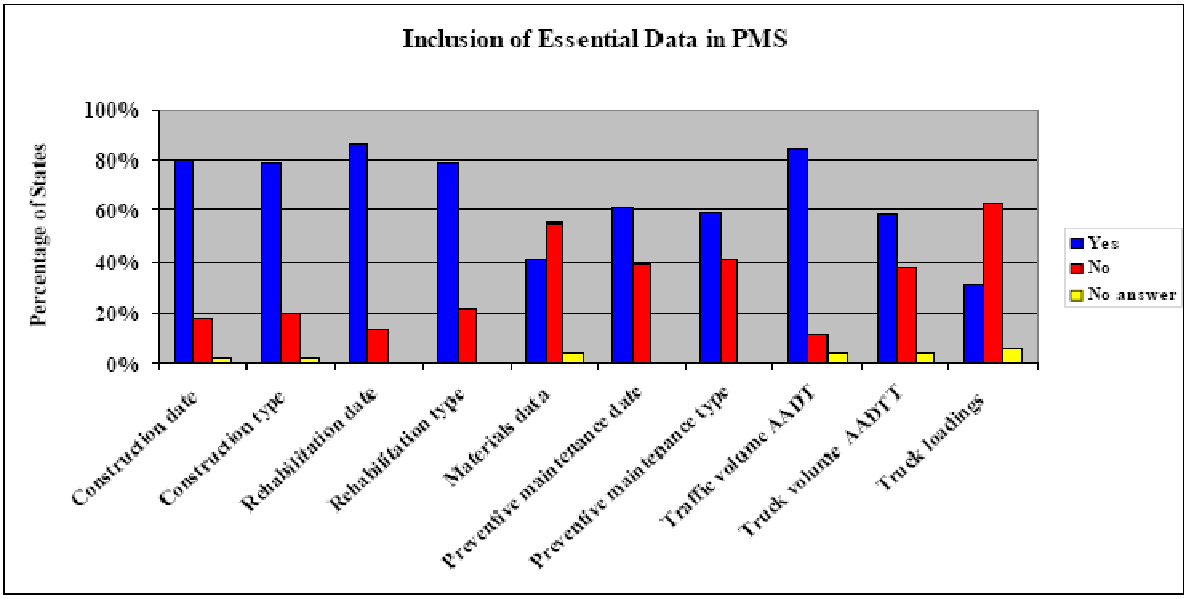

Figure 1-4. Essential Data in PMS (Saadatmand 2008).

According to the literature, some agencies have conducted research studies to determine the data that have the most significant impact on pavement performance. For example, the Vermont Agency of Transportation (VTrans) underwent a pavement performance modeling study to determine what data to include in their models. The study included an extensive statistical analysis of their data, since VTrans was trying to take as much pavement data into consideration as possible. The data were evaluated and tested statistically before being used to develop updated models.

The Vermont data set consisted of two classes of pavement data variables that were considered for inclusion in the pavement performance models: continuous data and categorical data. Continuous data are non-discrete, numerical attributes that could be used to model pavement performance using one of the several available model forms. Categorical data could also be used to model pavement performance but in a slightly different fashion than the continuous data. Due to its discrete and often non-numeric nature, categorical data are often used to create data subsets (families) instead of being directly incorporated into the model development. The models developed using the various categorical data can be compared to one another to see which combinations of data result in models with the most appropriate characteristics.

The types of continuous and categorical data that were to be considered in the initial model development are shown in tables 1-2 and 1-3, respectively. Each table provides the name and description of the data elements considered.

After selecting the continuous and categorical data elements, the corresponding data were extracted from the pavement management database in 0.1-mile segments in order to evaluate the appropriateness of each data element for predicting the behavior of four performance indexes: structural, transverse, ride, and rut. The extracted data were divided into data sets based upon the pavement surface types.

The next step in evaluating the use of the data elements for modeling pavement performance involved testing the statistical significance of the continuous data elements. For each surface type data set, the continuous data elements were tested individually for statistical significance to the individual condition indexes. Further, the categorical data elements were used to create data subsets so that the statistical significance of each continuous data variable could also be tested individually for each data subset. The data determined to have statistical significance was considered further for use in the performance model development.

Table 1-2. Continuous data to be considered in model development (Deighton 2004).

Type of Data	Attribute Name	Description
Cores	Depth	Represents the post treatment surface depth. Non-reclaim sections calc from pre-treatment cores depth plus any milling and overlay.
Frost Depth	Max Pen	Frost penetration in inches.
Frost Depth	Min Pen	Frost penetration in inches.
FWD Tests	D1	Center deflection (mu).
FWD Tests	D2	Deflection at sensor 2 (mu).
FWD Tests	D3	Deflection at sensor 3 (mu).
FWD Tests	D4	Deflection at sensor 4 (mu).
FWD Tests	D5	Deflection at sensor 5 (mu).
FWD Tests	D6	Deflection at sensor 6 (mu).
FWD Tests	D7	Deflection at sensor 7 (mu).
FWD Tests	D8	Deflection at sensor 8 (mu).
FWD Tests	D9	Deflection at sensor 9 (mu).
Pavement Types	Construction Year	Year of pavement construction or reconstruction. Engineered pavements only.
Traffic	AADT 2000	The AADT for the section from 2000.
Traffic	Heavy Trucks	Heavy Trucks per Day (Class 8-13).
Traffic	Heavy Trucks Percent	Heavy Trucks percent of traffic stream (Class 8-13).
Traffic	Total Trucks	Total Trucks per Day (Class 4-13).
Traffic	Total Trucks Percent	Total Trucks percent of traffic stream (Class 4-13).
Project History	Treatment Thickness	Depth of new material excluded cold in place material.
Project History	Treatment Age	Calculated from treatment year.

Table 1-3. Categorical data to be considered in model development (Deighton 2004).

Type of Data	Attribute Name	Description
Class	Class Number	1=class1, 2=state, 3=interstate
Districts	District	District number (1 to 9).
Frost	Frost Action	Indicates if section is affected by frost action. Note entire perspective is set to true.
Frost Depth	Frost Zone	Table of frost depth penetration ranges.
Lanes	Is Divided	Indicates divided highway sections – Number of lanes adjusted to reflect this.
Lanes	Lanes	Number of lanes.
Pavement Types	Pavement Type	Table code of pavement type.
Project History	Is OGFC	Indicates whether an open graded friction coarse was used as surface layer.
Project History	Treatment Class	New or Rehab
Project History	Treatment Type	Table code value of treatment.
Traffic	AADT 2000	The AADT for the section from 2000. Divided into three categories – Low: Less than 1500 – Medium: 1500 to 10,000 – High: Greater than 10,000
Traffic	FC	Functional Class
Traffic	Heavy Truck Percent	Heavy Truck Percent of traffic stream Divided into three categories – Low: Less than 4% – Medium: 4% to 10% High: Greater than 10%
Traffic	Total Truck Percent	Total Truck Percent of traffic stream Divided into three categories – Low: Less than 4% – Medium: 4% to 10% – High: Greater than 10%

1.2.2.3 Adequate Database

The development of performance models is based on being able to tie physical properties to a location in the field. Therefore, data must be stored using a common referencing system to support locating and linking acquired data from disparate sources. A data structure must also provide an environment that allows for data checking and manipulation to ensure that complete, reliable, and logical data are stored in the database. Each of these necessary data characteristics are discussed in more detail below.

1.2.2.3.1 Complete data

In order for a data set to be complete, data must be provided for the majority of the pavement sections that are to be represented by the model. When a section's data set does not possess all of the variables necessary to create the model, it cannot be included in the development of the final model. As a general rule, data should be provided for approximately 50 percent of the pavement sections or the resulting models will be accounting for the behavior of less than half the pavement sections. Caution must be used in developing a model with a variable that is not fully populated as the behavior of numerous sections cannot be predicted.

1.2.2.3.2 Reliable data

All data included in developing performance models must be reliable for the predictions to make sense. First, the data must come from a reliable source and must be measured accurately and without bias. Data must also be measured and collected in a consistent manner over time regardless of who collects the data . In addition, those acquainted with the data must be sure of the data and feel confident in its use for predicting performance. If, for example, an agency feels that its truck count data are more reliable than average annual daily traffic (AADT) data, the more reliable truck count data should receive more consideration than AADT in developing the models.

1.2.2.3.3 Logical data

For any data to be utilized in a model it must agree with engineering logic; that is, it must have the proper characteristics to make it a sensible choice for inclusion in the given performance model. To be specific, only data that have the proper correlation with the performance characteristics should be included in the model development. For instance, assume that an agency has a rut index from 0 to 100, with a score of 100 indicating that no rutting is present. During the process of developing its models, the analysis indicates that truck traffic has a positive correlation to the rut index, indicating that as truck traffic increases, so does the rut index. The correlation is considered to be counterintuitive because engineering logic would lead one to expect the rutting index to decrease as truck counts increased. This trend would then indicate that the agency should not use truck traffic data in the prediction of the rutting index.

Data that is continuous in nature must also be logical from the standpoint that it should not be clustered around certain data readings. If data are susceptible to being assigned a value that is rounded to the nearest whole number, it is actually a discrete variable and it is no longer a logical choice for a continuous data variable. Instead, it may be better used as a classification variable for separating pavement groups. For instance, if pavement thickness is recorded based upon design thickness it will often be recorded to the nearest 0.25 inch and acts as a discrete instead of a continuous variable.

Not only must the data be complete, reliable, and logical, but the data must also be maintained over time so that the models continue to reflect actual pavement performance trends. For that reason, the amount of the data needed for model development must be considered from a practical point of view to ensure that the agency can collect and maintain the data within any cost and time constraints.

1.2.2.4 Satisfaction of the Statistical Criteria Concerning the Precision of the Model

As another important step in the development of reliable performance models, model precision should be examined statistically. The examination of the statistical criteria depends upon the type of model developed. Prior to assessing the overall precision of a given model, it may be necessary to evaluate the predictive capability of different variables. This is the case with deterministic models that contain multiple variables for which multiple linear regression is conducted to return coefficients for each predictor variable. In addition to values of the coefficient for each variable for use in modeling, the statistical analysis also returns the statistical significance probability of each of the coefficients. The probability value (P-value) indicates the significance of the variable in the regression equation. For example, low probability values (<0.05) signify with 95 percent confidence that the coefficient is different than zero, and that the variable coefficients are statistically significant at predicting the given performance index or measure and should be included in the predictive model.

Beyond determining the statistical predictive capabilities of specific variables, the reliability of the models themselves can also be evaluated statistically. First, models should be examined for logical assignments of positive and negative coefficients. If models are logical then they can be examined statistically in terms of coefficients of determination (R-squared) and standard errors of estimate (SEE). Various model forms and performance predictors can be compared, and those with high R-squared values and low SEE values typically best serve as the pavement performance models.

Further statistical evaluation of the models can be conducted through the evaluation of residual plots of previously extracted data. For example, prior to model development, a certain percentage (e.g., 5 percent) of the data can be extracted and not included in the model development phase. Then using the extracted data, plots of model residuals (i.e., the relative difference between the predicted and actual values) should be created to evaluate the ability of each model to predict the performance of the pavement section. An example residual plot is shown in figure 1-5.

When the residual plots of the previously extracted data are created, they provide a visual representation of how well the models predict expected performance using actual data. An ideal residual plot shows an even balance of data points above and below the zero residual line along all treatment ages.

A visual examination of the residuals will reveal a significant amount of information regarding the fit of the model to the given data set. An evaluation of the residual plot can lead to further performance curve analysis. For example, if a chosen model is over predicting or under predicting a given performance indicator, some consideration should be given to a potential shift in the endpoint of these latter models to help reduce the amount of over- and under-prediction. All in all, the examination of the residual plots provides the details necessary to adjust the models in a manner to help reduce the scatter of the residuals due to the occurrence of outliers. In some cases, it may be impossible to overcome the extreme scatter in the data by further adjusting the models. Therefore, the model has to be accepted with the given bias. For figure 1-5, the residual plot shows that the prediction model is over estimating the condition early in the life of the pavement family while later in the life (approximately 10 to 12) years the predicted conditions are balanced. For this family model, adjustments may be made to the model intercept (point where the data crosses the y-axis) to correct the over-prediction.

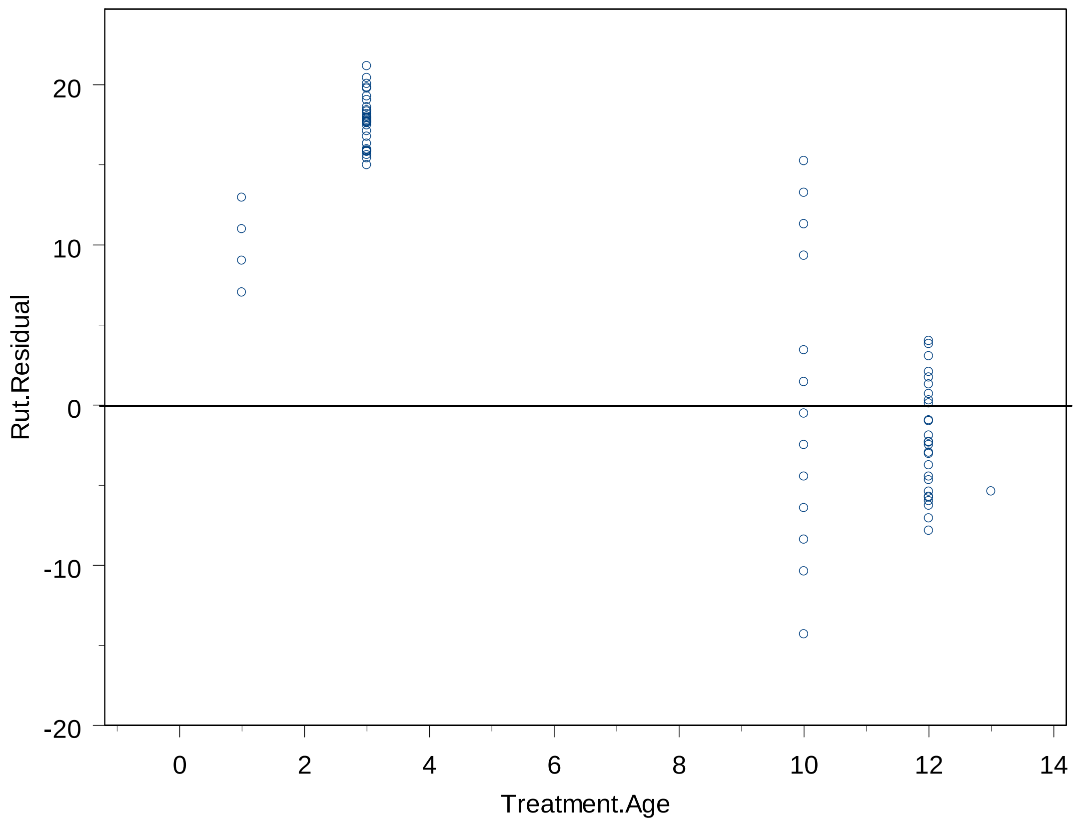

Figure 1-5. Example residual plot.

1.2.2.5 Summary

The creation of reliable performance models is important as the models are needed to provide a variety of information, including the prediction of future pavement conditions, the consequences of various investment strategies, and the appropriate type and timing for maintenance and rehabilitation treatments. The reliability of the performance models is dependent on the development of statistically sound models with proper model forms that are based on adequate and significant data.

As conveyed in the discussion, various agencies are following the needed criteria to develop performance models. More details regarding the performance modeling practices used in each State are provided in the following section.

1.3 State-of-the-Practice: Other State Agencies

The current pavement performance modeling practices used by state highway agencies (SHAs) were investigated through the use of a survey of State practice. The survey focused on identifying practices that contribute to the successful modeling of pavement condition data for pavement management purposes within SHAs. The online survey contained 23 questions and was distributed to pavement management engineers in each State through the website www.surveymonkey.com. The survey had a 76 percent response rate (37 of the 49 States). A copy of the survey that was distributed is provided in appendix A. A summary of the survey responses for all 37 agencies is provided in a matrix in appendix B. Details extracted from the matrix are discussed in more detail in the following section.

1.3.1 Survey Results

The survey included questions regarding pavement condition surveys and modeling practices. The first series of questions was focused on the pavement distresses that each agency is collecting as part of their data collection surveys for hot-mix asphalt (HMA), jointed plain concrete (JPCP), and continuously reinforced concrete (CRCP) pavements. The responses are displayed in figures 1-6 through 1-8 for HMA, JPCP, and CRCP, respectively.

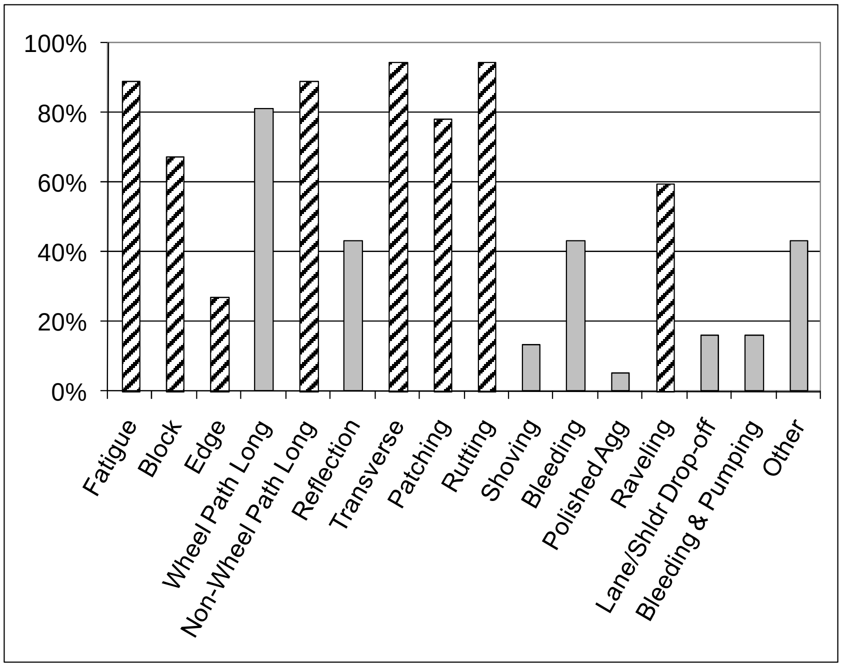

Figure 1-6. Percent of SHAs collecting HMA distresses.

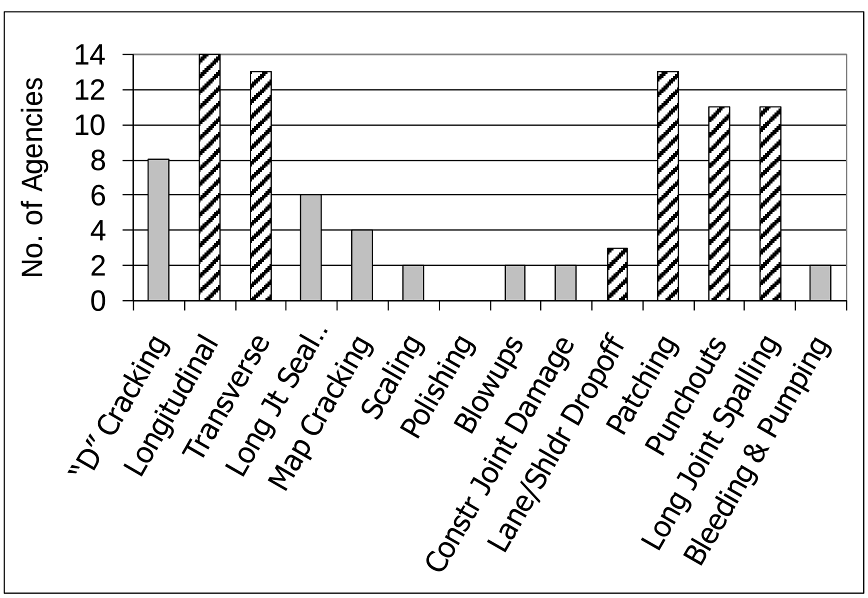

Figure 1-7. Number of SHAs collecting JCPC distresses.

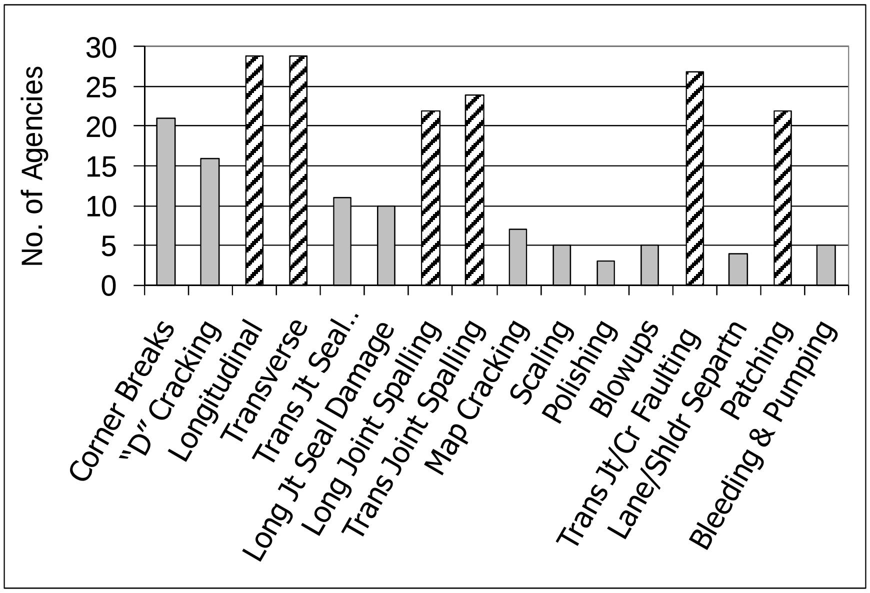

Figure 1-8. Number of SHAs collecting CRCP distresses.

The distresses that PennDOT collects are highlighted with striped columns in figures 1-6 through 1-8. Overall, there is a good deal of consistency in the types of distress data collected by PennDOT and the data collected by the responding States. The only significant exceptions include edge cracking on HMA pavements, lane shoulder separation on JPCP pavements, and lane/shoulder-dropoff on HMA and JPCP pavements.

In addition to examining what distress types are included in the condition survey, it is also important to examine the way distress data are defined. Therefore, the survey was used to ask if the SHA was using the Strategic Highway Program (SHRP) Long Term Pavement Performance (LTPP) *Distress Identification Manual* to identify and categorize pavement distresses. The resulting information to that question is shown in figure 1-9.

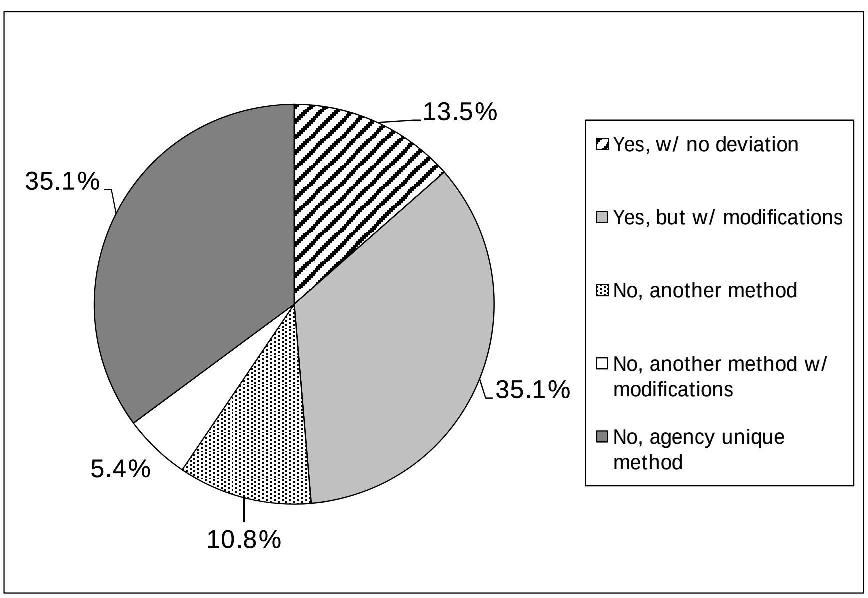

Figure 1-9. SHAs use of LTPP Distress Identification Manual.

As shown in figure 1-9, 35.1 percent of the 37 respondents use the definitions from the LTPP *Distress Identification Manual* with modifications or use their own unique method, indicating that a relatively large number of states have developed their own distress classifications for severity and extent. Of these 37 agencies, the majority (approximately 58 percent) are using a semi-automated method for collecting and analyzing the data, while 30 percent are using manual methods, and 13 percent are using automated methods.

These results also indicate that 100 percent of the agencies responding to the survey are using some form of pavement condition surveys. Although every agency has some form of condition survey, the types, rate, and amount of data collected vary tremendously based on the amount of data collected and the intervals between surveys.

The rates of collection also vary for the collection of roughness and skid data. Nearly all agencies are collecting roughness data and using it in their network-level pavement management decision making process. However, skid data are collected less frequently and often only for specific project-level needs.

Agencies were asked to indicate if they utilize individual indices to describe conditions for HMA, JPCP, and CRCP pavements. The results shown in figure 1-10 indicate that nearly all agencies utilize a ride index to describe the performance of their pavements. However, there are 6 agencies that do not calculate indices for HMA or JPCP, and 4 of those agencies do not calculate indices for their CRCP pavements. Even more agencies utilize overall indices as shown in figure 1-11, and only 2 agencies say they do not calculate an overall index to describe the condition of their pavements. Examples of the overall indices being used by the SHAs include:

- Pavement Condition Index (PCI).
- Present Serviceability Index (PSI).
- Pavement Distress Index (PDI).
- Pavement Quality Index (PQI).
- Remaining Service Life (RSL).
- Other (Overall Condition Index, Distress Score, Surface Distress Index, etc.)

For all surface types, the RSL is most consistently used as an indicator of overall pavement condition. However, there are other agencies that have created their own individual and/or overall indices that are unique to their agency. The overall indices are typically calculated from other indices rather than from raw distress data, as indicated in figure 1-12.

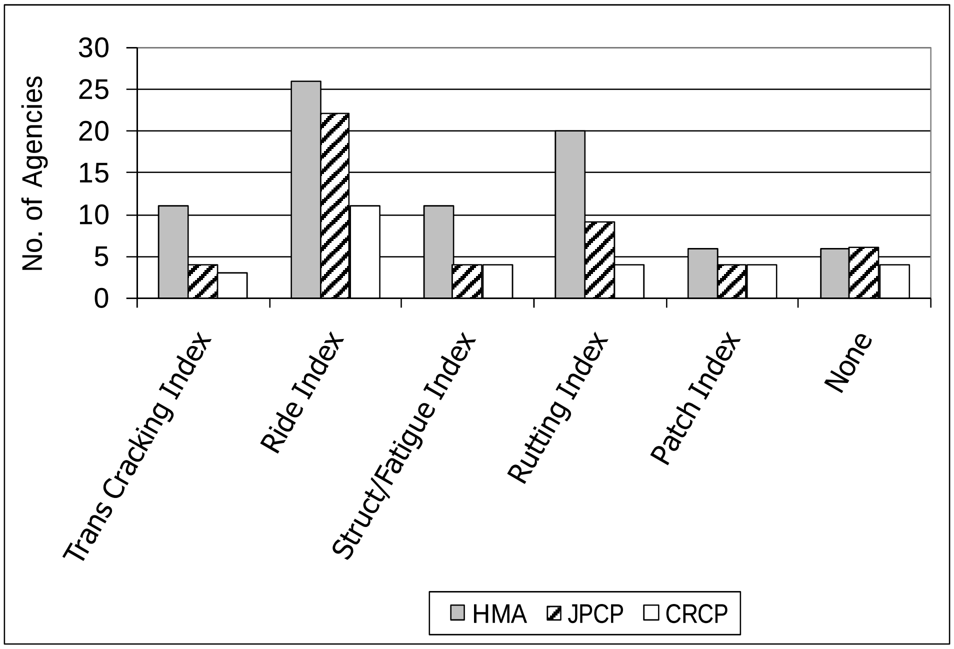

Figure 1-10. SHAs use of individual indices.

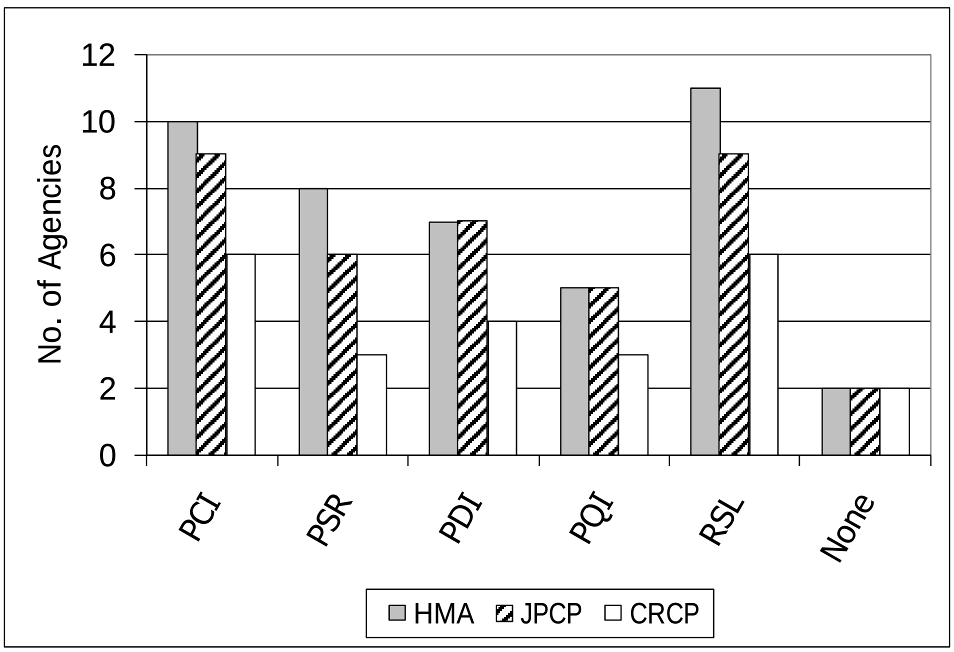

Figure 1-11. SHAs use of overall indices.

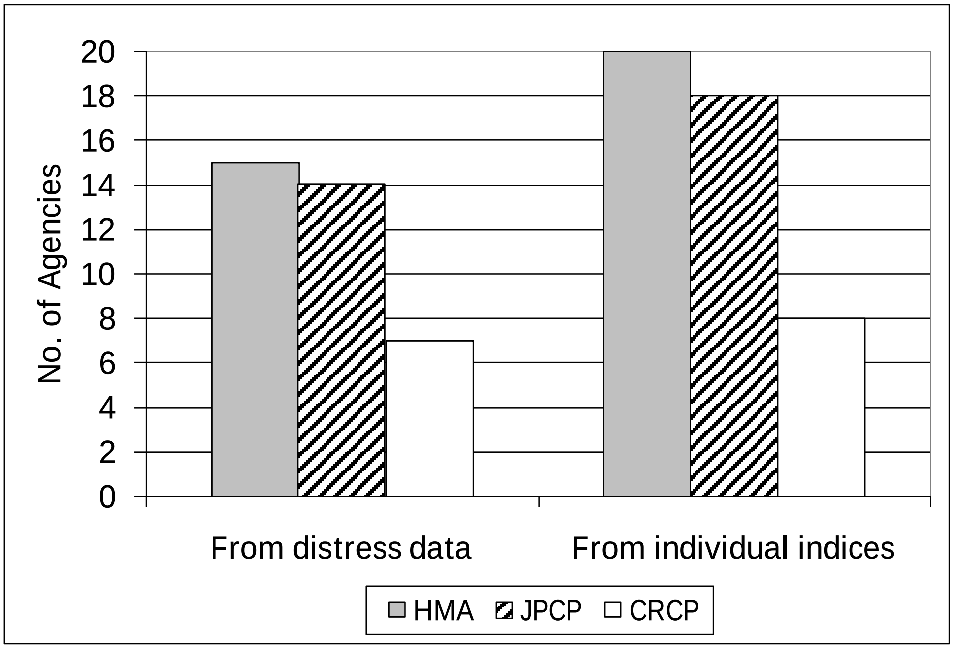

Figure 1-12. Calculation method for the overall index.

The survey of State practices also questioned the SHAs about their pavement performance modeling practices, including whether or not they had developed pavement performance models. The results of the survey revealed that 84 percent of the responding agencies had developed models. The responses indicate that 73 percent of them were created for pavement families, 10 percent for individual pavement sections, and 17 percent for a combination of families and individual pavement sections. Since PennDOT's practices are comparable to the practices of the other agencies responding to the survey, it appears that PennDOT has sufficient information available to develop pavement performance models. However, this assessment does not consider the quality of the data being used, which could be evaluated using the statistical tools discussed earlier.

To determine further information about pavement management practices, the survey included questions about the data collected and stored in the pavement management system as well as the data used in performance modeling. The results summarizing the collection of data are shown in figures 1-13 through 1-15, while the summary of data being utilized for performance modeling is shown in figures 1-16 through 1-18, respectively.

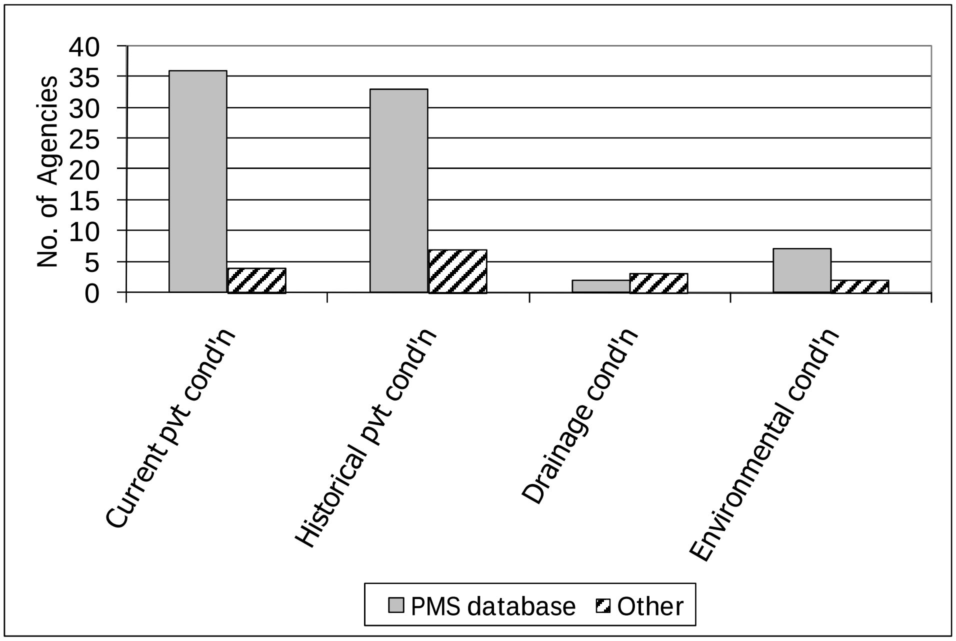

Figure 1-13. Condition data collected and stored in the pavement management database or other location.

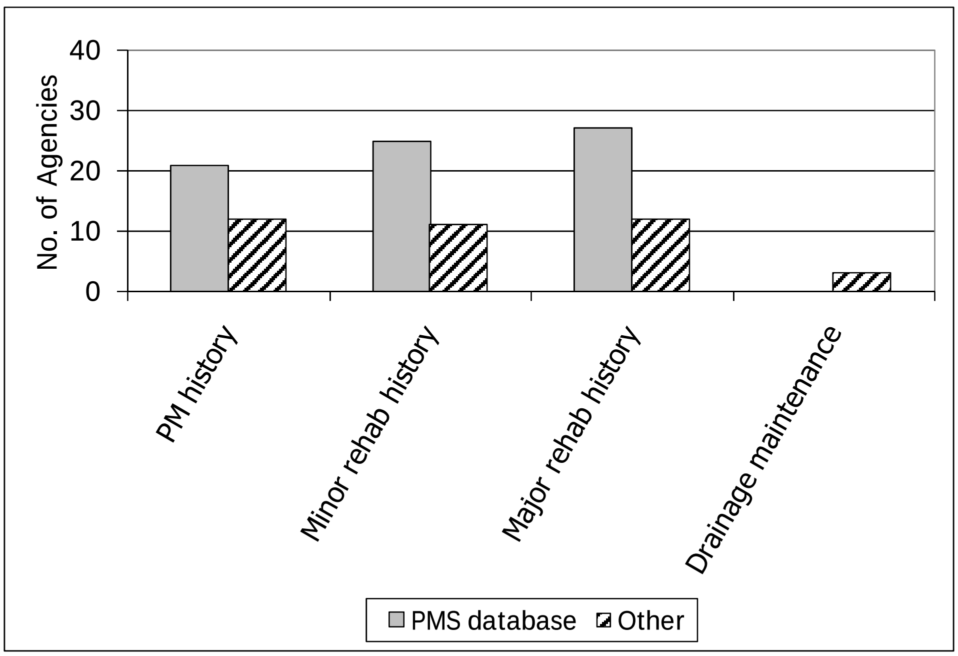

Figure 1-14. Preventive maintenance (PM) and rehabilitation data collected and stored in the pavement management database or other location.

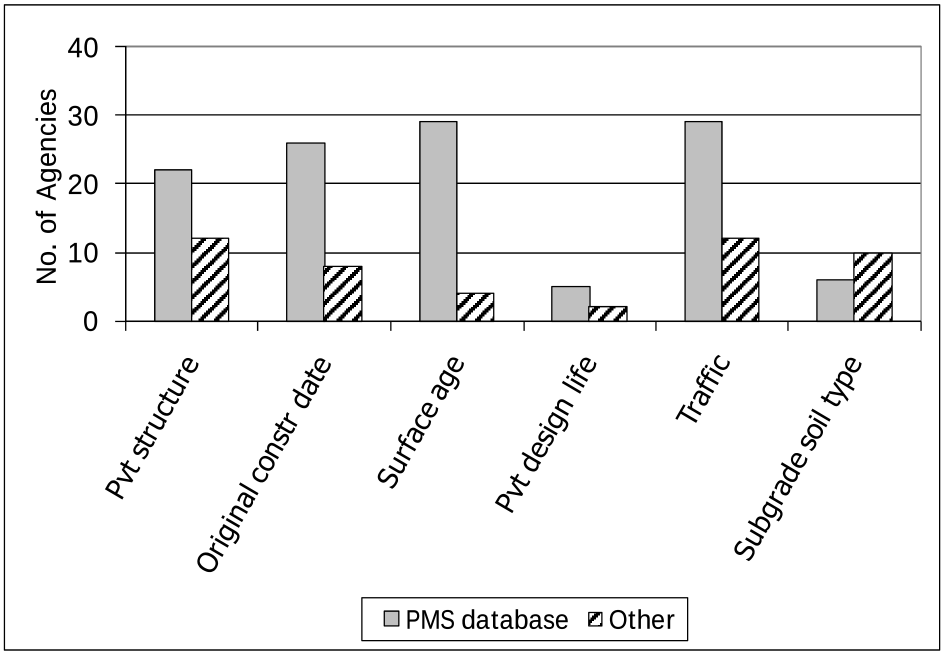

Figure 1-15. Design and construction data collected and stored in the pavement management database or other location.

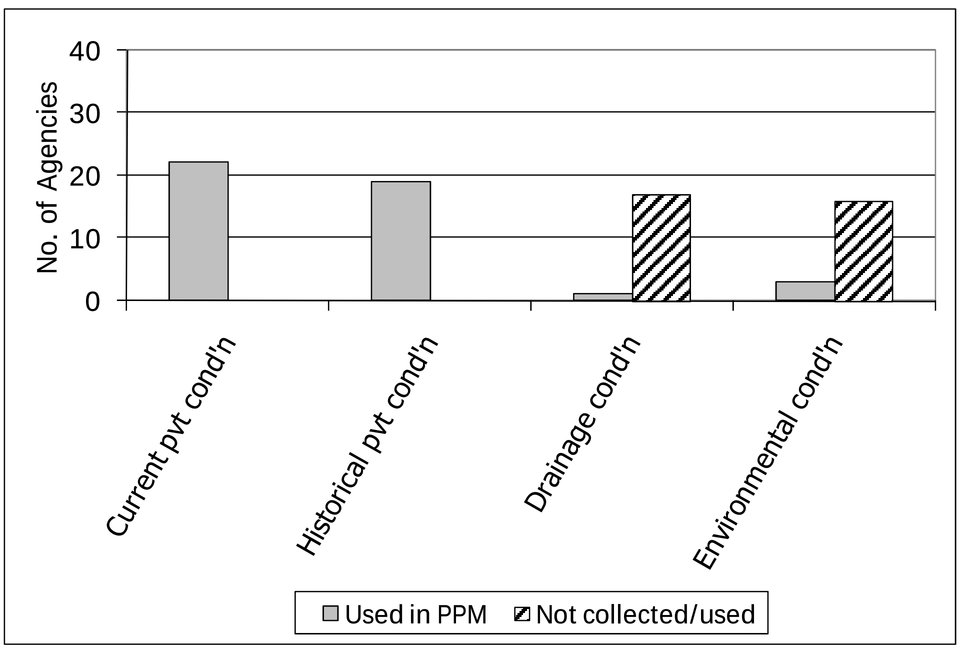

Figure 1-16. Condition data collected and used in pavement performance modeling.

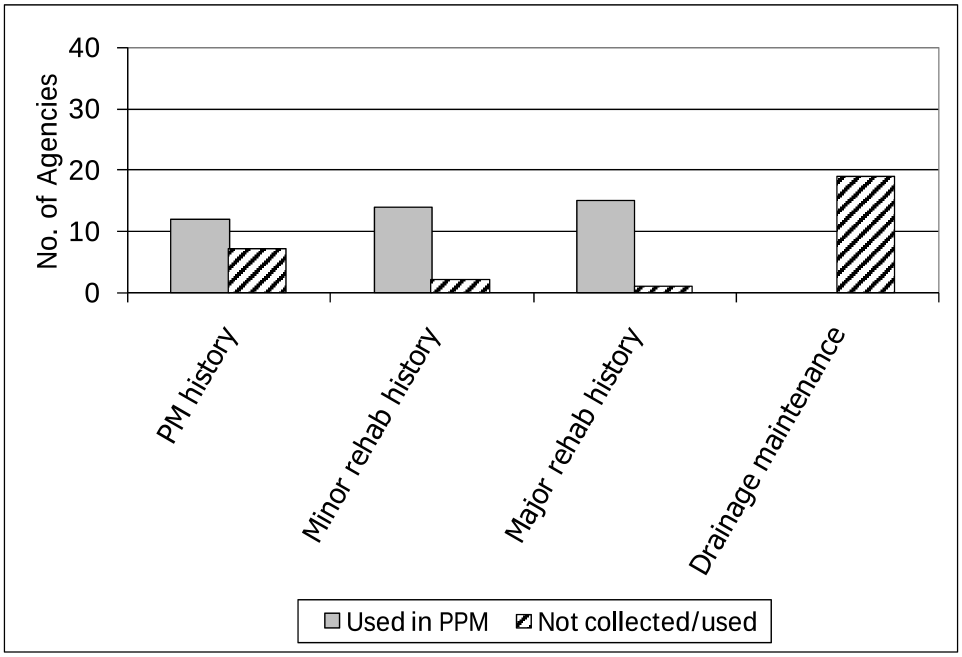

Figure 1-17. Preventive maintenance (PM) and rehabilitation data collected and used in pavement performance modeling.

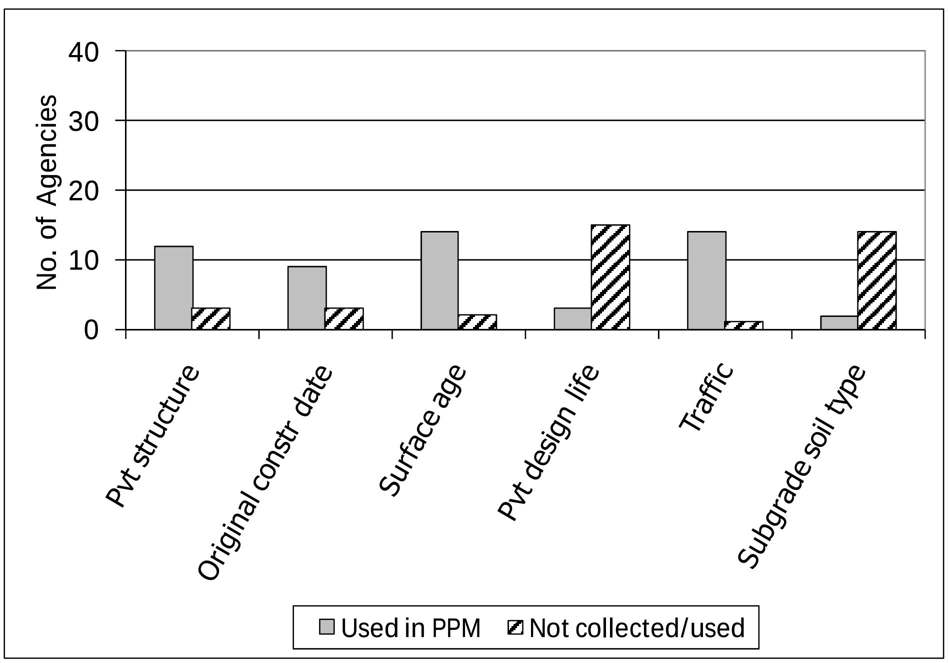

Figure 1-18. Design and construction data collected and used in pavement performance modeling.

Currently, a significant amount of data is being collected but not fully utilized for pavement performance modeling activities. However, current and past condition information, along with age, pavement structure, and traffic information, is being collected and used most often in the development of performance models.

As agencies work to incorporate pavement performance modeling into their pavement management efforts, there is also a need to establish a schedule for updating the performance models. However, as shown in table 1-4, nearly 65 percent of agencies have not set a schedule for model updates. Because many agencies have recently incorporated modeling into their practices, the majority of the updates have occurred in the last two years.

Table 1-4. Performance modeling update schedule.

Timing	Percent of Agencies	
	Schedule for Updating Models	Last Update of Models
1 year	27 %	42 %
2 years	3 %	13 %
3 years	0 %	3 %
4 – 6 years	6 %	16 %
> 6 years	0 %	26 %
No Schedule	64%	N/A

A significant number of agencies (67 percent) are working to incorporate separate performance models into their pavement management systems to model the behavior of pavements receiving preventive maintenance treatments. The survey also indicates that few agencies (only 15) have compared or are planning to use their pavement management models to calibrate the Mechanistic-Empirical Pavement Design Guide models in the next several years.

All of the information collected as part of the State survey will be used to help identify options available to PennDOT for developing pavement performance models later in this study.

1.3.2 Survey Summary

After a review of the results of the survey from the matrix included in appendix B, five SHAs were selected to be highlighted as specific case studies based on the strength of their pavement management practices and the similarity of the distress types utilized in the data collection processes to those used by PennDOT.

In addition to examining the practices used by other States, a comparison of the distress types collected by PennDOT and the other agencies responding to the survey was created and is provided in full in appendix C. Based on this information, a second set of tables was created that focuses on agencies collecting similar distress types with strong pavement management processes. This second set of tables, which highlights the States included as case studies, is shown in tables 1-5 through 1-7 for HMA, JPCP, and CRCP, respectively. The States selected to serve as case study States include Minnesota, North Dakota, Oklahoma, Oregon, and Washington.

Table 1-5. Comparison of HMA distresses collected by States to those collected by PennDOT.

HMA Distresses	**MN**	**ND**	**OK**	**OR**	**WA**
Fatigue Cracking	✓	✓	✓	✓	✓
Block Cracking *(Miscellaneous Cracking)*	•	✓	✓	✓	*
Edge Cracking	*	*	*	*	*
Non-wheel Path Longitudinal Cracking *(Miscellaneous Cracking)*	•	•	✓	✓	✓
Transverse Cracking	✓	✓	✓	✓	✓
Patches	✓	✓	✓	✓	✓
Rutting	✓	✓	✓	✓	✓
Raveling	✓	✓	✓	✓	✓

✓ = distress collected by agency.
• = distress collected by agency but categorized with another distress type.
* = distress not collected by agency.

Table 1-6. Comparison of JPCP distresses collected by States to those collected by PennDOT.

JPCP Distresses	MN	ND	OK	OR	WA
Longitudinal Cracking	✓	✓	✓	✓	✓
Transverse Cracking	✓	✓	✓	✓	✓
Joint Spalling	✓	✓	T	✓	T
Faulting of Transverse Joints and/or Cracks	✓	✓	✓	*	*
Patches	✓	✓	✓	✓	✓

✓ = distress collected by agency.
* = distress not collected by agency.
T = only transverse joint spalling not longitudinal is collected by agency.

Table 1-7. Comparison of CRCP distresses collected by States to those collected by PennDOT.

CRCP Distresses	MN	ND	OK	OR	WA
Longitudinal Cracking	✓	✓	✓	✓	*
Transverse Cracking	✓	✓	*	*	*
Lane-to-Shoulder Drop-off or Separation	*	*	*	D	*
Patches	✓	✓	✓	✓	*
Punchouts	✓	*	*	✓	*
Longitudinal Joint Spalling	✓	✓	*	✓	*

✓ = distress collected by agency.
• = distress collected by agency but categorized with another distress type.
D = only drop-off is collected by agency.

Tables 1-5 through 1-7 highlight the similarities in data collection practices between PennDOT and the five case study States. However, another consideration in the selection of the five States was the type of pavement management software they use because the type of software can influence the performance modeling processes of an agency. Therefore, by incorporating performance modeling information from agencies that use different software programs, a range of practices are represented. For example, the pavement management software programs used by the case study States are listed below:

- Minnesota – HPMA (Stantec Consulting).
- North Dakota – dTIMS (Deighton & Associates, Ltd.).
- Oklahoma – dTIMS (Deighton & Associates, Ltd.).
- Oregon – Agile Assets Pavement Analyst (Agile Assets, Inc.).
- Washington – Washington State Pavement Management System (WSPMS) Software developed specifically for Washington.

1.4 Summary of Featured Practice

The agencies selected to serve as case study States have a combination of strong pavement management and modeling practices and/or have similar data collection practices to those used in Pennsylvania. Details of each State's practices (including the survey procedure, performance modeling practices, and steps taken to advance their modeling efforts that might be applicable to PennDOT) are presented in the following sections.

1.4.1 Minnesota

The Minnesota Department of Transportation (Mn/DOT) is known for its strong pavement management and modeling practices, especially when it comes to the integration of preventive maintenance into its pavement management practices. Having collected pavement distress and roughness information since the 1960s, and having implemented pavement management software in the 1980s, Mn/DOT has a significant amount of experience with all pavement management practices, including pavement modeling.

1.4.1.1 Survey Procedure

The Mn/DOT has been using the same surface condition rating procedure since 2001. Referred to as the Surface Rating (SR), this rating procedure provides a numeric quantification of the pavement distress observed in the field. The SR is then used as an indicator of the potential maintenance and rehabilitation needs of the pavement. The SR ranges from 0.0 to 4.0, with a higher value indicating a pavement in better condition.

Initially, the SR was determined by two raters who would rate a pavement section while driving 5 to 10 mph from the shoulder of the roadway. Currently the SR rating is determined through semi-automated rating processes by central office technicians using computer workstations.

Given the level of effort required to determine the SR, Mn/DOT uses a 10 percent sampling rate that requires rating the first 500 feet of each mile. The SR survey is conducted in the outside lane of either the north or east direction on undivided roads and in the outside lane of both directions of travel for divided roadways. The SR rating is then used to describe the condition of the entire mile section.

In addition to the SR, Mn/DOT also collects International Roughness Index (IRI) information that is converted into a Ride Quality Index (RQI) using an equation developed based on input from road users. The RQI has a rating scale of 0.0 to 5.0, with a higher number indicating a pavement with a smoother ride.

Using the collected condition data, an overall pavement condition is represented in terms of a Pavement Quality Index (PQI). The PQI, which represents a combination of surface condition and ride quality, is calculated as the square root of the RQI times the SR (equation 1-6). Based on the potential values of the RQI and SR, the PQI has a potential range of 0.0 to 4.5.

$$PQI = \sqrt{(RQI * SR)} \quad (1\text{-}6)$$

Additional details of Mn/DOT's survey procedures and the calculation of the surface rating (SR) are provided in appendix D.

1.4.1.2 Performance Modeling Practices

Mn/DOT uses both individual section and default models to predict pavement condition over time. The individual section models are used when 3 or more data points are available for the pavement section since the last rehabilitation and necessary constraints are met.

For instance, to satisfy the constraint requirement the predicted condition must meet a predefined minimal level of service between a specified "Minimum" and "Maximum" life limit for the type of rehabilitation that was conducted. For example, if a medium overlay was defined to have a life limit of 5 to 15 years, and the regression analysis shows that 3 years of condition surveys for a specific pavement section predict that the terminal serviceability is 4 years, the section's behavior would be deemed "unrealistic" and a default curve would be used in its place. An "unrealistic" behavior might also be predicted if life extends beyond the "maximum" life limit. This is likely to occur if data points after rehabilitation show little deterioration in condition. Mn/DOT noted that over prediction of terminal serviceability occurs more often than under prediction.

Deterministic models are used for both site-specific and default models to predict RQI and individual distress quantities. Default RQI and individual distress models are created using a combination of surface type and prior maintenance activity. The creation of default models alone reaches into the thousands given all the needed combinations. The creation of the RQI models are developed using either linear, polynomial, or sigmoidal equations shown below in equation 1-7, 1-8 or 1-9, respectively.

$$RQI = a + b * Age \tag{1-7}$$

$$RQI = a + b * Age + c * Age^2 + d * Age^3 \tag{1-8}$$

$$RQI = a - \Delta RQI * e^{-\left(\frac{\rho}{Age}\right)^{\beta}} \tag{1-9}$$

where:

a, b, c, d, ρ, β = predicted coefficients

An example performance curve showing the prediction of RQI for a family of pavements defined as "bituminous over aggregate pavements that have received a thin overlay" is shown in figure 1-19. Initially, a linear model is created for all the RQI models. If the model has a low coefficient of correlation (also known as the R-squared value) then either an analysis is conducted to remove outliers, or another model form (polynomial or sigmoidal) is tried to improve the coefficient of correlation.

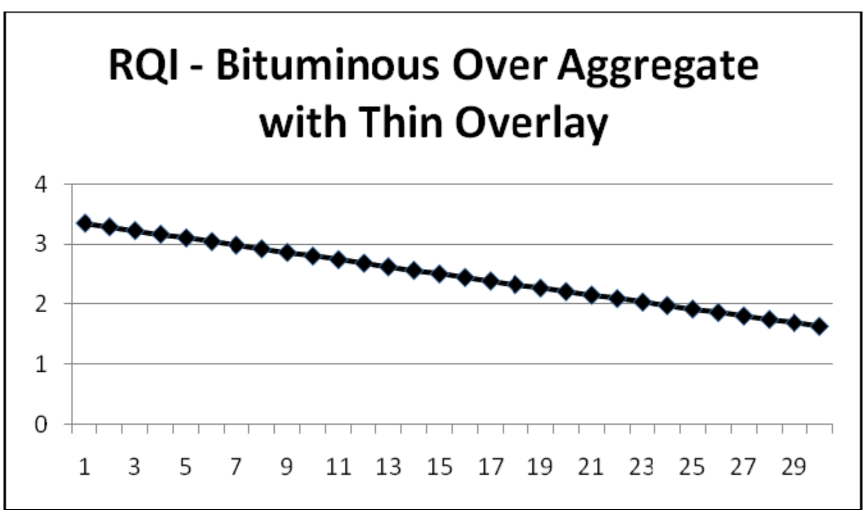

Figure 1-19. Example RQI performance model (Lukanen 1986).

In addition to the creation of predictive RQI equations, deterministic models are developed for use in predicting distress quantities for families based on surface types and prior maintenance activities. Distress quantities in terms of percent area are predicted using equation 1-10.

$$\text{Distress percent} = e^{(-k/Age)} \quad (1\text{-}10)$$

An example of the resulting model forms based upon the value of "k" is displayed in figure 1-20.

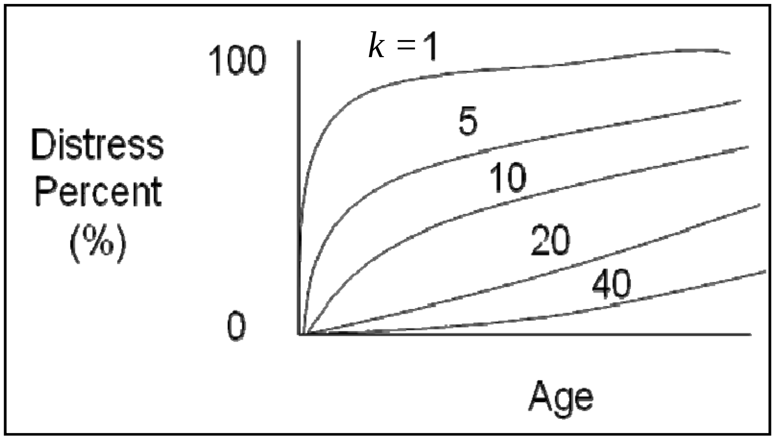

Figure 1-20. Distress percentages based upon age and "k" value (Lukanen 1986).

After the determination of the proper "k" value to predict future distress percentages, the predicted values can then be converted into the SR rating.

1.4.1.3 Steps Taken to Advance Modeling Efforts

Mn/DOT has a series of decision trees built into its pavement management software that provides for the selection of both preventive maintenance and rehabilitation treatments. In part, Mn/DOT was able to incorporate preventive maintenance treatments into its pavement management system because the agency elected to use individual distress information in its pavement management system in order to predict future conditions and trigger treatments. Because of this decision, Mn/DOT has been able to trigger preventive maintenance treatments based on estimated distress quantities and can describe the impact of preventive maintenance treatments in terms of the impact on each distress.

1.4.2 North Dakota

The North Dakota Department of Transportation (NDDOT) utilizes the dTIMS pavement management software that is designed and developed by Deighton & Associates, Ltd. Currently, their system is focused solely on predicting the change in IRI per year based upon historical data. However, additional indexes are calculated to describe the current condition of the pavements.

1.4.2.1 Survey Procedure

Pavement condition surveys are conducted by NDDOT using a semi-automated survey based on LTPP distress definitions. The information collected is then used to determine various indices. The overall index NDDOT uses is called the Distress Score, which is a 99-point index. A Distress Score of 99 indicates a pavement with no distress, while a value of 0 indicates a failed pavement. Deducts are then taken from 99 based upon the information shown in appendix E, where deducts for flexible, CRCP, and jointed reinforced concrete pavements (JRCP) can be found. The result is a calculated Distress Score for the pavement section.

In addition to the calculated Distress Score, NDDOT also calculates a Structural Index for flexible pavements and a Slab Cracking Index for the JRC pavements. The Structural Index is calculated by taking deducts due to alligator cracking, patching, and rutting, and subtracting them from 99. The Slab Cracking Index also begins with a value of 99 and is reduced based on deducts for corner breaks, longitudinal cracking, broken slabs, patching, and transverse cracking.

Example deducts for the flexible pavements are shown in tables 1-8 and 1-9 for alligator cracking and bleeding, respectively. As shown in tables 1-8 and 1-9, the deducts due to alligator cracking are more significant than those due to bleeding.

Table 1-8. Alligator Cracking deducts used by NDDOT (NDDOT 2009).

Alligator Cracking	**Extent**			
Severity	None	< 10%	10 – 30 %	> 30%
Hairline		2	4	6
Spalled and Tight	0	8	10	12
Spalled and Loose		14	16	18

Table 1-9. Bleeding deducts used by NDDOT (NDDOT 2009).

Bleeding	**Extent**			
Severity	None	< 10%	10 – 30 %	> 30%
Occasional Small Patches	0	1	2	3
Wheel Tracks Smooth		4	5	6
Little Visible Aggregate		7	8	9

1.4.2.2 Performance Modeling Practices

NDDOT also collects ride information in terms of IRI and uses that information to develop pavement performance models for use in its dTIMS pavement management system. Models for IRI were created for approximately 100 pavement families based on the last rehabilitation treatment, the highway performance classifications of the roadway, and the pavement type as listed below.

- Last rehabilitation treatment.
  - Preventive maintenance on flexible.
  - Preventive maintenance on rigid.
  - Minor rehabilitation on flexible.
  - Minor rehabilitation on rigid.
  - Structural overlay.
  - Major reconstruction.

- Highway performance classification.
  - Interstate.
  - Interregional.
  - State corridor.
  - District corridor.
  - District collector.
- Pavement type.
  - Asphalt on CRCP.
  - Asphalt on JRCP.
  - Full depth asphalt.
  - JRCP.
  - CRCP.

Example NDDOT models for full-depth asphalt sections on the State corridor are shown in figure 1-21. The predicted performance of the structural overlay (solid line) is expected to maintain its IRI value longer than the thin-lift overlay (dashed line) resulting in a smoother road. Similar models were developed for all pavement families.

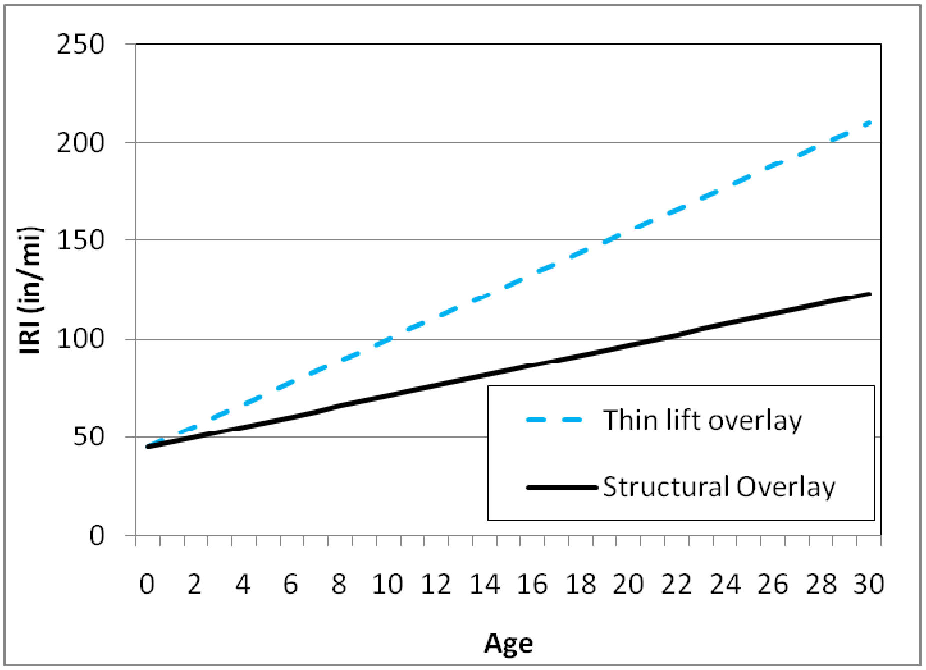

Figure 1-21. Example IRI performance model (NDDOT 2009).

1.4.2.3 Steps Taken to Advance Modeling Efforts

Of the five case study States, NDDOT has not done as much modeling as some of the other agencies. However, the models they have created are working well to provide them with the data they need. They are also in the process of developing a performance modeling tool that will assist them in using historical condition data to develop equations based upon a variety of selected criteria.

1.4.3 Oklahoma

The OkDOT first began its current pavement management efforts in 2000. Since that time, they have dedicated significant time and effort to developing strong pavement management practices, including a robust condition survey procedure and reliable pavement management models. OkDOT conducts its pavement management analysis using the dTIMS pavement management software developed by Deighton and Associates, Ltd.

1.4.3.1 Survey Procedure

The survey procedure utilized by OkDOT is a semi-automated survey based upon LTPP distress definitions. Information collected from the surveys is used to determine deducts associated with the distresses. The deducts are then used to calculate a variety of condition indices for each pavement surface type as detailed below:

- Hot-mixed asphalt (HMA).
    - Ride.
    - Structural.
    - Rutting.
    - Functional.
    - Overall Condition (PQI).

- JPCP.
  - Ride.
  - Fault.
  - Slab.
  - Joint.
  - Overall Condition (PQI).

- CRCP.
  - Ride.
  - Structural.
  - Overall Condition (PQI).

Each condition index is based on a 0 to 100 scale, with 100 representing a pavement in good condition and 0 representing a pavement in bad condition. The full explanation of the calculation of deducts and pavement condition indices are described in appendix F. An example calculation of the Structural Index for HMA pavements is shown in equation 1-11.

$$\text{Structural Index} = 100 - \text{Minimum}((\text{Fatigue 1 DV} + \text{Fatigue 2 DV} + \text{Fatigue 3 DV}), 100) \quad (1\text{-}11)$$

where:
Fatigue 1 DV = Low Severity Fatigue Deduct Value
Fatigue 2 DV = Medium Severity Fatigue Deduct Value
Fatigue 3 DV = High Severity Fatigue Deduct Value

Once individual indexes are calculated for the pavement sections, the overall condition (PQI) can be calculated. An example equation for PQI for HMA pavements is shown in equation 1-12.

$$\text{PQI} = 0.40*\text{Ride Index} + 0.30*\text{Rut Index} + 0.15*\text{Functional Index} + 0.15*\text{Structural Index} \quad (1\text{-}12)$$

Therefore, the PQI is a weighted average of the individual indices for the given pavement type.

1.4.3.2 Performance Modeling Practices

OkDOT uses deterministic family performance models that are focused on predicting the index as a function of age. The performance models were created for a given pavement family by plotting the condition of the sections versus the age of each corresponding section. Regression techniques were then applied to predict the behavior of the condition index based on the age of the pavement.

Before beginning the prediction of performance, pavement families were created for use in describing pavement types with similar expected performance. The pavement families used by OkDOT are described below based on pavement type, traffic volume, and expected curve endpoint. A summary of equations is provided in appendix F along with the information on the calculation of deducts and indices. An example pavement performance model for the structural index for HMA pavements with medium-high volume traffic is shown in figure 1-22.

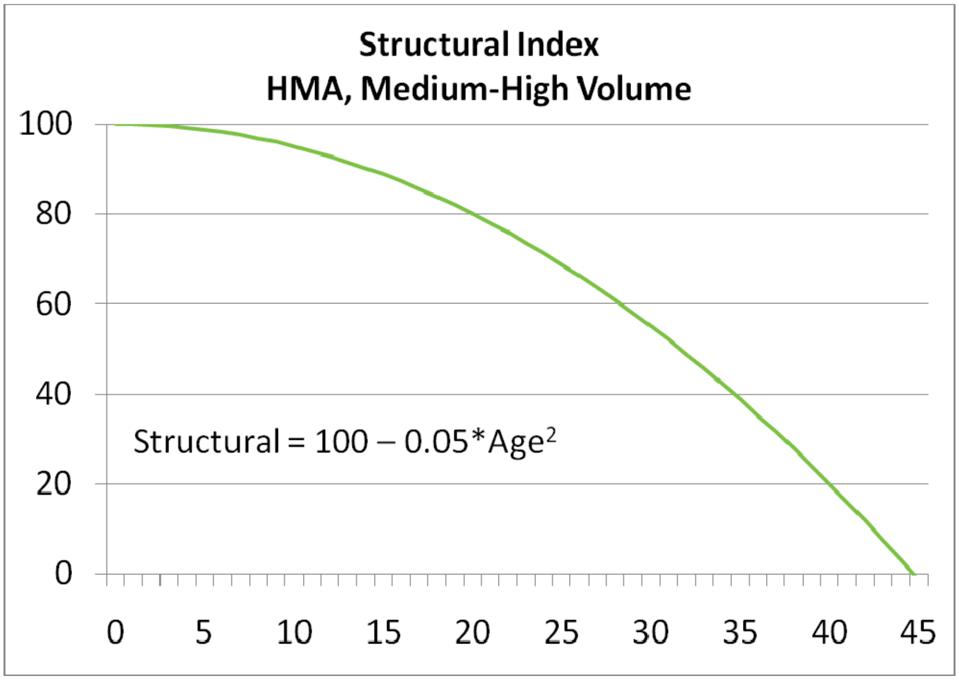

Figure 1-22. Structural index performance model for HMA pavements with medium-high traffic volumes (OKDOT 2009).

1.4.3.3 Steps Taken to Advance Modeling Efforts

OkDOT underwent a significant performance modeling study in 2001, which included the statistical analysis of performance data collected since developing their new condition indexes. Since that time, OkDOT has used the results of additional pavement condition surveys to review and refine the pavement management models. As a result, a significant number of models and pavement family classifications have been changed to reflect actual conditions. OkDOT reports that the use of actual condition data as a feedback loop has resulted in improved pavement management models.

1.4.4 Oregon

The Oregon Department of Transportation (ODOT) is utilizing pavement management software from Agile Assets, Inc. but has not fully employed the modeling capabilities available in the software. However, ODOT actively determines remaining service life (RSL) and uses it to predict the expected percentage of the network that will be in various condition levels (i.e., good, fair, poor, or very poor). RSL serves as an indicator of the amount of life that the pavement has left. Therefore, a RSL of 0 indicates that a pavement has exceeded its expected life.

1.4.4.1 Survey Procedure

ODOT currently uses a semi-automated pavement condition survey to determine the condition of all major roads. They are still using a manual survey on minor roads but expect to change over to an automated survey in the near future. Based on the conditions collected from the survey, ODOT determines the following condition indices for HMA and concrete (JPCP and CRCP) pavements.

- HMA.
  - Fatigue.
  - Rut.
  - Patching.
  - Raveling.
  - No-load (Environmental).
  - Overall.
- JPCP and CRCP.
  - Fatigue.
  - Rut.
  - Patching.
  - Overall.

ODOT has a documented procedure for calculating the condition indices, which is provided in appendix G. The process includes the calculation of an index factor for each severity level of each distress for all 0.1-mile increments that were surveyed. The index factor is calculated based on equation 1-13.

$$\text{Factor (typeX)}_{\text{(severity y)}} = 1.00 - A^*(\text{Measured Distress/Maximum Distress})^B \qquad (1\text{-}13)$$

where:
Type X = the distress type (e.g., fatigue, transverse, rutting, etc.)
Severity y = the severity level (i.e.., low, medium, high)
A and B = defined coefficients

For those distresses with more than one severity level, a composite index factor is calculated and condition indices are determined based on the index factors. An example calculation of the condition index from appendix G is provided in figure 1-23.

Example 1 (non-rut determines overall index): The field data for an asphalt concrete section from MP 37.8 to MP 37.9 indicates the following distress: 300 linear feet of low severity fatigue cracking, 500 linear feet of moderate severity fatigue cracking, and eight (8) low severity transverse cracks. The rut severity is low (between ¼" and ½") . Using Equations (1) and (2) and the appropriate coefficients and exponents from Table D-1, the overall index is computed for the given tenth-mile section as follows:

First, using Equation (1), calculate the index factor for each severity level for each distress type reported in the 0.1 mile segment:

$$\text{Factor (fatigue)}_{(low)} = 1.00 - 0.6*(300/1{,}000)^{0.1} = 0.468$$
$$\text{Factor (fatigue)}_{(moderate)} = 1.00 - 0.8*(500/1{,}000)^{0.1} = 0.254$$
$$\text{Factor (transverse)}_{(low)} = 1.00 - 0.33*(8/44)^{0.5} = 0.859$$
$$\text{Factor (rutting)}_{(low)} = 1.00 - 0.05*(1/1)^{1} = 0.950$$

Since no other detrimental conditions exist, the value for all other indices will be equal to 1.00 as shown in the following example:

$$\text{Factor (patching)}_{(low)} = 1.00 - 0.55*(0/6000)^{0.1} = 1.00 - 0.55*0.0 = 1.00$$

Second, with two severity levels measured for fatigue cracking, calculate the composite fatigue factor using Equation (2):

$$\text{Factor (fatigue)} = [(0.47*300)+(0.25*500)]/(300+500) = 0.333$$

Third, using the equations in Table D-4, determine the six condition indices. For the overall index, multiply each index factor together, excluding the rut index, to determine the non-rut index for the 0.1 mile segment. This non-rut index is compared to rut index and the lower of the two values, multiplied by 100, is the overall condition index for the 0.1 mile segment.

Rut index	*=(1.00-0.05)*100*	*= 95.0*
Fatigue index	*= 0.333*100*	*= 33.3*
Patching index	*= 1.00*100*	*= 100*
Raveling index	*= 1.00*100*	*= 100*
No Load index	*= 0.859*100*	*= 85.9*

Non-rut index = *Factor(fatigue)*Factor(transverse)*100* = *0.333*0.859*100* = *28.6*

The non-rut index is lower than the rut index, therefore:
Overall Index = *28.6*

Figure 1-23. Index calculation example from ODOT (ODOT 2008).

1.4.4.2 Performance Modeling Practices

ODOT performance modeling practices focus on the determination of RSL based on the use of the lowest of three RSL values: model, age, and rut. The Model RSL value is based on the use of the curves shown in figure 1-24, in which the overall index of 45 corresponds to an RSL of 0. The Age RSL is the estimated treatment life of the pavement minus the age since last treatment. Each year, the ODOT pavement management engineer manually adjusts the treatment life from the standard value for all 2,300 pavement sections in the ODOT network, using the past 5 years of condition ratings, rut depths, and IRI information as a basis for the engineering judgment. Finally, the Rut RSL is calculated on routes with high average daily traffic (ADT) and studded snow tire use. Oregon estimates that the wear rate of studded tire use is approximately 0.08 to 0.10-inch per year and estimates Rut RSL to be 0 when average rutting is 0.75-inch (ODOT 2008).

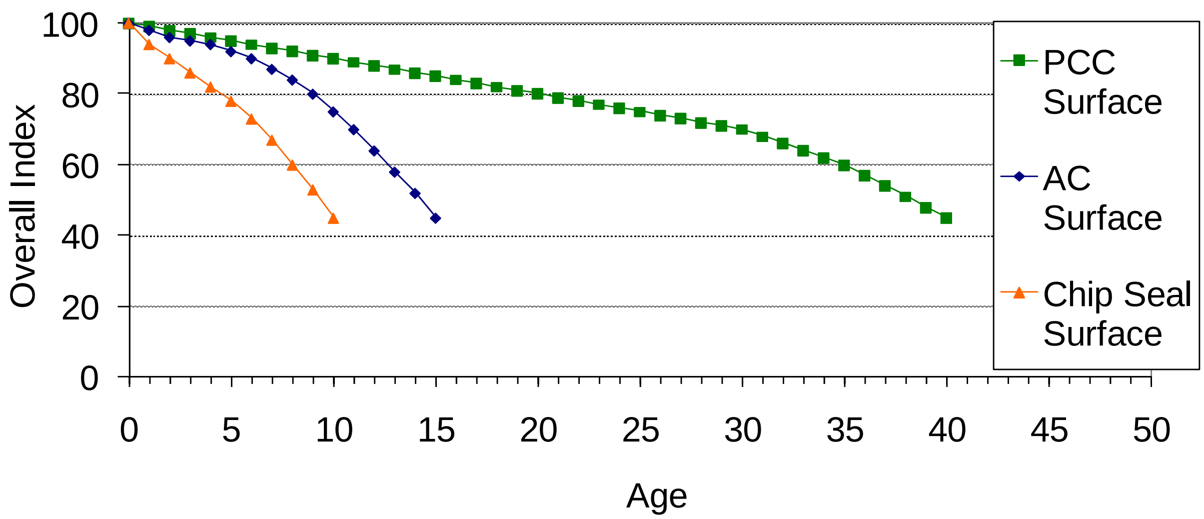

Figure 1-24. Model RSL used by ODOT.

Once the RSL is determined from the lowest of the Model, Age, and Rut RSL, the information is used by ODOT to forecast pavement condition and treatment selection using the following condition categories:

- RSL $\geq$ 5 is Good
- 0 > RSL > 5 is Fair
- RSL = 0 is Poor

1.4.4.3 Steps Taken to Advance Modeling Efforts

ODOT has considered creating additional models, such as percent cracking or IRI, but has not done so since the modeling of RSL has provided them with the information they need to forecast conditions and identify potential treatments.

1.4.5 Washington

The Washington State Department of Transportation (WSDOT) has utilized pavement management practices since the 1980s. Because of the significant amount of documentation available on its performance modeling practices, the steps involved in creating well-functioning performance models are clearly laid out. WSDOT has incorporated their pavement performance models into the Washington State Pavement Management System (WSPMS).

1.4.5.1 Survey Procedure

As with all agencies highlighted in this summary of State practice, WSDOT uses a semi-automated pavement condition survey to determine the condition of all roadways. WSDOT then uses the collected condition information to determine a pavement structural condition (PSC) index which ranges from 100 (good) to 0 (poor). This is done by relating surface distresses to alligator cracking for flexible pavements and by relating surface distresses to cracking for rigid pavement to determine applicable deduct values. Full details of how the distresses are converted to deducts are provided in appendix H. The deduct values are then subtracted from a value of 100 to determine the PSC.

WSDOT also collects rutting and ride information that is used in the pavement management system. The rut and ride data may be used in their raw state for some applications, but is also used to calculate and report pavement rutting condition (PRC) and pavement profile condition (PPC), respectively.

1.4.5.2 Performance Modeling Practices

The PSC is modeled for each individual pavement section using a power model as shown in equation 1-14 and figure 1-25.

$$PSC = C - mA^{P} \tag{1-14}$$

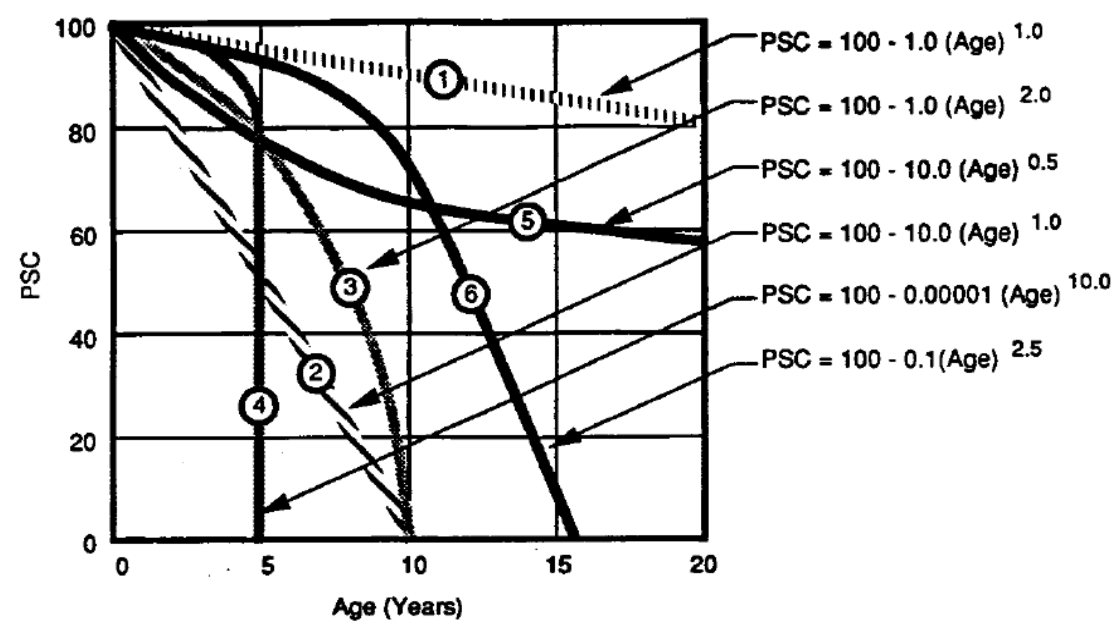

Figure 1-25. Example PSC power models (WSDOT 1993).

Approximately 8,000 individual pavement section models are created for all sections with 3 or more data points. For those sections with less than 3 data points, default performance models are used to describe the expected pavement performance. The WSDOT default pavement models for PSC are created based on surface type, functional classification, and state districts, while the default linear models for PPC and PRC are shown in equations 1-15 and 1-16, respectively.

$$PPC = 100 – 1.0*Age \tag{1-15}$$

$$PRC = 160 – 5.0*Age \tag{1-16}$$

The predictions developed in the WSPMS for each section are modeled in a way to let the given section "speak for itself." However, this process often resulted in overestimations of condition. Therefore, to better predict the predicted performance, a process was established whereby two data points are added to the available data from the standard (default) curve. Together, the actual and default data are used to get a final prediction of condition. An example of how this process is handled is shown in figure 1-26.

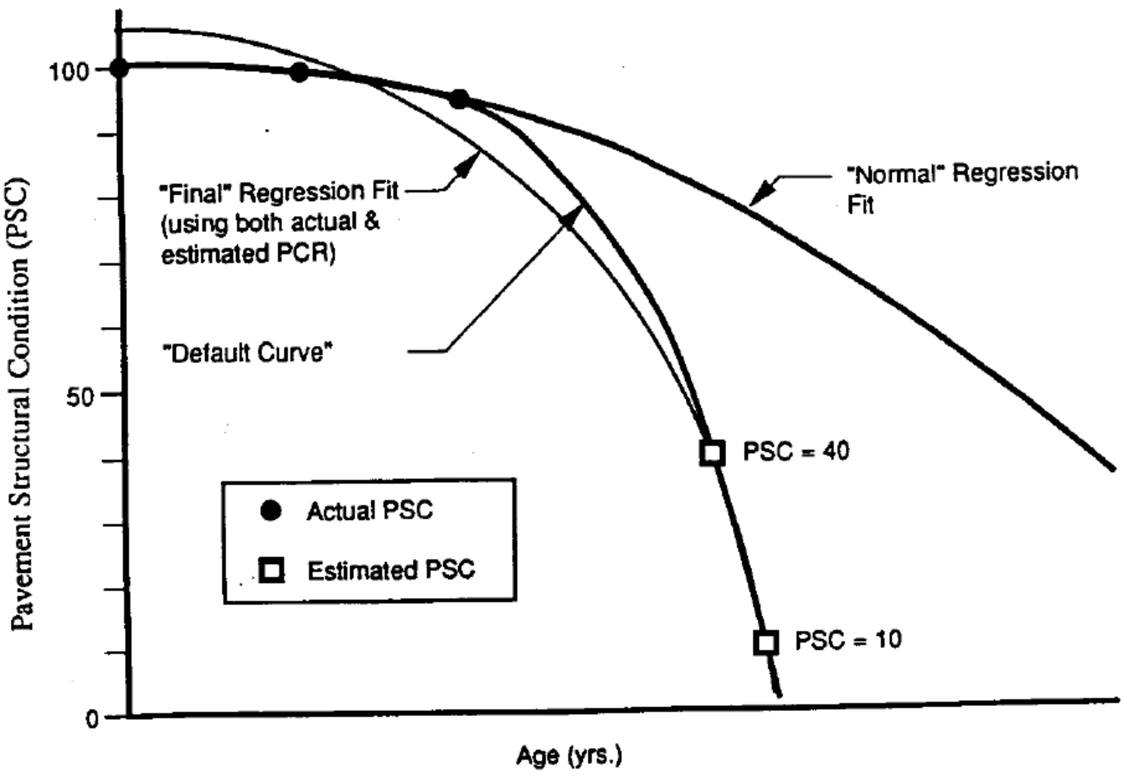

Figure 1-26. Regression process used in WSPMS to predict PSC (WSDOT 1993).

Because it utilizes past performance trends and incorporates the knowledge of typical pavement performance to give the most likely rate of future deterioration, WSDOT reports that the process results in a more realistic estimate of the project performance than if the adjustments were not made.

1.4.5.3 Steps Taken to Advance Modeling Efforts

WSDOT recently conducted a study to revise the pavement condition indices for rigid pavements. This was done to address specific pavement distress types that had been proposed to take into account pavement condition trigger levels now used by WSDOT (Jackson 2009). The resulting research report provides the details necessary for WSDOT to update these models in their pavement management system.

1.4.5.4 Case Study State Summary

A summary of the performance modeling and pavement management practices for the highlighted case study States is presented in table 1-10. This information, along with additional information available from the review of State practices, will be used in the next phase of the study to compare State practices to those used by PennDOT. As the results of the investigation into State practices show, there are several options available for developing useful pavement performance models. The States profiled in this section of the report have typically adapted their activities to best meet their agency's specific needs.

Table 1-10. Summary of practice for case study States.

JPCP Distresses	MN	ND	OK	OR	WA
Pavement Management System	HPMA	dTIMS	dTIMS	Pavement Analyst	WSPMS
Survey Type Used? Semi-automated (SA), manual (M) or both (B)	SA	SA	SA	B	SA
Indices created directly from distress data? Overall (O) or Individual (I)	O	I	I	I	O
Individual (I) or Family (F) Curves?	I	F	F	F	I
Model Indices (I) or Distresses (D)?	D	I	I	I	I

1.5 Summary

This chapter provides a review of pavement performance modeling practices being used by State highway agencies (SHAs). The review is comprised of the information obtained as part of the literature review conducted for this project. In addition, information on State practices was collected through the use of a questionnaire that was distributed to the pavement management engineer in each State. The collected information provides the foundation for benchmarking PennDOT's practices and for developing specific recommendations for creating and maintaining pavement performance models in the future.

CHAPTER 2 – PRACTICE COMPARISON

2.1 Introduction

In this chapter, PennDOT's previous performance modeling efforts are compared with modeling efforts in other state highway agencies (SHA). Looking back at past efforts is important because practices can often be improved by examining what approaches and processes have worked well in the past and which have not been successful. This chapter also compares PennDOT's pavement condition data collection practices with those in other SHAs and with the data collection needs associated with meeting the Highway Performance Monitoring System (HPMS) and Mechanical Empirical Pavement Design Guide (MEPDG) data requirements. The comparisons and findings included in this report will provide the insight needed for PennDOT to successfully move forward with the recommendations that will be included in the next chapter.

2.2 Summary of PennDOT Current Data Collection Activities and Past Performance Modeling Practices

To provide a comparison of PennDOT practices to those used by other states, it is important to understand the history of past pavement performance modeling efforts undertaken by PennDOT's Bureau of Maintenance and Operations (BOMO) along with the status of available pavement condition data. Therefore, information related to PennDOT's data collection methods and past pavement performance modeling efforts that are pertinent to the new modeling efforts are summarized in this section.

2.2.1 Pavement Condition Data Collection Methods

Pavement condition data serve as the basis for the development of pavement performance models. Current PennDOT automated data collection processes are documented in PennDOT Publication 336, *Automated Pavement Condition Survey Field Manual.* The documentation includes details regarding the collection and processing of profile and rutting data along with distress surveys for bituminous-surfaced pavements and certain rigid pavements referred to as Plain Cement Concrete Pavement (PCCP) and Reinforced Cement Concrete Pavement (RCCP). In addition to the automated surveys, windshield surveys are used to collect condition information for the continuously reinforced concrete pavements (CRCP). Data are collected on 100 percent of the 40,000+ centerline miles of state highways throughout the State over a 2 year period.

2.2.1.1 Profile Data

Profile data are collected at a minimum interval of 6 inches in both the outside and inside wheel paths of each bituminous-surfaced, PCCP, and RCCP roadway. The profile measurements are used to calculate the IRI, which is summarized for every 0.1-mile roadway segment. For jointed concrete pavements (PCCP and RCCP), IRI information is also summarized in 20-foot sections to provide roughness information for each slab. When distress data indicate that there is a broken slab in the PCCP or the RCCP, the IRI information is used to help assess the severity level of the broken slab.

2.2.1.2 Rut Data

Rut data are collected during the Automated Distress Condition Surveying program. The rut data, which are collected at a minimum of every 30 feet, provides a summary of the distance between the profile of the pavement to the bottom of the rut (a longitudinal distortion in the pavement cross-section). A severity level is assigned to each sampling interval based upon the average rut depth, as shown below:

Low Severity: 0.25 in ≤ Average Rut Depth < 0.5 in
Medium Severity: 0.50 in ≤ Average Rut Depth < 1.0 in
High Severity: Average Rut Depth ≥ 1.0 in

The total amount of rutting at each severity level is then totaled for both wheelpaths of the roadway section.

2.2.1.3 Pavement Distress Data

The types of pavement distress data collected by PennDOT vary based on the type of pavement surface being surveyed. For example, the distresses collected for bituminous-surfaced pavements, rigid pavements, and CRCP differ significantly. The distresses captured in each of the surveys are discussed in more detail below.

2.2.1.3.1 Bituminous-surfaced Pavements

PennDOT's distress surveys of bituminous-surfaced pavements focus on 7 distress types in addition to the collection of profile and rut information. Low, medium, and high crack severities are defined based on the following crack widths for all cracking distresses expect fatigue:

Low Severity: Hairline < Crack width ≤ 0.25 inch
Medium Severity: 0.25 inch < Crack width ≤ 0.50 inch
High Severity: 0.50 inch < Crack width

When cracking has been sealed and is in good condition the distress is classified as a low severity crack. All bituminous-surfaced distresses are recorded in the outside pavement lane.

2.2.1.3.1.1 Fatigue Cracking

Fatigue cracking is collected in the outside 30-inch wheelpath of the roadway. The severity of the cracking is classified using a combination of crack width and interconnection of the cracks. The severity of fatigue cracking is based upon the following crack widths:

Low Severity: Crack width ≤ hairline
Medium Severity: hairline < Crack width ≤ 0.25 inch
High Severity: 0.25 inch < Crack width

The length of distress at each severity level is then measured.

2.2.1.3.1.2 Transverse Cracking

The severity level of transverse cracking is classified according to the width of the crack. The quantity of transverse cracking is determined by the number of cracks at each severity level present on the roadway section along with the total length of cracking present.

2.2.1.3.1.3 Miscellaneous Cracking

Miscellaneous cracking is measured as the cracking observed in the 39-inch strip in the middle of the traffic lane. The severity level of miscellaneous cracking is classified according to the width of the crack. The quantity of miscellaneous cracking is determined as the total length of each severity level present. This distress compares to what other SHA refer to as non-wheelpath longitudinal cracking.

2.2.1.3.1.4 Edge Deterioration

Edge deterioration occurs in the outer 1.0-foot edge of the pavement. This deterioration is classified by the average crack width and the amount of material lost. The distress is recorded in terms of length of deterioration. There are only a few other States that include this distress in their survey procedure.

2.2.1.3.1.5 Bituminous Patching

Bituminous patching is rated for the entire width of the pavement lane but to be counted, the patch must be greater than 1.0 ft^2 but less than 400 ft long. The severity level is not assessed and instead all patches are rated at one severity level. Both the total number of patches in a segment and the total area patched are recorded.

2.2.1.3.1.6 Raveling/Weathering

Raveling/weathering is evaluated for the entire length of the pavement lane within each segment. The severity of the distress is classified as either medium or high depending upon the roughness of the pavement. The distress is recorded based upon the overall length of each severity level present.

2.2.1.3.1.7 Left Edge Joint Deterioration

Left edge joint deterioration is classified as low, medium, or high severity depending upon a combination of longitudinal construction joint width, the presence of adjacent cracking, and the potential loss of material or use of patching. The left edge joint deterioration is only recorded if the joint being rated lies to the right of the pavement markings.

2.2.1.3.2 Rigid Pavements (PCCP and RCCP)

PennDOT's rigid, jointed pavement distress surveys focus on eight distress types. The distress types are summarized primarily as the number of slabs or joints in a section affected by the distress.

2.2.1.3.2.1 Faulted Joints

Faulting is measured in the outside wheelpath and faulted joints are classified as either medium or high severity depending upon the elevation difference between the adjoining slabs. The number of faulted joints at each severity level is recorded.

2.2.1.3.2.2 Broken Slab

Broken slab severity is determined by a combination of average crack width, faulting and IRI. The highest level of faulting or IRI controls the severity level within a slab, and the number of broken slabs at each severity level (low, medium, and high) are counted. When a slab has been rated as being broken, no other distress types should be recorded.

2.2.1.3.2.3 Transverse Joint Spalling

The severity level for spalling is based upon the width of the spall and the length of the joint that is affected. The number of joints at each severity level is recorded.

2.2.1.3.2.4 Transverse Cracking

If a transverse crack is longer than 6 feet, it is measured. The severity level is determined based upon the width of the crack, the amount of spalling, or the severity of the faulting across the crack. The number of slabs at each severity level is recorded.

2.2.1.3.2.5 Longitudinal Cracking

Longitudinal cracking is recorded as the number of slabs at each severity rating. The severity rating is determined based upon the highest severity level of either average crack width, the width of spalling, or the amount of spalling along the crack.

2.2.1.3.2.6 Longitudinal Joint Spall

Longitudinal joint spall severity is based upon the length of the joint affected and the average spall width. Only medium and high severity spalling are recorded, but the amount of spalling at each severity level is recorded.

2.2.1.3.2.7 Bituminous Patching

Bituminous patching greater than 36 ft^2 is recorded for the entire width of the pavement lane within a section. All patches are rated at one severity level. The total number and area of the patches are recorded.

2.2.1.3.2.8 Portland Cement Concrete Patching

Portland cement concrete patching is rated in the same manner as bituminous patching.

2.2.1.3.3 Continuously Reinforced Concrete Pavements (CRCP)

CRCP pavements are rated using a windshield survey from the shoulder of the road. Since the survey of CRCP pavements is done manually, profile and rutting data are not collected for these pavements through the Automated Distress Condition Surveying program. A total of six distresses are considered when conducting CRCP surveys.

2.2.1.3.3.1 Longitudinal Joint Spall

Longitudinal joint spalls are recorded based upon the length of the joint affected. The severity is determined based upon the width of the spall. Low, medium, and high severity spalls are recorded.

2.2.1.3.3.2 CRC Transverse Cracking

Transverse cracking is recorded based upon the number of transverse cracks present in the section.. The severity level is determined based upon the crack width, spalling along the crack, and the presence of faulting along the crack.

2.2.1.3.3.3 Punchout

Punchouts are recorded based upon the number of occurrences at each severity level. The low severity level punchout is determined based upon the development of longitudinal cracking within the punchout. Medium and high severity punchouts are determined based upon the amount of faulting around the distress.

2.2.1.3.3.4 Rutting

Rutting on CRCP is due to wear on the pavement. Wear is likely where studded snow tire use is heavy. Rutting is recorded when the wear is greater than 0.5 inch over 50 percent of the pavement section.

2.2.1.3.3.5 Bridge Approaches

The condition of each bridge approach within a CRCP is determined based upon the general condition in terms of ride and distress level.

2.2.1.3.3.6 Damaged Terminal Joint

The number of damaged terminal joints in a section is recorded when there is distress associated with the steel I-beams that are embedded in the CRCP subslabs. The I-beams may have loose or missing flanges or have associated subgrade or subslab failures.

2.2.1.3.4 Shoulder Distresses

In addition to the distress types that are specific to each pavement type, there are two distress types that are collected as part of PennDOT's survey of shoulder conditions for both bituminous-surfaced and rigid pavements that apply to the condition of the roads. Those distresses include lane/shoulder separation and shoulder drop-off.

2.2.1.3.4.1 Lane/Shoulder Separation

Lane/shoulder separation severity is classified based upon the width of the opening between the traffic lane and the paved shoulder.

2.2.1.3.4.2 Shoulder Drop-off

Shoulder drop-off is classified as low, medium or high severity depending upon the difference in elevation between the outside shoulder and the traveled surface.

2.2.2 Past Pavement Performance Modeling Efforts

An effort was made by PennDOT in 2008 to develop pavement condition deterioration models using data collected as part of the Automated Pavement Condition Surveys. The desired outcome of this work was to create models that could predict the pavement performance and could be used to determine future treatment needs.

During the study, performance models were undertaken for both concrete and bituminous-surfaced pavements. Following is a summary of the activities undertaken during that effort; full details of the analysis are provided in appendix I.

2.2.2.1 Concrete Pavement Models

PennDOT began its 2008 study by examining the condition data for concrete pavements to determine if performance models could be created. To begin, 10 years of condition data for one county in the State was selected for the analysis. The results showed inconsistencies in the distress data for both severities and extents. Given the results, a second county was selected and it was found to have the same inconsistencies in data.

In the hopes of overcoming the data inconsistencies, an examination of condition data for the entire State concrete pavement network was conducted. Prior to analysis, the extent of each severity type for transverse cracking was converted to a numerical rating based upon the values in table 2-1. In addition to the data shown in table 2-1, a rating of 0 was used when there was no distress present. The first set of performance curves, which examined each severity level of transverse cracking separately, evaluated pavement sections by 5-year age ranges (e.g., 6 to 10 years old, 11 to 15 years old.). The results of the analysis, which looked at the average rating (conversion) values from 2003 to 2007, showed no significant data trends (see figure 2-1). The expected trend in the figure would be an increase in the conversion value with an increase in survey year. This trend is expected because as survey years increase pavement ages increase, which is expected to correspond with increases in distress extents. The increase in distress extents leads to a corresponding increase in the conversion values. However, the trend in figure 2-1 shows little change in the condition of the pavement sections across 5 years of the data.

Table 2-1. Rating (conversion) values based upon distress extents and severities.

Extent (% of overall segment length or area)	Severity		
	Low	Medium	High
1 – 10	1	11	21
11 – 20	2	12	22
21 – 30	3	13	23
31 – 40	4	14	24
41 – 50	5	15	25
51 – 60	6	16	26
61 – 70	7	17	27
71 – 80	8	18	28
81 – 90	9	19	29
91 – 100	10	20	30

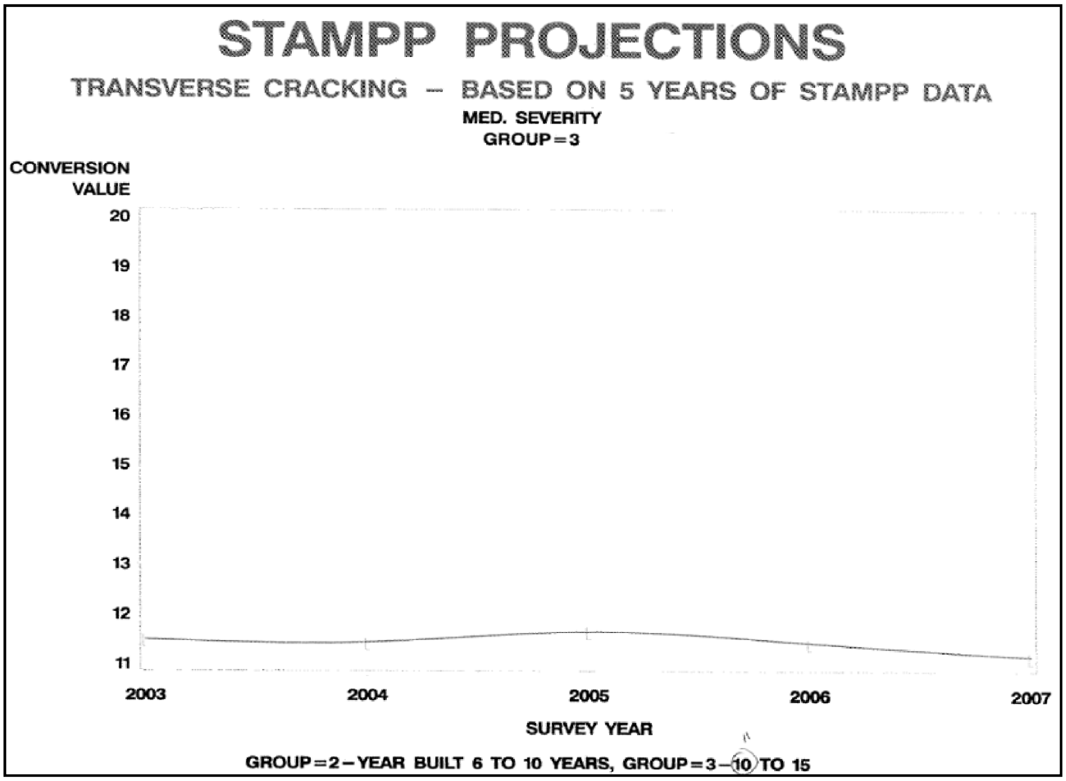

Figure 2-1. PennDOT trial performance model (PennDOT 2009).

Since the use of multiple years of data did not result in expected trends, pavements with the same age were analyzed again over a 5-year period. Expected performance trends were not observed in these data either. The same trend was true for sections that were grouped together because they had the same severity level for each distress type.

To continue the analysis, plots of pavement sections with distress at each severity level were placed on the same graph so that any decreases in the amount of distress at one severity might be offset by observations of increasing extent of a higher severity level (e.g., as distress change from medium to high severity). The observations from these modeling efforts showed some promise in terms of expected trends but did not fully capture the desired performance. A final attempt was made to plot performance over a 5-year period for all corresponding extent levels together (e.g., 1, 11, and 21). The performance observed was inconclusive and resulted in some unexpected downward trends. Overall, several efforts were made to create performance models for the concrete pavements but none displayed expected trends.

2.2.2.2 Bituminous-Surfaced Pavement Models

Models were also attempted for bituminous-surface pavements. The development of bituminous-surfaced pavement models began with the selection of several pavement sections that had experienced recent significant distress, including portions of I-70 and I-81. The condition data for each severity level of distress were converted to numerical ratings using the details included in table 2-1. The ratings were then averaged for each year of performance for each severity of each distress type. Two sets of averages were created. The first set included the use of ratings of zero (no distress) and the second set did not. Consistent deterioration trends could not be established for either set of data. Conditions on sections of I-90 and I-78 along with additional sections of I-81 were also evaluated. In these additional studies, the condition data were converted to extents by totaling the lengths of each severity level and dividing by the total length of all segments. The extents were then used to determine a rating that could be plotted. The results showed a slight upward trend for some distress types (indicating a slight deterioration in condition) while others remained relatively constant.

Specifically, an analysis of the performance trends related to fatigue cracking for the bituminous-surfaced pavements was also conducted by plotting all severity levels on the same graph. The data showed no conclusive trends in performance. Additional performance trends were examined for average extent values based upon age. Instead of predicting performance without treatment, the models indicated that there is some consistency in the age at which certain pavement improvements are placed. This analysis was expanded to determine whether district influenced the trends in the treatment cycles, but no conclusions could be reached.

2.3 Comparison of PennDOT Practices to Other SHAs

Comparisons between PennDOT's data collection methods and pavement performance modeling practices and those of other States are documented in this section. The comparisons are provided in matrix form. The matrices include comparisons of distresses collected, condition types modeled, distress types modeled, model types, and modeling families. Also, when information about statistical and quality testing of final models is available, those details are also provided.

2.3.1 Data Collection Methods

In an effort to evaluate and later recommend new performance modeling techniques for PennDOT, an examination of data collection methods used by other SHAs was conducted. During the survey of State practice, which was conducted as part of task 1 of this project, the bituminous-surfaced pavement distress types collected by SHAs were assessed. The results are presented in table 2-2. The comparison of rigid pavement distresses collected by PennDOT and other SHAs on PCCP, RCCP, and CRCP are shown in table 2-3. It should be noted that standard state abbreviations were used in each table.

Table 2-2. Comparison of bituminous-surfaced pavement distresses collected by PennDOT to the other SHAs.

Distresses (Recorded)	PA	AK	AL	AR	AZ	CA	CO	CT	DE	FL	GA	IA	IN	KS	KY	ME	MI	MN	MO	MT
Fatigue Cracking	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
Block Cracking	•		✓	✓	✓				✓	✓	✓	✓	✓	✓			✓	✓		✓
Edge Cracking	✓		✓	✓	✓						✓		✓				✓			
Longitudinal Cracking																				
• Wheel Path	--	--	✓	✓	✓	✓	✓	✓	--	✓	✓	✓	✓	✓	--	✓	✓	✓	--	✓
• Non-wheel Path	•	--	✓	✓	✓	✓	✓	✓	--	✓	✓	✓	✓	--	✓	✓	✓	✓	--	✓
Transverse Cracking	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
Patches	✓		✓	✓	✓	✓			✓	✓	✓	✓	✓		✓		✓	✓	✓	✓
Potholes																				
Rutting	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓		✓	✓	✓
Shoving											✓		✓	✓						
Bleeding				✓	✓						✓		✓				✓			
Polishing													✓							
Raveling	✓		✓	✓	✓					✓	✓		✓		✓		✓	✓	✓	✓
Water Bleeding/Pumping				✓							✓		✓							

✓ = distress collected by agency.

(green highlight) = highlighted marks indicate that the distress is collected by the noted agency and PennDOT.

• = distress collected by PennDOT but categorized as miscellaneous cracking.

Table 2-2. Comparison of bituminous-surfaced pavement distresses collected by PennDOT to the other SHAs (cont.).

Distresses (Recorded)	PA	ND	NH	NJ	NM	NV	NY	OH	OK	OR	SD	TN	TX	UT	VA	WA	WI	WV	WY
Fatigue Cracking	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Block Cracking	•	✓		✓		✓		✓	✓	✓	✓	✓	✓	✓			✓	✓	✓
Edge Cracking	✓				✓			✓									✓	✓	
Longitudinal Cracking																			
• Wheel Path	--	✓	✓	✓	✓	--	✓	--	✓	✓	--	✓	✓	✓	✓	✓	✓	✓	✓
• Non-wheel Path	•	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Transverse Cracking	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Patches	✓	✓		✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
Potholes																			
Rutting	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Shoving					✓												✓		
Bleeding		✓			✓	✓		✓		✓			✓	✓	✓	✓	✓		✓
Polishing																	✓		
Raveling	✓	✓			✓	✓		✓	✓	✓			✓	✓		✓	✓		✓
Water Bleeding/Pumping					✓			✓									✓		

✓ = distress collected by agency.

■ = highlighted marks indicate that the distress is collected by the noted agency and PennDOT.

• = distress collected by PennDOT but categorized as miscellaneous cracking.

Table 2-3. Comparison of rigid pavement distresses collected by PennDOT to the other SHAs.

	Distresses (Recorded)	**PA**	**AK**	**AL**	**AR**	**AZ**	**CA**	**CO**	**CT**	**DE**	**FL**	**GA**	**IA**	**IN**	**KS**	**KY**	**ME**	**MI**	**MN**	**MO**	**MT**
PCCP and RCCP	Corner Breaks				✓	✓		✓			✓	✓		✓				✓			
	Durability Cracking					✓							✓	✓	✓	✓		✓	✓	✓	
	Longitudinal Cracking	✓			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓		✓	✓		✓
	Transverse Cracking	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓		✓	✓		✓
	Joint Seal Damage (Transverse/Longitudinal)				✓		✓			✓	✓			✓		✓					
	Spalling of Joints (Transverse/Longitudinal)	✓			✓	✓	✓				✓		✓	✓		✓		✓	✓	✓	L
	Map Cracking					✓				✓				✓				✓			
	Scaling										✓			✓				✓			
	Polishing													✓							
	Blowups											✓		✓							
	Faulting of Transverse Joints/Cracks	✓		✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓		✓	✓		✓
	Lane-to-Shoulder Dropoff/Separation	✓												✓		✓					S
	Patches	✓			✓					✓	✓	✓	✓	✓		✓		✓	✓	✓	✓
	Water Bleeding/Pumping				✓						✓			✓							
		PA	**AK**	**AL**	**AR**	**AZ**	**CA**	**CO**	**CT**	**DE**	**FL**	**GA**	**IA**	**IN**	**KS**	**KY**	**ME**	**MI**	**MN**	**MO**	**MT**
CRCP	Durability Cracking					✓							✓			✓		✓	✓	✓	
	Longitudinal Cracking				✓	✓	✓			✓			✓			✓		✓	✓		
	Transverse Cracking	✓		✓	✓	✓	✓			✓			✓			✓		✓	✓		
	Joint Seal Damage (Longitudinal)						✓			✓											
	Map Cracking					✓				✓								✓			
	Scaling					✓												✓			
	Polishing																				
	Blowups															✓					
	Faulting of Transverse Construction Joints			✓		✓							✓			✓		✓	✓		
	Lane-to-Shoulder Drop-off/Separation	✓														✓					
	Patches	✓			✓					✓			✓			✓		✓	✓	✓	
	Punchouts	✓			✓		✓									✓		✓	✓		
	Spalling of Longitudinal Joints	✓					✓						✓			✓		✓	✓	✓	
	Water Bleeding/Pumping				✓																

✓ = distress collected by agency.

S = only joint separation is collected by the agency.

= highlighted marks indicate that the distress is collected by the noted agency and PennDOT.

Table 2-3. Comparison of rigid pavement distresses collected by PennDOT to the other SHAs (cont.).

	Distress (Recorded)	PA	ND	NH	NJ	NM	NV	NY	OH	OK	OR	SD	TN	TX	UT	VA	WA	WI	WV	WY
PCCP and RCCP	Corner Breaks		✓		✓	✓			✓	✓	✓	✓		✓	✓	✓		✓	✓	✓
	Durability Cracking		✓						✓	✓		✓	✓	✓				✓		✓
	Longitudinal Cracking	✓	✓		✓	✓		✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
	Transverse Cracking	✓	✓		✓	✓		✓	✓	✓	✓		✓		✓	✓	✓	✓	✓	✓
	Joint Seal Damage (Transverse/Longitudinal)					✓					✓	T		T		✓				
	Spalling of Joints (Transverse/Longitudinal)	✓	✓		L	✓		✓	✓	T	✓	✓		T	✓	✓	T	✓	T	✓
	Map Cracking				✓													✓	✓	
	Scaling																	✓		
	Polishing																	✓		
	Blowups															✓		✓		
	Faulting of Transverse Joints/Cracks	✓	✓		✓	✓		✓	✓	✓		✓	✓	✓	✓	✓		✓	✓	✓
	Lane-to-Shoulder Dropoff/Separation	✓			D	D					D				D	✓		✓		
	Patches	✓	✓						✓	✓	✓		✓	✓	✓	✓	✓	✓		✓
	Water Bleeding/Pumping								✓									✓		
		PA	**ND**	**NH**	**NJ**	**NM**	**NV**	**NY**	**OH**	**OK**	**OR**	**SD**	**TN**	**TX**	**UT**	**VA**	**WA**	**WI**	**WV**	**WY**
CRCP	Durability Cracking		✓									✓								
	Longitudinal Cracking		✓						✓	✓	✓					✓			✓	
	Transverse Cracking	✓	✓						✓							✓			✓	
	Joint Seal Damage (Longitudinal)										✓					✓				
	Map Cracking																		✓	
	Scaling								✓											
	Polishing								✓											
	Blowups		✓																	
	Faulting of Transverse Construction Joints																		✓	
	Lane-to-Shoulder Dropoff/Separation	✓									D					D				
	Patches	✓	✓						✓	✓	✓			✓		✓				
	Punchouts	✓							✓		✓	✓	✓	✓		✓				
	Spalling of Longitudinal Joints	✓	✓						✓		L	✓				✓				
	Water Bleeding/Pumping								✓											

✓ = distress collected by agency

T = only transverse joint spalling not longitudinal is collected by the agency.

L = only longitudinal joint spalling not longitudinal is collected by the agency.

D = only lane-to-shoulder dropoff is collected by the agency.

= highlighted marks indicate that the distress is collected by the noted agency and PennDOT.

For both tables 2-2 and 2-3, the distresses collected by PennDOT have been noted with a check mark in the "PA" column. A check mark is used in the other columns to indicate agencies that are collecting the same distress types. Shading was also added to indicate when the distresses collected by the SHAs match those collected by PennDOT. Table 2-2 does not indicate the addition of left edge deterioration in the survey procedure as this distress type was added to the PennDOT rating procedure in 2009 and knowledge of this distress did not exist at the time of the project survey. However, it is expected that the collection of this distress type is included by many States as part of non-wheelpath longitudinal cracking.

As tables 2-2 and 2-3 indicate, the majority of distresses collected by other SHAs match those being collected by PennDOT. Using this information to identify states that are collecting similar distress types coupled with information from the task 1 survey, Minnesota, North Dakota, Oklahoma, Oregon, and Washington were selected for case studies.

Details regarding data collection frequencies and coverage rates used by each agency are provided in table 2-4. The information provides a reference for PennDOT to compare their data collection procedures to those used by other agencies. The information shows that PennDOT's distress, rutting and roughness data collection procedures are similar to those used by Oklahoma, Oregon, and Washington, but other states like Minnesota and North Dakota collect data on a much lower percentage of their pavement area.

In addition to examining PennDOT's procedures to the case study States, it is also important to assess how PennDOT's standards for data collection compare to those needed to comply with other initiatives. Two specific initiatives were investigated. First, PennDOT's pavement condition data were compared to the new reporting requirements for HPMS. Secondly, the research team investigated the match between PennDOT's data collection efforts and the data requirements to calibrate the MEPDG models. The HPMS comparison is provided in table 2-5 and the MEPDG comparison is provided in table 2-6. Table 2-5 shows that in most cases the data being collected by PennDOT are consistent with the 2010 requirements for HPMS reporting.

Table 2-4. Summary of practice for case study States.

	Minnesota	North Dakota	Oklahoma	Oregon	Washington State
Data Collection Frequency and Coverage					
Distress data	~60% annually; 1st 500-ft of ea. mile or pavement change in right lane (both directions for divided highways)	1st 500-ft of ea. mile (2-lane roads: collected in alternating directions, 4-lane roads: collected in driving lane for both directions)	100% annually of outside lane in predominate direction (both directions for divided highways); distresses rated per 0.01-mile section	50% annually for 100% coverage every 2 years; 0.1-mile sampling of outside lane in one direction surveyed (both directions for interstate)	100% annually of outside lane in one direction (both directions for divided highways)
Roughness and Rutting data	100% annually in both wheel paths	100% annually	50% annually; 100% annually for interstate and NHS[1]	100% annually for NHS; other roads every 2 years, except minor collectors	100% annually in both wheel paths
Skid data	Project-level only	Not collected	1/3 of network annually	50% annually for 100% coverage every 2 years; data is collected every 1/2-mile	50% annually for 100% coverage every 2 years

[1] NHS: National Highway System (http://www.fhwa.dot.gov/planning/nhs/)

Table 2-5. Review of PennDOT's use of HPMS data specifications.

HPMS Data Specification	HPMS Requirements	PennDOT Practice
International Roughness Index, IRI (in/mile; nearest integer)	Average of left and right quarter-car IRI for all NHS and Principal Arterial universe[1] sections and Rural Minor Arterial sample[2] sections. Also record month and year data collected (MM/YYYY). IRI should be measured annually for the NHS and biennially for all other required sections. AASHTO R43-07 is recommended for providing IRI data to the HPMS.	PennDOT annually collects profile data for both the outside and inside wheel paths using a quarter-car simulation for NHS routes, and determines the IRI for every 0.1-mile roadway segment averaging both wheel paths. Data is collected biennially all other routes.
Present Serviceability Rating, PSR (nearest 0.1)	Required only where IRI is not reported for all Urban Minor Arterial, Major Collector, and Urban Minor Collector sample[2] sections.	Not required where an IRI value is recorded.
Rutting (average, nearest 0.1 in)	All paved bituminous-surfaced and composite pavement sample[2] sections consistent with IRI inventory direction and lane. AASHTO PP38-00 or the LTPP protocol are to be followed for the data collection. Record maximum rut depth at 50-ft intervals.	PennDOT annually collects rutting data a minimum of every 30 ft for NHS routes, then categorizes the severity level for each sample interval according to rut depth (in), and totals the amount for both wheel paths of the roadway. Data is collected biennially for all other routes.
Faulting (average; nearest 0.1 in)	All paved jointed concrete pavement sample[2] sections consistent with IRI inventory direction and lane. AASHTO R36-04 or the LTPP protocol are to be followed for the data collection.	PennDOT annually measures joint faulting in the outside wheel path for NHS routes, and records the distress per number of faulted joints as either medium or high severity, based on elevation of fault. Data is collected biennially for all other routes.

[1] Universe sections: Data reported for all roadway links in the system.
[2] Sample sections: Data reported for a randomly selected sample of roadway links in the system.

Table 2-5. Review of PennDOT's use of HPMS data specifications (cont.).

HPMS Data Specification	HPMS Requirements	PennDOT Practice
Fatigue Cracking (nearest 5%)	Report biennially percent area with fatigue cracking for bituminous-surfaced sections, and percent of cracked slabs for PCC sections. All paved bituminous-surfaced, PCC, and composite pavement sample[2] sections consistent with IRI inventory direction and lane. AASHTO PP44-01 or the LTPP distress identification manual should be followed as a guide.	PennDOT annually collects cracking data for a roadway's outside lane on NHS routes. Data is collected biennially for all other routes. Fatigue cracking is collected in the outside 30-in wheel path, and is measured by length and severity, which is based on crack width and interconnectivity.
Transverse Cracking (nearest 1 ft/mile)	Report biennially the summation of the lengths of all transverse cracks in each mile section for all paved bituminous-surfaced, PCC, and composite pavement sample[2] sections consistent with IRI inventory direction and lane. AASHTO PP44-01 or the LTPP distress identification manual should be followed as a guide.	PennDOT collects cracking data for a roadway's outside lane. Transverse cracking is measured per roadway section by total length per level of severity, which is based on crack width.
Year of Last Improvement, Year of Last Construction, and Year of Last Overlay (required format: YYYY)	All paved sample[2] sections.	Construction history data is incorporated into PennDOT's roadway management system.
Material types (Surface type, base type, soil type	All paved sample[2] sections.	Pavement type and layer attributes are incorporated into PennDOT's pavement information database. As built information is used as much as possible.
Thickness of Rigid Pavement (nearest 0.5 in)	Actual measured value for all paved sample[2] sections consistent with IRI inventory direction and lane.	
Thickness of Flexible Pavement (nearest 0.5 in)		
Thickness of Base (nearest 1 in)		
Thickness of Last Overlay (nearest 0.5 in)	Actual measured value for all paved sample[2] sections consistent with IRI inventory direction and lane.	Maintenance treatment data is incorporated into PennDOT's pavement information database.

[1] Universe sections: Data reported for all roadway links in the system.
[2] Sample sections: Data reported for a randomly selected sample of roadway links in the system.

Table 2-6. Review of PennDOT's use of MEPDG "Analysis Parameter" inputs.

MEPDG Input Variable	Comments
FLEXIBLE DESIGN TYPE: Bituminous surface type	
Initial IRI (in/mile)	PennDOT collects profile data for both the outside and inside wheel paths, and determines the IRI for every 0.1-mile roadway segment. *PennDOT will need to determine a standard initial and terminal IRI for design.*
Terminal IRI (in/mile)	
Bituminous surface down cracking, longitudinal cracking (ft/mile)	PennDOT collects cracking data for a roadway's outside lane. • Fatigue cracking is collected in the outside 30-in wheel path, and is measured by length and severity, which is based on crack width and interconnectivity. • Transverse cracking is measured per roadway section by total length per level of severity, which is based on crack width • Miscellaneous cracking is collected in the inner 39-in section of the lane, and is measured by length and severity, which is based on crack width. *PennDOT's fatigue cracking would need to be converted into the ft/mile measurement. However, miscellaneous cracking is not collected in a manner that easily facilitates the classification of longitudinal cracking.*
Bituminous bottom up cracking, fatigue cracking (%)	
Bituminous thermal fatigue cracking (ft/mile)	
Chemically stabilized layer fatigue fracture (%)	PennDOT does not use chemically stabilized layers. *This input will not apply for PennDOT.*
Permanent deformation—total pavement (in)	PennDOT collects rutting data a minimum of every 30 ft, then categorizes the severity level for each sample interval according to rut depth (in), and totals the amount for both wheel paths of the roadway. *The collected information will provide the details needed to summarize total pavement deformation but will not have the information needed to determine the amount of distress due to the bituminous layer only.*
Permanent deformation—bituminous only (in)	
RIGID DESIGN TYPE: JPCP	
Initial IRI (in/mile)	PennDOT collects profile data for both the outside and inside wheel paths, and determines the IRI for every 0.1-mile roadway segment, as well as per slab. *PennDOT will need to determine a standard initial and terminal IRI for design.*
Terminal IRI (in/mile)	
Transverse cracking (% cracked)	PennDOT collects transverse cracking data for number of slabs with cracks > 6 ft long, and assesses severity according to crack width, amount of spalling, or severity of faulting. *The number of slab cracks can be converted into the needed cracking percentage.*
Mean joint faulting (in)	PennDOT measures joint faulting in the outside wheel path, and records the distress per number of faulted joints as either medium or high severity, based on elevation of fault. *The collected information could be used to estimate the mean joint faulting.*

Table 2-6. Review of PennDOT's use of MEPDG "Analysis Parameter" inputs (cont.).

MEPDG Input Variable	Comments
RIGID DESIGN TYPE: CRCP	
Initial IRI (in/mile) Terminal IRI (in/mile)	PennDOT collects profile data for both the outside and inside wheel paths, and determines the IRI for every 0.1-mile roadway segment. *PennDOT will need to determine a standard initial and terminal IRI for design.*
Punchouts (per mile)	PennDOT records the number of punchouts per severity level. *PennDOT can summarize this information for this input.*
Maximum crack width (in)	PennDOT records transverse cracking based on the number of cracks, and measures severity based on crack width and occurrence of spalling and/or faulting. *PennDOT may want to use available classification data and crack width information to determine a standard initial and terminal IRI for design.*
Minimum Crack Load Transfer Efficiency (LTE%)	PennDOT does not record this information. *PennDOT will need to determine a value. The acceptable range of MEPDG values is between 50 and 90.*
Minimum crack spacing (ft)	Minimum crack spacing is not captured. *PennDOT will need to decide on a value. The default MEPDG value is 3 ft.*
Maximum crack spacing (ft)	Maximum crack spacing is not captured. *PennDOT will need to decide on a value. The default MEPDG value is 6 ft.*

In some cases, PennDOT's current practices can be modified to meet the HPMS data specifications. For instance PennDOT records PCC joint faulting as the total number of occurrences at each severity, with severity based on fault elevation. If fault elevation is also recorded, it can be used to meet the HPMS requirement by averaging the section's faulting and reporting it the nearest 0.1 inch. PennDOT's measurement of fatigue cracking can also be modified to estimate the percent cracking required by the HPMS. The HPMS also requires rutting data be reported on a 50-ft interval, whereas PennDOT currently requires a minimum 30-ft interval.

Other construction history data required by HPMS (e.g., construction year, pavement structure layer thicknesses, and so on) are reportedly included in PennDOT's pavement management database. Although, the HPMS 2010+ Data Specifications (posted to the FHWA website June 1, 2009) states that thickness data should be "actual measured" values, the 2009 Draft Data Collection Field Manual (posted November 10, 2008, and into which the Data Specifications will be incorporated) notes that final design values are satisfactory.

Regarding the data requirements to calibrate the MEPDG models, as summarized in table 2-6, PennDOT may need to record additional information and/or conduct additional tests to have the necessary information to calibrate the models for bituminous-surfaced pavements. Notes of some basic steps that PennDOT might take to use their available information or collect addition information are provided in italics for each MEPDG input variable included in table 2-6. For example, without the collection of some additional data, some input variables, such as surface-down and bottom-up cracking for bituminous-surfaced pavements, will have to rely on the default model in the MEPDG software for design analyses.

2.3.2 Modeling Practices

While PennDOT has conducted preliminary work to develop pavement performance models, the models have not been finalized. A survey of State practices in pavement management conducted as a part of this study found that approximately 84 percent of the responding agencies had developed models. Of those agencies using performance models, 73 percent of them were created for pavement families, 10 percent for individual pavement sections, and 17 percent for a combination of families and individual pavement sections as indicated in table 2-7.

Table 2-7. Summary of agencies that develop performance models and the level at which they are created.

Agency	Has your agency developed performance models?	Modeling Approach
Alabama DOT	No	N/A
Alaska DOT	Yes	For individual pavement sections
Arizona DOT	Yes	For individual pavement sections and when sufficient data doesn't exist use default pavement families
Arkansas SHTD	No	N/A
California DOT	No	N/A
Colorado DOT	Yes	For individual pavement sections and when sufficient data doesn't exist use default pavement families
Connecticut DOT	Yes	For pavement families
Delaware DOT	Yes	For pavement families
Florida DOT	Yes	For individual pavement sections and when sufficient data doesn't exist use default pavement families
Georgia DOT	Yes	No response
Indiana DOT	No	N/A
Iowa DOT	Yes	For pavement families
Kansas DOT	Yes	For pavement families
Kentucky Trans Cabinet	No	N/A
Maine DOT	Yes	For pavement families
Michigan DOT	Yes	For individual pavement sections and when sufficient data doesn't exist use default pavement families
Minnesota DOT	Yes	For individual pavement sections and when sufficient data doesn't exist use default pavement families
MoDOT	Yes	For pavement families
Montana DOT	Yes	For pavement families

Agency	Has your agency developed performance models?	Modeling Approach
NDDOT	Yes	For pavement families
Nevada DOT	Yes	For pavement families
New Jersey DOT	Yes	For pavement families
New Mexico DOT	Yes	For individual pavement sections
New York State DOT	Yes	For pavement families
NHDOT	Yes	For pavement families
Ohio DOT	Yes	For pavement families
Oklahoma DOT	Yes	For pavement families
Oregon DOT	Yes	For pavement families
South Dakota DOT	Yes	For pavement families
Tennessee DOT	No	N/A
Texas DOT	Yes	For pavement families
Utah DOT	Yes	For pavement families
Virginia DOT	Yes	For pavement families
Washington State DOT	Yes	For individual pavement sections
West Virginia DOH	Yes	For pavement families
WIsDOT	Yes	For pavement families
Wyoming DOT	Yes	For pavement families

Further details of the performance modeling practices used by each of the case study agencies are highlighted in table 2-8. Information highlighted in the table includes the condition and distress types that are modeled, the model types used, data collection methods, model groups, quality testing of models, and data collection rates. Table 2-8 shows that each agency has its own unique method for handling the collection of condition data and the development of performance models. In essence, each agency has customized its data modeling efforts to match its unique needs. The one parameter that each case study agency has in common is the use of deterministic models. However, other than that detail there are differences in all other performance modeling attributes. Additional details of the practices used by other SHAs are included in appendix J.

The performance modeling efforts conducted by PennDOT in 2008 cannot be compared to many of the details in table 2-8 as no specific practices have been initiated. However, data collected by PennDOT can be compared to some of the modeling practices used by the case study agencies. For example, the number of distresses collected by PennDOT (7 bituminous surfaced distresses, 8 PCCP and RCCP, and 6 CRCP) is larger than the number of individual indices used by the case study agencies. For example, Oklahoma uses a total of 4 individual indices for HMA pavements, 4 indices for JPCP, and 2 indices for CRCP, which is 11 less indices than PennDOT. Therefore, it may be advantageous for PennDOT to consider grouping various distress types together in order to reduce the number of models. Considerations such as these will be used to develop the modeling recommendations included in chapter 3 of this report.

Table 2-8. Summary of practice for case study States.

	Minnesota	North Dakota	Oklahoma	Oregon	Washington State
Condition Types Modeled					
Overall Indices					
HMA:	PQI,RSL	Distress Score, RSL	PQI	PCI, RSL	PSC, Modified RSL
JPCP:	PQI,RSL	Distress Score, RSL	PQI	PCI, RSL	PSC, Modified RSL
CRCP	PQI,RSL	Distress Score, RSL	PQI	PCI, RSL	--
Distress Types Modeled					
Ride Indices	Ride Quality Index (RQI)		Ride		Pavement Profile Condition (PPC)
HMA:	✓		✓		✓
JPCP:	✓		✓		✓
CRCP:	✓		✓		--
Structural/Fatigue Indices				Fatigue	Pavement Structural Condition (PSC)
HMA:		✓	✓	✓	✓
JPCP:		--	--	✓	✓
CRCP:		--	✓	✓	--
Rutting Indices				Rut	Pavement Rutting Condition (PRC)
HMA:			✓	✓	✓
JPCP:			--	✓	✓
CRCP:			--	✓	--
Patching Indices				Patching	
HMA:				✓	
JPCP:				✓	
CRCP:				✓	
Other Indices	Surface Rating (SR)	JPCP: Slab Cracking	HMA: Functional Index; JPCP: Fault Index, Slab Index, Joint Index	HMA: Raveling Index, Environmental Index	JPCP: Grinding Index, Dowel-Bar Retrofit Index, and Reconstruction Index
Model Indices (I) or Distresses (D)?	D	I	I	I	I
Indices created directly from distress data? Overall (O) or Individual (I)	O	I	I	I	O

Table 2-8. Summary of practice for case study States (cont.).

	Minnesota	North Dakota	Oklahoma	Oregon	Washington State
Model Types					
Deterministic	✓	✓	✓	✓	✓
Probabilistic	--	--	--	--	--
Survival	--	--	--	--	--
Data Collection Methods					
Pavement distress data collection methodology	State Guidelines[1]	SHRP LTPP Modified	SHRP LTPP Modified	State Guidelines[2]	NWPMA[3]
Survey Type Used? Semi-automated (SA), manual (M), or both (B)	SA	SA	SA	B	SA
Model Groups					
Individual (I) or Family (F) Curves?	I	F	F	F	I
Models developed for…					
Statewide	✓	--	--	--	--
Network-level	--	✓	✓	✓	--
Project-level	--	--	--	✓	✓
Other	--	NDDOT HPCS[4]	--	--	--
Quality Testing of Models					
Statistical analysis of pavement performance models?	Linear model evaluated using Coefficient of Determination (R^2)—to improve R^2, outliers are removed or a polynomial or sigmoidal model is used	No	Coefficient of Determination (R^2)	No	Best fit regression through historical data—anomalies not removed
Pavement Management Systems	HPMA	dTIMS	dTIMS	Pavement Analyst	WSPMS

[1] Minnesota State Guidelines: http://www.dot.state.mn.us/materials/manuals/pvmtmgmt/distressmanual.pdf
[2] Oregon State Guidelines: http://www.oregon.gov/ODOT/HWY/CONSTRUCTION/docs/pavement/Distress_Survey_Manual.pdf
[3] NWPMA: NorthWest Pavement Management Association (nwpma-online.org)
[4] NDDOT Highway Performance Classification System: interstate, interregional corridor, state corridor, district corridor, district collector.
[5] NHS: National Highway System (http://www.fhwa.dot.gov/planning/nhs/)

2.4 Summary

This chapter summarizes PennDOT's data collection and performance modeling efforts and compares them with practices in other States. PennDOT's practices are also compared to the HPMS and MEPDG data requirements to determine whether any deficiencies exist. The findings will be used to develop specific recommendations for developing and maintaining pavement performance models.

CHAPTER 3 – PROPOSED MODELING OPTIONS

Using the knowledge of data collection and modeling practices summarized in chapters 1 and 2 of this report, three approaches are proposed to PennDOT for developing its pavement performance models. A preferred approach is also recommended.

3.1 Objectives for the Proposed Modeling Approaches

As demonstrated earlier in this report, there are many different approaches that agencies can take to develop pavement performance models. The approaches used by other agencies have been influenced by the type of pavement condition surveys conducted, the software used, and the importance of pavement distress information to identify feasible treatments. Therefore, the first step in developing recommendations involved identifying the specific objectives that PennDOT intends to accomplish through the development of the models. The objectives provided by PennDOT are listed below.

1. Provide a methodology for predicting future funding needs.

   One reason for developing pavement performance models is to predict future conditions and, based upon the predicted condition, determine treatment recommendations and corresponding funding needs. Being able to conduct "what-if" funding scenarios is a high priority for PennDOT; this need is a major impetus for the implementation of a pavement management system.

2. Provide practical and implementable predictions that can be explained to decision makers.

   Many agencies would like transparent pavement management recommendations based on reliable data and performance models that reflect actual conditions. Likewise, PennDOT would like its pavement performance models to be easily explained to all stakeholders including decision makers. In addition, PennDOT prefers a transparent process that can be easily explained to all stakeholders.

   To accomplish this objective, many agencies use deterministic models that incorporate a limited number of variables. These models are used because of the simplicity in predicting condition based on age. More robust equations are not frequently used because they are not easily understood by all users and they are more susceptible to errors in data.

3. Select models that may be easily incorporated into pavement management software.

   It is important that the models PennDOT uses can be easily incorporated into the pavement management system it is preparing to select and implement. Therefore, a probabilistic approach was not considered, as many software programs do not easily accommodate probabilistic models without requiring extensive software modifications or a conversion of the probabilistic models to a deterministic format.

4. Utilize existing data collection procedures and historical data as much as possible.

PennDOT would like to be able to implement its models without having to dramatically change its current data collection practices. Therefore, the use of existing data collection procedures and historical data collected by the Roadway Management Division of the Bureau of Maintenance and Operations was be a priority in developing recommendations.

Using the goals that PennDOT intends to achieve through the development of the models, there are several key considerations that must be weighed when determining modeling approaches. These considerations include the following:

- What will the model predict?

  When developing models, consideration must be given to whether the models are going to predict distresses, individual indices (e.g., cracking index, rutting index, etc.), or an overall index. The prediction of individual distresses is a more complicated approach than the development of predictions of either individual indices or an overall index.

- How will an overall index be calculated?

  The overall index can be calculated using deduct values based solely upon distress or a combination of both distress and ride. Depending upon the needs of the agency, either option is a viable approach.

- What rating scale will be used?

  A variety of rating scales are used by various agencies. The most prominent scale is a 100-point scale. However, a scale can be based on any value desired by the agency.

- Should models be developed for pavement families or should individual models be developed?

  Performance models can be created for groups of pavements, known as "families," or for each individual pavement section. Many agencies focus on the development of family models, as this is a simpler method that results in the development of a smaller number of equations. The family modeling approach is also sometimes easier to incorporate into a pavement management system than individual models.

- What type of model will be used?

  The majority of agencies use deterministic models, because their form makes them easier to explain to users and they are often easier to incorporate into the pavement management system Nevertheless, there are agencies that utilize other forms, including probabilistic or expert models. .

- What variables will be considered in the model?

  Pavement performance models can contain a variety of variables. However, the majority of models include the incorporation of age as the primary predictor of condition. Some agencies do expand their models to consider additional factors such as traffic, layer thicknesses, and so on. However, the effort to incorporate additional variables can be significant.

- Who will develop the models?

  Models can be developed by an agency or through the use of consultants or software vendors. The choice often depends upon the skills of available staff within the agency.

- What pavement management software will be used?

  The development of models is also dependent upon the pavement management software that the agency will use. For example, some systems incorporate individual pavement models more readily than others.

- What level of effort is required to develop the models?

  The level of effort needed to develop models is another major consideration when moving forward with model development. For example, the development of distress models for individual sections requires a more significant effort than the development family models.

These key considerations collectively help shape model development. As proposed modeling options are developed for PennDOT, a summary of the practices of the key states is presented table 3-1 to highlight how each agency approached these key considerations.

Table 3-1. Key modeling considerations for the case study states.

Key Considerations	Minnesota	North Dakota	Oklahoma	Oregon	Washington
Model Predicts	Distress	IRI – current Index – planned	Individual Indices	Overall Index	Overall Index
Calculated Overall Index	Pavement Quality Index (PQI)	Distress Score	Overall Condition Index	Overall Index (correlated to RSL)	Pavement Structural Index (PSC)
Rating Scale	4.5- point	99-point	100-point	100-point	100-point
Model Groupings	Individual	Family	Family	Family	Individual
Type of Model	Deterministic	Deterministic	Deterministic	Deterministic	Deterministic
Variable in Models	Age	Age	Age	Age	Age
Model Developer	Consultant then Internal	Software Developer	Consultant then Internal	Internal	Internal
PMS Software	HPMA	dTIMS	dTIMS	Pavement Analyst	WSPMS
Level of Effort	High	Low	Medium	Medium	Medium

3.2 Proposed Modeling Approaches

Three options for developing pavement performance models for PennDOT are presented. Each approach takes into consideration the lessons learned from the study of practices in other SHA and the goals established by PennDOT. The following sections describe each of the three options and provide model development flow charts and supporting documentation.

3.2.1 Option 1: Maintain Current Treatment Selection Matrix and Develop Supporting Distress Performance Models

The first proposed option for model development allows for the use of the current treatment selection matrices in their present form. This option includes the development of performance models for each combination of distress type and severity level, which could be created either for pavement families or for each individual pavement section. A sample flowchart illustrating how the models would be created under this option is provided in figure 3-1, and the process is discussed in more detail below.

3.2.1.1 Determine Modeling Approach

Before models are developed, consideration must be given to whether individual or family distress models are desired for the modeling process. Because this modeling option focuses on the development of distress models, it is a very involved process even when considering family modeling versus section-specific modeling.

The HMA and jointed concrete pavements are classified as Interstate, National Highway System (NHS) non-Interstate, or non-NHS. Each roadway classification is then divided into urban and rural pavement subgroups. Each of the subgroups are then divided into three average daily traffic (ADT) ranges (<5,000; 5,000 to 15,000; and >15,000). Therefore, a total of 342 models (i.e., 19 distress type severities * 3 classes * 2 subgroups * 3 traffic ranges) would be required for HMA pavements and 396 models (i.e., 22 distress type severities * 3 classes * 2 subgroups * 3 traffic ranges) for jointed concrete pavements. However, the models for CRCP would be significantly less complicated than those needed for HMA and jointed concrete pavements, as only six models are needed to describe the six distress types that are used in the CRCP treatment selection matrix.

Nevertheless, a total of 744 performance models would be needed to describe all pavement families included in the treatment selection matrices. The use of this many models creates a significant modeling effort as it is not only necessary to model each distress for each pavement family, but it also makes it necessary to properly describe how distress types progress from severity levels.

As an alternative to developing distress models for pavement families, individual models, which will provide even more detail, can be created. However, because a model is created for each separate pavement section, the development of individual models is a very involved process requiring more effort to create and oversee than family models. Also, the use of individual performance curves may be limited based upon the pavement management software selected by PennDOT.

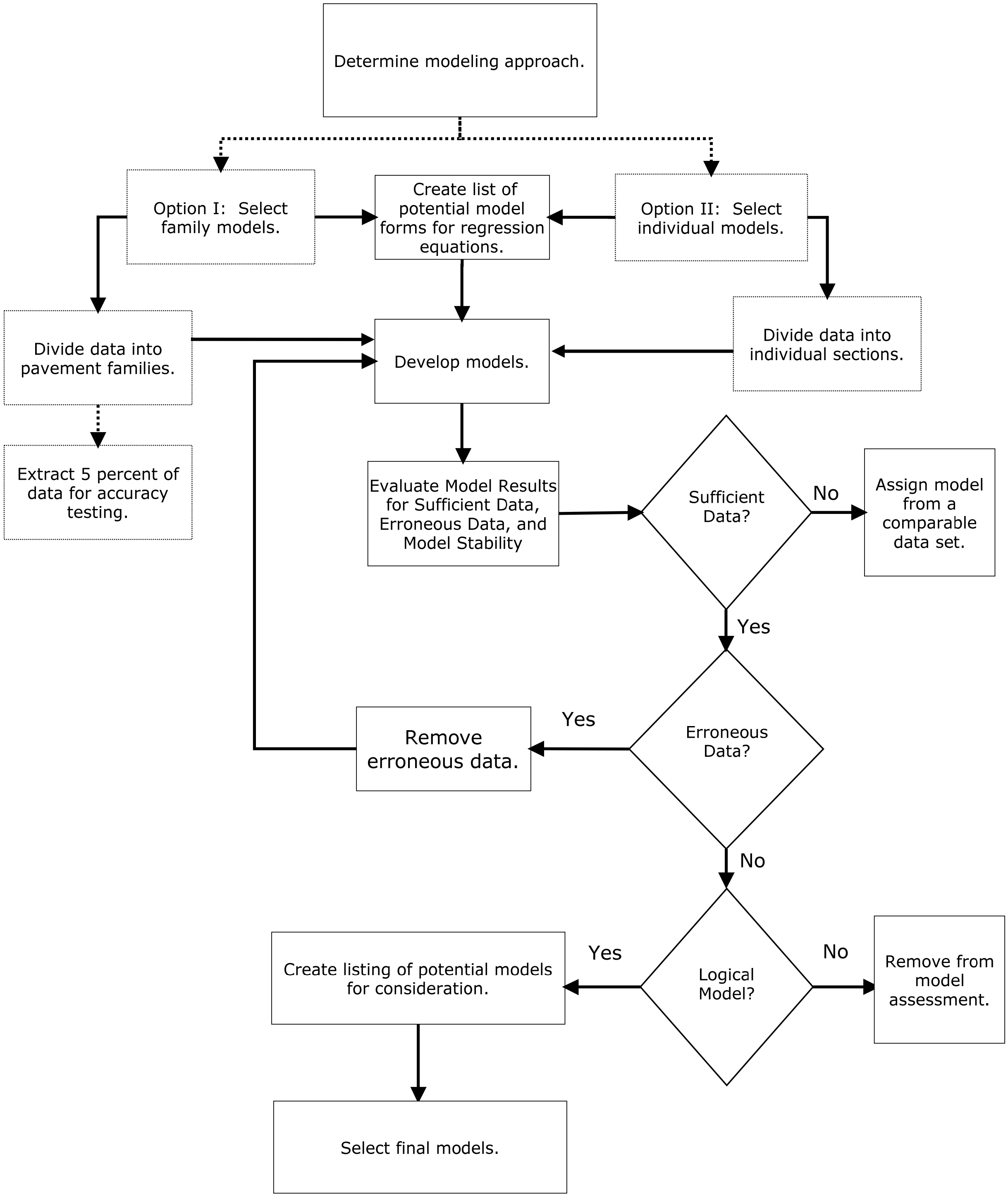

Figure 3-1. Option 1 model development workflow.

3.2.1.2. Option I: Select Family Models

If the family model option is the selected modeling approach, then there are a few steps that should be taken initially so that model accuracy can be assessed after the initial models are developed.

3.2.1.2.1 Divide Data into Pavement Families

Prior to model development, the data should be divided into the eighteen pavement family groupings for both HMA and jointed concrete. CRCP data should be grouped into one family.

3.2.1.2.2 Extract 5 Percent of Data for Accuracy Testing

A random 5 percent of the data from each pavement family should be extracted for later use in verifying the robustness of the developed family models as described in section 3.2.4.

3.2.1.3 Option II: Select Individual Models

If modeling individual pavement sections is the selected modeling approach, there is no need for examining modeling accuracy as the given data dictate the model behavior. However data must be organized in a manner to allow for proper division of data.

3.2.1.3.1 Divide Data into Individual Sections

Prior to model development, the data should be divided into individual pavement sections or labeled in a manner that will allow for easy division of the performance data into needed groupings for model development.

3.2.1.4 Create List of Model Forms

When deciding on potential models for analysis under either the family or individual modeling approach, a list of model forms should be developed for use in examining regression equations. For example, the model forms utilized by Mn/DOT to develop equations to model distresses were based upon the following equation:

$$\text{Distress percent} = e^{(-K/Age)} \qquad (3\text{-}1)$$

Values of K were determined based upon an algebraic solution of K for each observed distress and age. The resulting K values were then averaged for each Mn/DOT pavement family. Additional model forms that should be examined include linear, polynomial, power, and sigmoidal, which are detailed in chapter 1 of this report. This modeling example assumes that age is the primary variable used in modeling. PennDOT may wish to expand the modeling to include multivariate regression analysis with additional continuous variables such as pavement thickness, base thickness, and so on. If additional variables are added to the analysis, PennDOT will need to compile a list of variables to examine; determine if the data are complete, logical, and reliable as described in chapter 1; and finalize a list of selected variables for use in model development. It is recommended that PennDOT proceed with modeling the various distress types using only age in order to reduce complexity. However, other options are available if age does not prove to be a robust enough predictor.

With the various model forms and desired predictive variables determined, a list should be developed for each combination of model form (e.g., linear, polynomial) and distress type (e.g., alligator cracking, miscellaneous cracking) to be examined.

3.2.1.5 Develop Models

After selecting the appropriate model forms to consider, various types of statistical analysis software or modeling tools can be used to develop the deterministic models for each type of distress. Also, depending upon the pavement management software selected by PennDOT, modeling efforts may be conducted using that software.

If a single variable analysis is used, the behavior of the independent variable (most likely age) can be used to explain the behavior of the distress type for the chosen data set. For the multivariate regression, the behaviors of several independent variables can be used in combination to explain the behavior of the distress types. If developing multiple variable regression equations, time must be taken to use a step-wise addition and deletion process to determine the best combination of continuous variables to include in the models. In using either linear or multiple variable modeling, engineering judgment must be used to determine whether the regression analysis will be conducted using unconstrained or fixed intercept regression equations. An unconstrained equation will allow for the data itself to predict the intercept of the equation, while the fixed intercept regression equation requires the intercept to be specified. Fixed intercepts are often used when modeling pavement performance as the distress level or starting index is a known value. However both methods can be evaluated during model development to determine the best method for the PennDOT data.

3.2.1.6 Evaluate Results for Sufficient Data, Erroneous Data, and Logical Models

Prior to model selection, the data sets used to create the performance models should be evaluated to ensure that inspections were conducted at least three times over a time span greater than 5 years. If sufficient data do not exist, a default model that seems representative of the behavior of the given pavement family or individual section will need to be assigned to the data. Also, default models will be used when developed models do not follow expected trends such as increasing condition with time or traffic.

The data used to create the models should also be evaluated for erroneous data. Performance data may be removed for certain pavement sections when examined conditions are known to be in error. The given data set can then be reevaluated to develop a new performance equation with the erroneous data removed. Erroneous data might include the occurrence of significant decreases in distress quantities with no corresponding work activities, indicating that work history data is missing or there has been an error in data collection. Errors in the work history are the most common cause of errors in pavement age, which significantly impact the accuracy of the predicted condition.

In addition to providing accurate data for model development, the models must prove to be logical to be considered adequate descriptors of pavement performance. For the developed models to be considered logical, the developed models should result in performance trends that follow engineering logic.

3.2.1.7 Create Listing of Final Models for Consideration

Those models that were determined to have sufficient accurate data and to have been logical should be plotted and summarized. The summarized data should be in tabular form and should document the final equations along with the resulting R-squared values.

3.2.1.8 Select Final Models by Analysis of R-squared and Visual Fit of Data

Using the lists of R-squared values along with visual examination of the fit of the performance models to the plotted data as a basis, engineering judgment is needed to select final models for each data set. Selecting the final model is not as simple as selecting the "optimal" model for a given data set based only on R-squared values. Instead, the modeling results should be examined to determine which data grouping provides the "optimal" model. Models that provide a combination of the highest R-squared values along with a "good" visual fit of the performance curve to the example data should be selected. The developed curves should also display expected curvatures for the combination of the given data set and the modeled performance index.

3.2.2 Option 2: Maintain Existing Treatment Selection Matrix for Current Needs and Develop an Overall Index to Model Future Needs

As an alternative to the labor-intensive process associated with option 1, the second option involves combining distress information into a single overall index for predicting conditions, while continuing to use the treatment selection matrix for determining short-range treatment recommendations. Under this approach, two-year plans detailing specific work needed to repair the pavement network can be developed using the results of pavement condition surveys and the current treatment selection matrices, as is currently done. However, the performance models would be used to predict an overall index, allowing future conditions and budgets to be estimated for planning purposes. The predictions of overall condition will be tied to costs for maintenance and rehabilitation (M&R) activities at each condition level for estimating future budget requirements. For example, if the overall index were based upon a 100 to 0 scale representing excellent to poor condition, respectively, pavements with an overall condition of 40 to 0 might represent those sections in need of reconstruction. An average reconstruction cost would be assigned to all sections triggered for work in this condition range, and total planning budgets for years beyond the two-year specific plans could be estimated.

The modeling effort for this option would still follow the flowchart in figure 3-1 and the descriptions provided under option 1. The primary difference between this option and option 1 is that the creation of the overall index and supporting calculations would need to occur prior to the workflow shown in figure 3-1. The additional proposed steps that follow are outlined in figure 3-2 and described in the following sections.

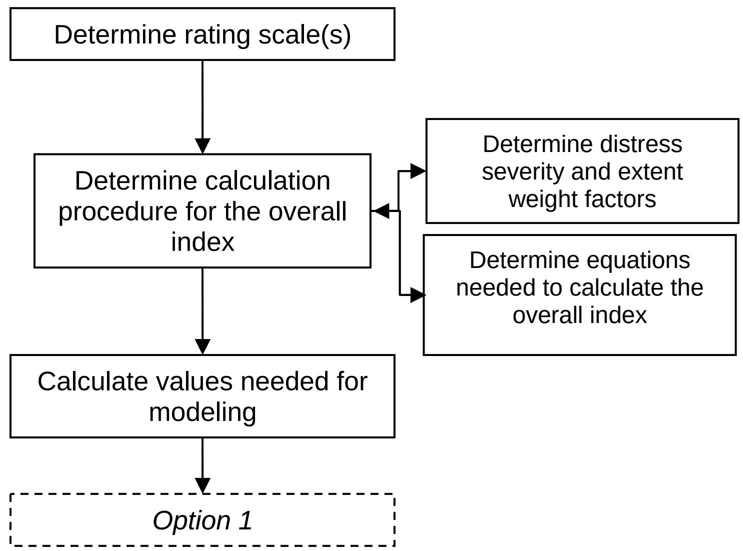

Figure 3.2. Option 2 model development workflow.

3.2.2.1 Determine Rating Scale for the Overall Index

Some agencies, such as Oklahoma, Oregon, and Washington State DOTs, use condition index scales that range from 0 to 100, where a rating of 100 indicates an excellent pavement condition. North Dakota uses a similar scale, with a maximum value of 99 for a pavement without distress. Alternatively, Minnesota DOT's surface rating (SR) index uses an ascending scale that ranges from 0.0 to 4.0, with a 0.0 representing an excellent pavement. While any desired rating scale can be set by PennDOT, given current state practices, the majority of agencies utilize a 100-point scale when setting up their indices.

3.2.2.2 Develop Calculation Procedure for the Overall Index

It is suggested that PennDOT's index be developed in a manner similar to the one used by Minnesota as documented in appendix D. The development of an overall index will include the determination of the weighting of all distress types and the development of the calculation steps. This endeavor will require that a study be conducted so that past condition data can be used to determine realistic overall indices that correlate to appropriate treatments and/or treatment categories.

3.2.2.3 Calculate Values Needed for Modeling

Once the process for calculating the overall index is developed, the index needs to be established for all historical survey records so that an overall index accompanies all past surveys. In addition to calculating the overall index for pavement sections, there is a need to determine the pavement age that corresponds to each index value that will be used in modeling. Therefore, prior to the initial development of the performance models, some database work is needed to link performance information with known M&R work. The comparison of survey and M&R dates will allow for the calculation of the pavement age. The age information should then be linked to the corresponding condition. This information will prove invaluable in the development of the performance models. These steps would then lead back to the use of figure 3-1 to conduct the remaining modeling.

3.2.2.4 Determine Modeling Approach

Following the flowchart in figure 3-1, it is recommended that PennDOT should focus on the development of family models instead of individual distress models. However, if more detail is desired, individual models could be examined if the chosen pavement management software includes the ability to easily create individual models.

If family models are used, instead of developing 342 models for the HMA pavements and 396 models for the jointed concrete pavements (as presented in option 1) only eighteen models (3 classes * 2 subgroups * 3 traffic ranges) are needed for HMA pavements and 18 are needed for jointed concrete pavements. Additionally, one overall index model for the entire CRCP family would be created. Therefore, a total of thirty-seven models that predict the overall index would be created under the family modeling option as described in table 3-2.

3.2.2.5 Create List of Model Forms

A list of potential model forms should be developed to examine potential regression equations. For this option, only family models for an overall index are being developed, so the following regression equations should be examined for each of the thirty-seven pavement families in table 3-1.

- Linear: $\text{Overall Index} = b_0 + b_1 * \text{Age}$ (3-2)
- 2nd order Polynomial: $\text{Overall Index} = b_0 + b_1 * \text{Age} + b_2 * \text{Age}^2$ (3-3)
- 3rd order Polynomial: $\text{Overall Index} = b_0 + b_1 * \text{Age} + b_2 * \text{Age}^2 + b_3 * \text{Age}^3$ (3-4)
- Power: $\text{Overall Index} = b_0 - b_1 * \text{Age}^{b2}$ (3-5)

where:

$b_0, b_1, \ldots b_n$ = predicted coefficients

Table 3-2. Family groupings for the development of the Overall Index models.

Model Number	Surface Type	Classification	Location	ADT Level
1	HMA	Interstate	Urban	<5,000
2	HMA	Interstate	Urban	5,000 to 15,000
3	HMA	Interstate	Urban	>15,000
4	HMA	Interstate	Rural	<5,000
5	HMA	Interstate	Rural	5,000 to 15,000
6	HMA	Interstate	Rural	>15,000
7	HMA	NHS non-Interstate	Urban	<5,000
8	HMA	NHS non-Interstate	Urban	5,000 to 15,000
9	HMA	NHS non-Interstate	Urban	>15,000
10	HMA	NHS non-Interstate	Rural	<5,000
11	HMA	NHS non-Interstate	Rural	5,000 to 15,000
12	HMA	NHS non-Interstate	Rural	>15,000
13	HMA	non-NHS	Urban	<5,000
14	HMA	non-NHS	Urban	5,000 to 15,000
15	HMA	non-NHS	Urban	>15,000
16	HMA	non-NHS	Rural	<5,000
17	HMA	non-NHS	Rural	5,000 to 15,000
18	HMA	non-NHS	Rural	>15,000
19	Jointed Concrete	Interstate	Urban	<5,000
20	Jointed Concrete	Interstate	Urban	5,000 to 15,000
21	Jointed Concrete	Interstate	Urban	>15,000
22	Jointed Concrete	Interstate	Rural	<5,000
23	Jointed Concrete	Interstate	Rural	5,000 to 15,000
24	Jointed Concrete	Interstate	Rural	>15,000
25	Jointed Concrete	NHS non-Interstate	Urban	<5,000
26	Jointed Concrete	NHS non-Interstate	Urban	5,000 to 15,000
27	Jointed Concrete	NHS non-Interstate	Urban	>15,000
28	Jointed Concrete	NHS non-Interstate	Rural	<5,000
29	Jointed Concrete	NHS non-Interstate	Rural	5,000 to 15,000
30	Jointed Concrete	NHS non-Interstate	Rural	>15,000
31	Jointed Concrete	non-NHS	Urban	<5,000
32	Jointed Concrete	non-NHS	Urban	5,000 to 15,000
33	Jointed Concrete	non-NHS	Urban	>15,000
34	Jointed Concrete	non-NHS	Rural	<5,000
35	Jointed Concrete	non-NHS	Rural	5,000 to 15,000
36	Jointed Concrete	non-NHS	Rural	>15,000
37	CRCP	All	All	All

3.2.2.6 Develop Models

Statistical analysis software such as SAS, S-Plus, or other comparable software should be utilized to examine the various proposed models for each pavement family. Both constrained (setting the intercept to 100 if a 100-point index is used) and unconstrained regressions should be examined. The selected software should have the ability to accept database files as a means of importing data for the analysis. Using the software, each proposed model form should be examined for all thirty-seven families.

3.2.2.7 Evaluate Results for Sufficient Data, Erroneous Data, and Logical Models

The data for each model should be evaluated for sufficiency and errors. The developed models should also be evaluated for stability. The same procedures detailed in the *Evaluate Results for Sufficient Data, Erroneous Data, and Logical Models* section of option 1 should be utilized in this step.

3.2.2.8 Create Listing of Final Models for Consideration

The logical models with sufficient non-erroneous data that were developed should be plotted and summarized in tabular form. The summarized data should document the final equations along with the resulting R-squared values.

3.2.2.9 Select Final Models by Analysis of R-squared and Visual Fit of Data

Models that provide a combination of the highest R-squared values along with a "good" visual fit of the performance curve to the example data should be selected. The developed curves should also display expected curvatures for the combination of the given data set and the modeled index.

3.2.3 Option 3: Compress Current Treatment Selection Matrix and Develop Performance Models for Individual Indices

A third performance modeling option is to develop individual pavement condition indices for individual distress types. The general modeling efforts for this option would follow the workflow presented in figure 3-1 and the descriptions provided in option 1. However, modeling would focus on the development of models for individual indices rather than for distresses. As a result of PennDOT's efforts to develop pavement distress treatment selection matrices, much of the necessary distress criteria in relation to treatment selection have been established, allowing for a relatively easy transition to the development of individual pavement surface distress indices.

Many agencies use distress information to calculate individual indices. They typically use the indices to predict conditions and to select appropriate treatments and also to calculate an overall index that can be used to report network conditions using a single metric. The first step in developing the individual indices is to review the types of distress being collected and to determine whether any can be combined into a logical index. For instance, some agencies combine fatigue cracking and rutting into a structural condition index.

The steps involved in developing individual indices are outlined in the literature (Baladi and Snyder 1988). They include the following:

- Determine the types of pavement distress indices (e.g., surface distress index, roughness index) to develop.
- Determine the rating scales to be used for the for distress indices (e.g., bounded from 0 to 100).
- Set threshold value for distress index scales. Threshold value represents the point at which a pavement is in need of maintenance, major/minor rehabilitation, or reconstruction.
- Determine weight factors for severity and extent of distress to calculate individual distress indices.
- Determine weight factor for each distress included to calculate the overall pavement distress index.

Each of these steps is detailed in the following sections, and the workflow for accomplishing the development of the individual indices is provided in figure 3-3. The workflow outlined would occur prior to that shown in figure 3-1.

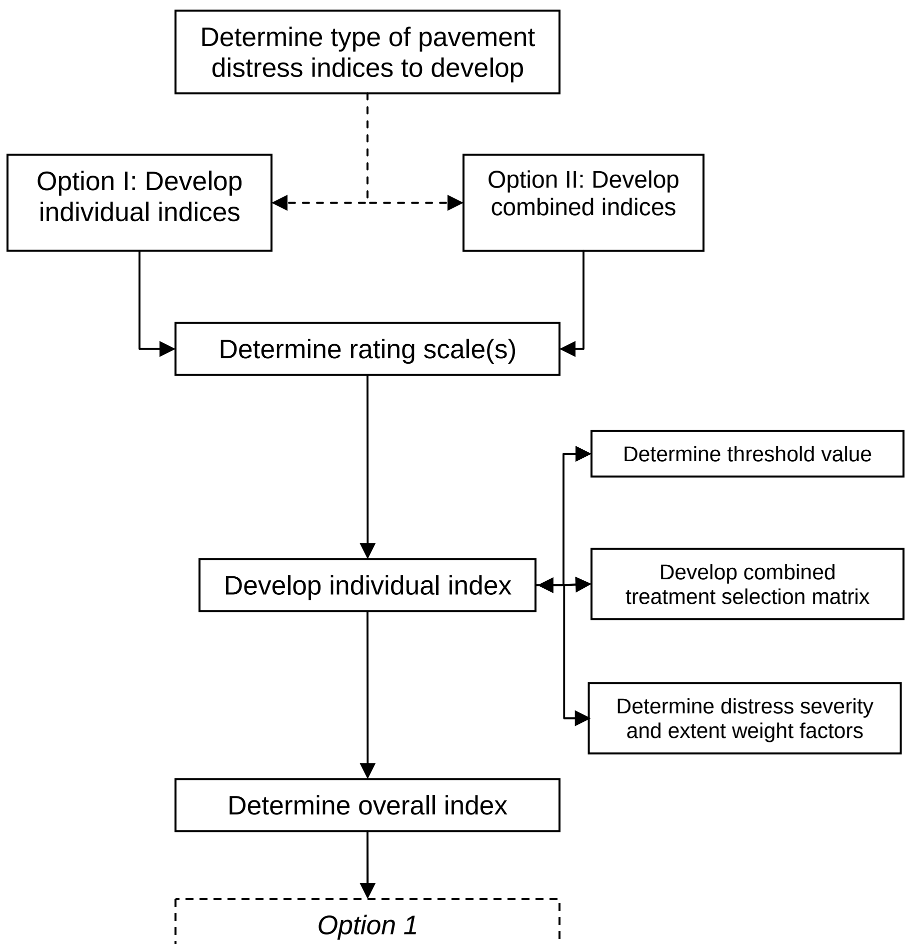

Figure 3-3. Option 3 model development workflow.

3.2.3.1 Determine Type of Pavement Distress Indices to Develop

Given the current distresses collected, the types and definitions of distress indices can be developed. For example, an individual index can be developed for each type of cracking PennDOT measures on HMA pavements: fatigue cracking, transverse cracking, and miscellaneous cracking, as well as edge deterioration—for a total of four indices representing just cracking distresses. Based upon the distresses currently collected by PennDOT, an individual distress index would need to be created for the seven HMA, eight jointed concrete, and six CRCP distresses.

There is also the option of developing an index that combines multiple distress types to consolidate the number of indices that need to be created and modeled. For example, Oklahoma DOT uses a total of four individual indices for bituminous pavements that represent a total of seven distress types. A combined cracking index can be developed with different weight factors for each type of cracking measured. Such an effort would result in the need for another study, so it is recommended to begin with individual distress indices and assess at a later time whether any distress types can be combined.

3.2.3.2 Determine Rating Scale

The next step in the individual index creation is to select the desired rating scale. As mentioned under option 2, the majority of state agencies including Oklahoma, Oregon, and Washington, use a scale from 0 to 100, where a rating of 100 indicates an excellent pavement condition. It is recommended that PennDOT follows the practices of the majority of states and utilizes a 100-point scale for the individual indices.

3.2.3.3 Develop Individual Index

With the rating scale set, the next step is to develop the individual indices. This multi-step effort requires PennDOT to determine threshold values for the indices that indicate when different M&R action should be taken; calculate weight factors for each distress type, severity, and extent combination; and combine the current three-table treatment selection matrices for each distress into one matrix (since all three distress severities will be incorporated into the index).

Individual indices will be linked to general treatment categories, so it is important to examine the PennDOT M&R treatments. According to its document, *Treatment Matrices, Material Quantities and Dollar Needs Calculations* (2003), PennDOT categorizes treatments into five "treatment groups." The five treatment groups and associated treatments are listed in table 3-3, while figure 3-4 shows an example treatment selection matrix for transverse cracking on bituminous pavements. The treatment selection matrix defines how specific treatments are triggered. Since transverse cracking is only one distress type, it is possible to have other distress types present which would result in additional treatments being triggered. If more than one treatment is triggered, the highest resulting treatment group is assigned. Instructions for comparing all treatments triggered with specified treatment combinations are summarized in table 3-4.

Table 3-3. PennDOT pavement distress treatments and treatment groups.

PennDOT Treatment Groups	PennDOT Treatments
1. Routine Maintenance	0 Routine Maintenance 1 Crack Seal 2 Skin Patch 3 Manual Patch 4 Manual Patch, Crack Seal 5 Manual Patch, Skin Patch 6 Mechanized Patch 7 Base Repair, Manual Patch 8 Base Repair, Mechanized Patch
2. Seal Coat	9 Seal Coat 10 Level, Seal Coat 10 Recycle, Level, Seal Coat, Base Repair
3. Minor Rehabilitation	12 Microsurface/Thin Bituminous Overlay 13 Resurface 14 Level, Resurface
4. Major Rehabilitation	15 Level, Resurface, Base Repair 16 Mill, Level, Resurface 17 Mill, Level, Resurface, Base Repair
5. Reconstruction	18 Reconstruction

Table 3-4. PennDOT pavement distress treatment combinations matrix.

<table>
<tr><th colspan="2" rowspan="2"></th><th colspan="14">TREATMENT</th></tr>
<tr><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>10</th><th>11</th><th>12</th><th>13</th><th>14</th><th>15</th><th>16</th><th>17</th></tr>
<tr><th rowspan="14">TREATMENT</th><th>4</th><td></td><td></td><td></td><td></td><td></td><td rowspan="2">9 & 3</td><td rowspan="2">10 & 3</td><td rowspan="2">11 & 3</td><td rowspan="2">12 & 3</td><td></td><td></td><td></td><td></td><td></td></tr>
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</table>

All others may be combined for total segment need.

DISTRESS: TRANSVERSE CRACKING

Low Severity

# of Cracks/ ½ mile	Interstate						NHS - Non Interstate						NON- NHS					
	Urban			Rural			Urban			Rural			Urban			Rural		
Extent	<5K	5 - 15K	>15K	<5K	5 - 15K	>15K	<5K	5 - 15K	>15K	<3K	3 - 10K	>10K	<3K	3 - 10K	>10K	<1K	1 - 3K	>3K
0 - 50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
51 - 100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
101 - 150	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
151 - 250	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
> 250	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Medium Severity

# of Cracks/ ½ mile	Interstate						NHS - Non Interstate						NON- NHS					
	Urban			Rural			Urban			Rural			Urban			Rural		
Extent	<5K	5 - 15K	>15K	<5K	5 - 15K	>15K	<5K	5 - 15K	>15K	<3K	3 - 10K	>10K	<3K	3 - 10K	>10K	<1K	1 - 3K	>3K
0 - 50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
51 - 100	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
101 - 150	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
151 - 250	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
> 250	1	14	16	1	16	16	1	14	16	1	14	16	9	13	13	9	13	13

High Severity

# of Cracks/ ½ mile	Interstate						NHS - Non Interstate						NON- NHS					
	Urban			Rural			Urban			Rural			Urban			Rural		
Extent	<5K	5 - 15K	>15K	<5K	5 - 15K	>15K	<5K	5 - 15K	>15K	<3K	3 - 10K	>10K	<3K	3 - 10K	>10K	<1K	1 - 3K	>3K
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
>0 - 50	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
51 - 100	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
101 - 150	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
151 - 250	16	16	16	16	16	16	14	14	14	14	14	14	9	13	13	9	13	13
> 250	16	16	16	16	16	16	16	16	16	16	16	16	9	13	13	10	13	13

0. Routine Maintenance 1. Crack Seal 9. Seal Coat 10. Level, Seal Coat 13. Resurface 14. Level, Resurface
16. Mill, Level, Resurface

NOTE: When the segment length does not equal ½ mile, the number of cracks per ½ mile equals: (# of cracks) / (segment length) x (2640) (Segment length in feet.)

Figure 3-4. PennDOT treatment selection matrix for transverse cracking on bituminous pavements.

3.2.3.3.1 Determine Threshold Value

The next step in creating the individual indices is to take the proposed 100-point condition scale and correlate treatments and treatment groups to ranges of conditions. For this example, four condition ranges are provided in table 3-5.

Table 3-5. Example of ascending pavement condition scale correlated to PennDOT treatments.

Pavement Condition Scale		Description	PennDOT Treatment Groups	PennDOT Treatments
100		Very Good	1. Routine Maintenance	0, 1, 2, 3, 4, 5, 6, 7, 8
85		Good	2. Seal Coat	9, 10, 11
75		Fair	3. Minor Rehabilitation	12, 13, 14
65		Poor	4. Major Rehabilitation	15, 16, 17
50		Very Poor	5. Reconstruction	18

Based upon the correlations, threshold values must be set to take the first step in determining the individual index formulas. Given the values set in table 3-4, the threshold value at with reconstruction is required is set at 50. As an example, the equation needed to calculate the transverse cracking index (TCI) formula is provided in equation 3-6. :

$$TCI = 100 - \left[100 - Th \left(\frac{n_L}{L} + \frac{n_M}{M} + \frac{n_H}{H} \right) \right] \quad (3\text{-}6)$$

where:

- Th = threshold value
- n_L = actual extent of low severity cracks per half mile
- n_M = actual extent of medium severity cracks per half mile
- n_H = actual extent of high severity cracks per half mile
- L = maximum acceptable distress of low severity cracks per half mile
- M = maximum acceptable distress of medium severity cracks per half mile
- H = maximum acceptable distress of high severity cracks per half mile

With the threshold set at 65 to match the point where rehabilitation is required, the maximum allowable distress for each severity is set. Figure 3-4 indicates that for medium severity cracking, minor/major rehabilitation is specified once the number of cracks per half mile is greater than 250 and average daily traffic (ADT) is greater than 5,000. However, for high severity transverse cracking, the shift from routine maintenance (i.e., crack sealing) to rehabilitation occurs once the number of cracks per half mile exceeds 150 for all traffic levels.

Substituting the extent values for medium and high severity transverse cracking as determined by reviewing PennDOT's treatment selection matrix (figure 3-4), the resulting equation is the following:

$$TCI = 100 - \left[35\left(\frac{n_L}{L} + \frac{n_M}{250} + \frac{n_H}{150}\right)\right] \quad (3\text{-}7)$$

3.2.3.3.2 Determine Distress Severity and Extent Weight Factors

Because the treatment selection matrix does not indicate anything other than that routine maintenance should be performed for low severity transverse cracks, it is not as straightforward to determine a suitable maximum extent for such cracks. However, a value can be determined based on the point where transverse cracking requires crack sealing; for 50 medium severity cracks per half mile, the TCI value is 91, and for the same number of high severity cracks, the TCI is 85.

Then set the number of low severity cracks equal to the maximum allowable extent of medium severity cracks. This provides a worst case scenario where all low severity cracks will deteriorate to medium severity by the time of the next survey:

$$TCI = 100 - \left[35\left(\frac{n_L}{L} + \frac{n_M}{250} + \frac{n_H}{150}\right)\right] \quad (3\text{-}8)$$

$$85 = 100 - \left[35\left(\frac{250}{L} + \frac{0}{250} + \frac{0}{150}\right)\right] \quad (3\text{-}9)$$

$$85 = 100 - 35\left(\frac{250}{L}\right) \boxed{\therefore L = 583} \quad (3\text{-}10)$$

If the TCI demarcating crack sealing is set at 91, *L* will equal 972.

Thus, for this example, the transverse cracking index calculation can be expressed as follows, figuring conservatively:

$$TCI = 100 - \left[35\left(\frac{n_L}{583} + \frac{n_M}{250} + \frac{n_H}{150}\right)\right]\text{; or} \quad (3\text{-}11)$$

$$TCI = 100 - \left(0.06n_L + 0.14n_M + 0.23n_H\right) \quad (3\text{-}12)$$

In this example, the weight factors for each severity and extent of distress equal 0.06, 0.14, and 0.23 for low, medium, and high severity transverse cracks, respectively. (A less conservative approach—setting *L* equal to 972—would result in a weight factor of 0.036 for low severity cracking.) If similar equations are developed for the other crack types currently measured by PennDOT, the weight factor for each could then be determined based on engineering experience and included to calculate an overall, combined pavement cracking distress index.

3.2.3.3.3 Develop Combined Treatment Selection Matrix

Once the distress index scale for transverse cracking has been developed, it can be incorporated into PennDOT's treatment selection matrix. This will allow the three separate severity tables to be combined into just one, as shown in figure 3-5. Further modifications can retain the treatment selection distinctions made between traffic levels.

3.2.3.4 Determine Overall Index

After developing distress indices (either individual per distress or combined per distress type), an overall index can be calculated using all or some of the indices by determining weight factors for each of the indices included in the calculation. For example, as discussed previously, Oklahoma DOT uses a 0 to 100 scale for its fatigue cracking index, which it calls its Structural Index. OkDOT uses the same scale for its Ride Index Rut Index, and Functional Index. The overall pavement quality index (PQI) can be calculated after providing each index a weight factor; an example equation for HMA pavements is shown below:

$$PQI = 0.40*\text{Ride Index} + 0.30*\text{Rut Index} + 0.15*\text{Functional Index} + 0.15*\text{Structural Index} \quad (3\text{-}15)$$

The final weights used to establish an overall index should be developed by PennDOT once the types of indices have been determined.

3.2.4 Assessing Model Reliability

After models are developed using either option 1, 2 or 3, the models should be assessed for reasonableness. Using the developed models, predicted distresses and/or indexes will be calculated and compared to the known values. This assessment will be conducted for all family developed models but is not needed if individual pavement section modeling was conducted. Based upon the assessment of the accuracy of the models, final adjustments will be made to the models and the resulting models will be ready for use in a pavement management analysis. The general steps in assessing the ability of the developed models to predict performance are displayed in figure 3-6.

<u>DISTRESS</u>: **TRANSVERSE CRACKING**

TCI	Interstate			NHS – Non-Interstate						Non-NHS					
				Urban			Rural			Urban			Rural		
	<5K	5 – 15K	>15K	<5K	5 – 15K	>15K	<3K	3 – 10K	>10K	<3K	3 – 10K	>10K	<1K	1 – 3K	>3K
100 – 90	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
90 – 86	1	1	1	1	1	1	1	1	1	0	1	1	0	0	1
85 – 76	1	1	1	1	1	1	1	1	1	1	9	9	1	1	9
75 – 66	1	14[1]	16	1	14	16	1	14	16	9	13	13	9	13	13
65 – 51	16	16	16	14	16	16	14	14	16	9	13	13	10	13	13
50 – 0	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18

[1] Treatment 16 (Mill, Level, Resurface) is also suitable for use on Rural Interstate.

0. Routine Maintenance 1. Crack Seal 9. Seal Coat 10. Level, Seal Coat 13. Resurface 14. Level, Resurface 16. Mill, Level, Resurface 18. Reconstruction

NOTE: When the segment length does not equal ½ mile, the number of cracks per ½ mile equals: $\frac{\text{\# of cracks}}{\text{segment length, ft}} \times 2640$

Figure 3-5. Example of PennDOT treatment selection matrix modified to include distress index scale.

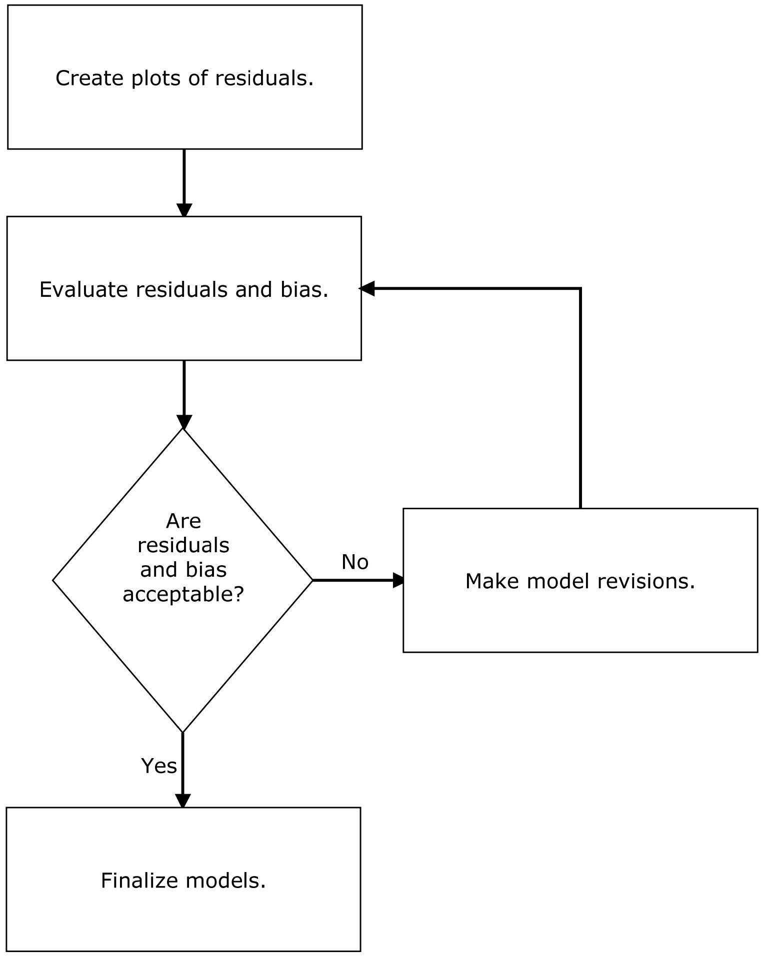

Figure 3-6. Assessment of models workflow.

3.2.4.1 Create Plots of Residuals

Using the previously extracted data from the data sets, plots of model residuals (relative difference between the predicted and actual values) should be created to evaluate the ability of each model to predict the performance of the pavement section. The creation of the residual plots is a manual process of determining residuals and creating plots of the residuals over the ages of the treatments using either a spreadsheet or statistical analysis software.

3.2.4.2 Evaluate Residuals and Bias

When the residual plots of the previously extracted data are created, they provide a visual representation of how well the models predict expected performance using actual data. An ideal residual plot shows an even balance of data points above and below the zero residual line along all treatment ages.

A visual examination of the residuals will reveal a significant amount of information regarding the fit of the model to the given data set. An evaluation of the residual plot can lead to further performance curve analysis. For example, if a chosen model is over-predicting or under-predicting a given index, some consideration should be given to a potential shift in the endpoint of these latter models to help reduce the amount of over- and under-prediction. All in all, the examination of the residual plots provides the details necessary to adjust the models in a manner which helps reduce the scatter of the residuals due to the occurrence of outliers. In some cases, it may be impossible to overcome the extreme scatter in the data by further adjusting the models. In these cases, the model has to be accepted with the given bias.

3.2.4.3 Make Revisions

Depending upon the results of the examination of the residual plots, revisions should be made to the model by shifting either data analysis parameters or data analysis subsets. In making these revisions to the models, some consideration must also be given to combining models or to using the same models for several pavement families. The resulting models and those data sets with insufficient data should be further evaluated to determine whether it makes sense to use a different model to describe the behavior of the family, or if its data should be combined with any of the other models to make larger data sets. Several general steps can be followed when deciding to combine the use of models:

1. For each surface type, the form of each performance model can be compared to the other performance models for all indices.
2. For family models, the plotted performance models, which provide a visual representation of the model form, can be examined.
3. Using engineering judgment, those models with very similar model curvature and endpoints (within 1 to 3 years) can be utilized to describe the other performance family that was created based upon a smaller data set.

Combining models reduces the number of models used in the pavement management software.

3.2.4.4 Finalize Models

Using all the data summarized during the model development process, final models must be selected for all pavement subsets. Not only do the final models need to be assigned depending upon the given data subsets used to group the pavement performance data together, but default models must be determined for use in assigning deterioration rates to pavement sections that might not have been accounted for in the family models.

3.3 Recommendations

Using the four goals established by PennDOT (as described earlier in the chapter) as a basis, the various modeling options have been evaluated to determine which provides the best overall approach to pursue. The results of that analysis are presented in table 3-6 and indicate that both modeling approaches 2 and 3 are reasonable approaches for PennDOT to consider.

Table 3-6. Ability of proposed modeling approaches to meet desired goals.

Modeling Option	Goal 1. Predict future funding needs	Goal 2. Practical and implementable	Goal 3. Incorporate into software	Goal 4. Utilize existing data collection procedures
1	Yes	No	Limited	Yes
2	Yes	Yes	Yes	Yes
3	Yes	Yes	Yes	Yes

Of the two modeling options, each has its advantages and disadvantages when used as a methodology for performance model development. The level of effort required with modeling option 3 is significantly greater than with option 2, as it will require the development of up to 21 indices for the individual distress types of HMA, jointed concrete and CRCP. Option 3 will also require the development of a second set of treatment selection matrices. While these activities are realistic, they present a significant effort that can be avoided if an overall index is used to predict performance, as outlined in option 2.

Based upon these details, it is recommended that PennDOT initially proceed with their modeling efforts using the steps outlined in option 2. Option 2 provides a means of using the current treatment selection matrix to determine treatment options on a 2-year horizon while utilizing predicted conditions from an overall index to determine future funding needs. The option both maintains the use of the significant level of detail that has been worked into the current treatment matrices and provides an implementable performance modeling option. A summary of the recommendations relative to option 2 are provided below:

- The pavement performance models will predict overall pavement condition.
- The overall index will be calculated using distress and ride.
- A 100-point rating scale will be used for the overall index.
- Pavement family models will be developed for the prediction of the overall index. These will be in accordance with the categories in the treatment selection matrix.
- The model form will be deterministic.
- The pavement performance models will use surface age as the independent variable used to predict pavement age.
- The models will be developed in-house with the use of consultants or University personnel if help is needed.
- The model development will begin before the selection of a pavement management system, as the implementation of pavement management software is at least a year away.

Given the modeling recommendations, a final summary of the overall steps needed to develop the performance models according to the proposed option are summarized below:

- Develop the overall condition index.
- Calculate overall index and surface age for all historical condition survey data.

- Develop pavement performance family models using proposed option.
- Assess models for reliability.
- Implement final models.
- Update models (initially every 2 years with new data collection).

3.4 Summary

This report provides a summary of the current state-of-the-practice regarding performance modeling around the country, as well as additional information regarding data collection procedures that is directly linked to the pavement management process. PennDOT's practices were compared to those used by other agencies around the country and performance modeling options were developed based on the overall goals of the performance model development. Of these options, modeling option 2 was recommended. This option allows PennDOT to maintain the current treatment selection matrix for the selection of treatments for a 2-year programming cycle while supporting the development of an overall index that is used to model future funding needs.

As PennDOT moves forward with the selected modeling approach, the details outlined in this report can guide the process. As evidenced in this report, the process for developing performance models is somewhat dictated by the data available. In the past, initial attempts by PennDOT to model individual distress types did not show significant promise. However, the use of other modeling options, or the use of age as a predictor, may prove to have better predictive capabilities than past efforts. Therefore, although option 2 is the recommended modeling approach, if data issues arise that complicate the development of models in the prescribed manner, it may be more advantageous to further examine a different modeling option, such as option 3. Modeling is not a clear-cut step-by-step process and the details of the individual options may need some adaptation to allow the most robust models to be developed.

3.5 References

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