Although the use of two or more individual indices is useful for estimating treatment needs, this practice adds a level of complexity to the pavement management system that must be considered. This additional complexity arises because treatment rules and performance models must be developed for each index. Even an agency with just three surface types and three individual indices, must develop at least nine different performance models (three times three) and treatment rules that cover each index. In addition, impact rules that define the conditions after a treatment is applied have to be defined for each of the indices. Treatment and impact rules are discussed in more detail in Section 6.4.

4.12 OTHER FACTORS INFLUENCING PAVEMENT CONDITION SURVEYS

Many agencies have well established procedures in place for evaluating pavement conditions that date back 10 to 20 years. Some agencies have modified their original pavement condition survey procedures to reflect changes in technology, most notably the change from manual to automated surveys. However, it is probable that additional changes may be required to accommodate some of the recent changes taking place in pavement management. A brief summary of some of the more significant changes that are impacting pavement management is provided in this section.

4.12.1 The Use of Preventive Maintenance Treatments

Many agencies have adopted pavement preservation programs that include the use of preventive maintenance treatments on roads in relatively good condition. These programs are cost effective because of the use of low-cost interventions that keep the road in good condition longer, thus deferring the need for more costly rehabilitation treatments. As discussed further in Section 6.4.4, preventive maintenance treatments are primarily focused on addressing functional forms of deterioration, such as deficiencies caused by poor ride, poor pavement surface characteristics, hardening of the asphalt, or minor cracking. A key to the successful use of preventive maintenance treatments is early intervention, before excessive deterioration is present.

However, most pavement management condition survey procedures were developed to identify and prioritize rehabilitation treatments. Therefore, they have not typically been designed to include the types of triggers normally needed to identify appropriate preventive maintenance treatments, such as those listed below (Zimmerman and Peshkin 2004):

- Sealed versus unsealed cracks or fine cracks
- Raveling or weathering
- Flushing
- Oxidation

As a result, some agencies are considering changes to their data collection procedures to incorporate these forms of pavement deterioration. Even without making changes to the data collection procedures, there are ways to incorporate preventive maintenance treatments into a pavement management system.

For instance, the results of a pavement management analysis could be used to identify candidate sections for preventive maintenance based on existing measures (e.g., pavement sections in good condition with little structural deterioration), without trying to determine the most appropriate type of treatment to apply. After candidate sections are identified using the pavement management system, treatment selection could be determined by Maintenance and Operations personnel who are in the field and more familiar with the particular needs of the candidate sections.

Pavement management systems can also be used to document the performance of preventive maintenance treatments over time. This information provides valuable information to verify the cost-effectiveness of preventive maintenance treatments, but also provides feedback to further improve the models used to trigger candidate sections for pavement preservation activities.

4.12.2 Increased Use of Performance Measures

Another change that is occurring nationally is the increased use of strategic performance measures as a quantifiable indicator of service provided to the traveling public. The use of performance measures helps improve communication among stakeholders by providing a basis for communicating impacts of funding decisions and providing a degree of transparency in the agency's decision making. By linking performance targets to funding allocations, agencies are better prepared to achieve their stated objectives.

Changes in the types of performance measures used at the upper levels of transportation agencies are likely to occur over the next few years. These changes could impact the types of performance metrics collected by field personnel since it is important that tactical performance measures are aligned with strategic performance measures. For instance, if safety is considered to be an important performance measure for strategic purposes, it will be important that pavement management is able to report the impact of different funding scenarios and treatment programs on safety-related performance measures. Similarly, with the increased focus on sustainability, pavement management will have to identify and begin monitoring measurements of sustainability for the treatments included in the analysis.

4.12.3 New HPMS Requirements

Beginning in 2010, new requirements went into effect for the HPMS that changed the types of data reported by state DOTs for the NHS (FHWA 2008b). HPMS data are used at the national level for funding apportionment, performance measures, highway statistics, condition reporting, and for FHWA's transportation planning and policy studies. Since states are responsible for reporting HPMS information to the FHWA, the HPMS requirements impact the type and frequency of data collected.

With regard to pavement condition data, the new HPMS requirements specify annual reporting of IRI data and the addition of cracking, rutting, and faulting. Other data requirements include the date of last overlay, date of last reconstruction, and thickness of the latest overlay. Therefore, agencies that have not incorporated this information into their pavement management system will have to modify their data collection approaches to meet these requirements.

4.12.4 MEPDG Model Calibration Requirements

The MEPDG includes models that have been calibrated and validated using data from the FHWA's LTPP program (AASHTO 2008). Although the LTPP database represents data from locations representing a variety of geography, climatic conditions, construction materials, construction practices, traffic compositions and volumes, and other pavement design variables, agencies implementing the MEPDG are advised to calibrate the models using local field data to achieve more reliable performance predictions for their conditions as shown in the *Guide for the Local Calibration of the Mechanistic-Empirical Pavement Design Guide* (AASHTO 2010). Pavement management is a logical resource to provide the data, but studies have shown that the required data are not currently found in most pavement management databases (APTech 2010). However, pavement management databases could be enhanced to address this need.

The MEPDG considers both structural and functional pavement performance characteristics in its estimates of predicted pavement damage. The IRI is used to forecast pavement smoothness using the initial as-constructed IRI and changes in smoothness due to the propagation of distress, site factors (such as subgrade), and maintenance activities. For flexible pavements, smoothness is based on the amount of load-related fatigue cracking (including both bottom-up and top-down fatigue cracking), thermal cracking, and permanent deformation (rutting) (AASHTO 2008). The distress considered in rigid pavements includes faulting and transverse cracking, and punchouts on continuously reinforced concrete pavement (CRCP) (AASHTO 2008). These models have been incorporated into the new AASHTOWare DARWin-ME pavement design software, which builds upon the MEPDG. To calibrate the models in DARWin-ME using local data, condition data on each of these distresses must be available. Therefore, in the absence of the information as part of a network-level pavement condition survey, special condition surveys for the purposes of calibration efforts will be required.

4.13 CHAPTER SUMMARY

There are many ways to assess the structural and functional condition of a pavement. At the state DOT level, ride is the most frequently used pavement condition metric, although pavement distress information is also commonly used to provide more information about the type of deterioration that is occurring. The results of pavement condition surveys are used to determine one or more pavement condition indices, which provide a means of identifying and prioritizing treatment needs. While many agencies have been using their data collection procedures for years, there are a number of industry changes that may influence the type of data collected and the frequency with which it is collected. For instance, new HPMS reporting requirements include cracking, rutting, and faulting for the NHS. The new mechanistic-empirical design procedures that have recently been developed require calibration of the performance models using pavement management data. Additionally, new technology is being developed that may influence an agency's ability to assess pavement structural condition at a network level. These, and other types of changes, are forcing agencies to periodically revisit their data collection activities to determine whether adjustments are needed to continue to meet changing agency demands.

CHAPTER FIVE

Pavement Performance Modeling

5.1 INTRODUCTION

Pavement prediction models serve several important roles in the pavement management process. For instance, they play a part in 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.
- Establishing performance criteria for performance specifications and warranty contracts.

In addition, performance models can be used to provide feedback on pavement designs or on the effectiveness of different maintenance strategies. Given the contribution of the models to these pavement management functions, their accuracy is important to prevent agencies from incorrectly estimating the year in which rehabilitation is needed, the level of repair needed, or the future condition of the network. Therefore, the more closely the performance models reflect agency-specific deterioration patterns, the less likely it is that there will be misrepresentations of future condition levels or treatment needs. This correlation places a high degree of importance on the quality of the pavement condition data used to develop the models.

In the field of pavement management, various terms are used to describe pavement performance models, including *deterioration models* or *prediction curves*. In essence, each of these terms describes the equation in which the changes in pavement condition over time are represented.

5.2 DATA REQUIREMENTS FOR PAVEMENT PERFORMANCE MODELING

The literature details the data requirements that must be satisfied to develop reliable performance models (Darter 1980, Lytton 1987). Based on the previous work, the following factors should be considered in selecting the modeling approach and determining the availability of sufficient data for the development process (Darter 1980):

- **An adequate source of data**—Different types of models require different types of data, so it is important that the availability of adequate data is considered before beginning the modeling process. Each variable used in modeling must be available for each of the pavement sections included in the pavement management system. Further, the data must be maintained over time so the models continue to predict reasonable values.
- **Consideration of the most significant variables influencing pavement performance**—There are many variables that can have an impact on how pavements perform over time, including climate, traffic, layer thicknesses, and material properties. While an agency may want to incorporate all of these variables into its pavement performance models, it is often impractical to do so because most pavement management databases do not have adequate records to support the use of multiple independent variables. The family modeling approach discussed in Section 5.4.1 provides a means of indirectly accounting for important variables in the modeling process when the data are not available (or reliable enough) to be used directly in model development. If an agency does elect to use multiple independent variables in the development of its models, statistics programs can help to determine the degree of influence of each variable on pavement performance.
- **A functional form that fits the data**—Pavement performance models describe, using equations, the expected change in pavement condition performance over time. The change in condition can take a number of different forms (or shapes), depending on the type of equation used. The modeling form selected should fit the data and should reflect the typical deterioration patterns for the agency.
- **Satisfaction of criteria for precision and accuracy**—As discussed, pavement performance models are used extensively in a pavement management system. Therefore, it is important that the models provide reasonable estimates of changes in condition with time. As discussed in Section 5.5, there are several statistical methods available to evaluate the reliability of a performance model, including the coefficient of determination (R^2).

Lytton (1987) goes on to add that the principles and limitations associated with each model should be well understood to help ensure that the models are not being used outside of their intended purpose.

5.3 PERFORMANCE MODELING APPROACHES

When developing pavement performance models, the first step is to consider what the models are going to predict. Typically, pavement management systems predict changes in one of the following indices representing pavement condition over time:

- **Distress severity and extent**—Including changes in the amount and severity of a particular distress, such as fatigue cracking, rutting, or faulting.
- **Individual pavement condition indices**—Including changes in a structural crack index, roughness index, etc.
- **Composite indices**—Including changes in a composite index such as the PCI discussed in Section 4.11.1

There are advantages and disadvantages to each method of predicting pavement condition, as shown in Table 5-1. For instance, it can be difficult to accurately predict changes in a composite index because of the subjectivity in the index and the number of combinations of distress that can result in the same index. For example, a pavement section that has a composite index of 80 (on a scale of 0 to 100) might exhibit early fatigue cracking (a form of structural deterioration) or the rating might have resulted from block cracking (an environmental form of deterioration). Although both pavement sections have the same condition index and the same age, the section with the fatigue cracking would be expected to deteriorate much faster than the section with block cracking. However, since a single composite index model does not necessarily differentiate between the distress combinations that resulted in the rating, it is unlikely that the performance model will be able to predict different rates of deterioration for the two sections. This concern might be addressed by predicting the rate of deterioration for individual pavement condition indices, but the number of performance models that must be developed increases based on the number of indices considered.

Perhaps the most complex approach is predicting changes in distress severity and extent, such as predicting the progression of fatigue cracking over time as it changes from low severity to high severity. Models that predict distress severity and extent involve determining the point at which the distress is first seen as well as the propagation of the distress with time once it appears. Because of the complexity in modeling individual distress, an agency may elect to combine distress severities for a particular distress type to avoid modeling the progression of distress from one severity to another. For instance, all longitudinal crack severities would be combined and the total amount of cracking that will occur over time is predicted. It would be much more difficult to try to predict the progression of a crack from low severity to high severity.

Table 5-1. Advantages and Disadvantages of Predicting Different Types of Pavement Condition Variables

Predicted Variable	Advantages	Disadvantages
Distress severity and extent	• Provides specific estimates of future distress quantities. • Predictions are provided in a format that is closely related to the manner in which data are collected.	• Requires both the initiation of distress and the amount of distress over time to be modeled. • May be difficult to incorporate into the pavement management software.
Individual indices	• In general, indices are easier to model than distress severity and extent. • The predicted conditions relate to factors that trigger treatments.	• Models must be developed for each index. • Update requirements can be onerous because of the number of models. • If a composite index is used in conjunction with individual indices, there may be discrepancies between the predicted conditions using the individual index models and those used to predict the composite index (Note: this issue is eliminated if the individual indices are modeled and the composite index is calculated from the predicted indices, as discussed in Section 4.11.1).
Composite index	• This is likely the simplest approach, which results in the fewest number of models. • Because of the limited number of models, updating the models is relatively simple.	• Different rates of deterioration associated with different distress types are masked. • May not satisfy the needs of some stakeholders who want more detailed models.

Once it is determined what the models should predict, the type of model must be selected. In pavement management, four types of models are commonly used to predict future pavement conditions: deterministic, probabilistic, Bayesian, and subjective (or expert-based) models. Each of the four approaches is summarized here and described further in the subsequent sections:

- **Deterministic models**—These models 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). The models are typically developed based on the results of a statistical analysis.
- **Probabilistic models**—These models predict a range of values for the dependent variable, such as the likelihood that a pavement will change from each of the various condition states to another in a single reporting cycle.

- **Bayesian models**—These models combine both objective and subjective data. Each of the variables used in the model is described in terms of a probability distribution.
- **Subjective (or expert-based) models**—These models are similar to deterministic models, except that the relationships between an independent and dependent variable are based on expert opinion rather than historical data.

Depending on the variables used, the models can be further classified as mechanistic, mechanistic-empirical, or empirical. Mechanistic models are based on fundamental principles of pavement behavior, while empirical models are based on the results of experiments or experience. Mechanistic-empirical models include portions of both approaches and relate the predicted condition to measured deterioration, such as distress or roughness, through regression equations (FHWA 1998). Therefore, mechanistic-empirical models are commonly used in pavement management.

5.3.1 Deterministic Models

Deterministic models are often used by agencies that have historical pavement condition information or sufficient survey results that they can identify statistically-significant pavement deterioration trends. These models are developed from a regression analysis in which a statistical relationship between two or more variables is established. The statistical relationships in these models are not exact and include some amount of variability. The magnitude of the variability is based on factors such as the quality of the data, the appropriateness of the independent variables to predict the dependent variables, and the range of data in the data set.

Because the correlation between the independent variables and the dependent variables is not exact, an approach for determining the best statistical fit of the data must be used. A common approach in pavement management applications is to use the least squares regression technique, which minimizes the sum of the squared differences between the line generated by the regression equation and the actual data points.

Deterministic models may take many forms (e.g., shapes) depending on the type of equation used (e.g., linear, quadratic, or sigmoid). It is common in pavement management to use a single independent variable to predict the dependent variable (e.g., pavement condition). Pavement age (e.g., years since last major rehabilitation) or traffic volumes are commonly used independent variables.

The use of only one independent variable simplifies the development of the models and overcomes the issues that arise when a database does not contain complete or accurate records for all of the variables included in the equation. For instance, if traffic volume is a variable in the equation, but traffic counts have not been conducted for 15 years, the model will have to use the data that are available; however, the accuracy of the predictions would be suspect. Similarly, if pavement thickness is included as one of the variables, but the database does not contain complete records with this information, the validity of the predictions could also be questioned. This concept is discussed in Section 5.4.

5.3.2 Probabilistic Models

Probabilistic models differ from deterministic models in that instead of predicting a single value for pavement condition, the likelihood of a pavement being in one of several condition states (or categories) is predicted. Probabilistic models are not used as commonly as deterministic models in pavement management, likely because most pavement management software programs are not equipped to input these types of models without converting them to one of the deterministic model forms. However, they represent a direct way of accounting for pavement variability, which may be attractive to some agencies. For pavement management purposes, the literature discusses the use of Markov and Semi-Markov transition probabilities (FHWA 1998, Lytton 1987, Shahin 2005, Haas et al. 1994). The Markov probabilistic approach is based on the current pavement condition and assumes that the probability of changing from one condition state to another is independent of time. Since the models depend only on the current condition state, there is no opportunity to include other variables (such as traffic loading or environmental factors) that often contribute to performance and that are often changing over time, unless families are created and separate transition matrices are developed for each family. The semi-Markov approach is designed to overcome the independence of time assumption used when changing from one pavement condition state to another pavement condition state. Semi-Markov models allow transition probability matrixes to be created and used together to provide piecewise increments of time. According to Shahin (2005), probabilistic modeling is particularly useful for predicting individual distress information.

5.3.3 Bayesian Models

Bayesian statistical decision theory is emerging as a modeling technique for pavement management. While this methodology typically uses both objective and subjective data to predict performance, models can be developed using only subjective data. Regression analysis is used to develop the models, but each of the variables is assumed to be random and to have an associated probability distribution.

Because subjective data can be used to supplement objective data, Bayesian regression can be useful for agencies that have recently begun the implementation of pavement management, that have changed their pavement condition rating procedures (e.g., no historical data are available), or that have introduced new designs or materials into their network. It also provides a way to override the influence of poor quality data or to supplement expert models with field data as they become available. An example of the development of pavement performance models using Bayesian regression is provided in *MDOT Pavement Management System: Prediction Models and Feedback System* (George 2000).

5.3.4 Subjective or Expert-Based Models

Another, less formal way of incorporating subjective opinions into pavement performance models is to develop subjective, or expert-based, models. As with Bayesian models, this approach is useful when historical condition data are not available, when new practices or materials are being used, or when the agency has little confidence in its condition data.

The process used to develop subjective performance models may be informal or formal. In an informal process, an individual (or a group of individuals) develops an equation that describes the rate of deterioration for a particular set of conditions. For example, assuming an average rate of deterioration of 3 points per year (on a 100-point scale) is a type of subjective model.

In a formal process, a panel of experts typically identify ages at which certain events take place. These age/condition combinations are either plotted manually on a graph or they are input into a regression analysis and an equation is developed. For instance, if an agency uses a pavement condition rating between 0 and 100, the panel might be asked to describe the condition at which reconstruction is needed. A follow-up question would determine the number of years at which reconstruction would be expected. Then, a line is drawn connecting the point set by the experts with the point at which the pavement is constructed (with age of 0 and a perfect condition). The shape of the line can be drawn to reflect either a linear model or a curved model, depending on the experts' opinions. Intermediary points could also be added to help shape the curve.

5.4 FAMILY MODELING AND SITE-SPECIFIC MODELS

The modeling approaches discussed in the previous section can be used to develop deterioration rates for a pavement family, in which one model is used to represent the rate of deterioration for a group of pavement sections with similar characteristics; or site-specific models, in which the predicted conditions are based on the unique characteristics of a particular pavement section. A description of each approach is provided.

5.4.1 Family Models

Since pavement management databases rarely include all of the variables considered to be important for modeling pavement performance and there are frequently data variability or completeness issues that further limit the availability of data for modeling purposes, the family modeling approach was developed. This method simplifies the modeling process by reducing the number of independent variables in the performance model to a single independent variable (usually pavement age or traffic) that is used to predict future pavement conditions. The equation can be reduced to one independent variable by using other variables to group pavement sections into *families* that have similar characteristics and performance patterns. The pavement performance model developed for the family is used in the pavement management system to represent the rate of deterioration for all of the pavement sections that meet the family definition. As one would expect, the definition of pavement families must be comprehensive enough that each pavement section in the pavement management database falls into one, and only one, pavement family.

A family modeling approach might be used to divide asphalt- and concrete-surfaced pavements, for example, to reflect the differences in their deterioration rates. To reflect differences in performance based on traffic characteristics, the asphalt-surfaced family may be further separated into families for asphalt-surfaced interstate highways and asphalt-surfaced non-interstate highways. This subsequent separation for interstate and non-interstate highways provides a way to take differences in traffic into account without requiring the availability of accurate traffic counts in the database. A similar approach could be used by establishing families based on "heavy" traffic volumes or "light" traffic volumes.

Pavement managers may also use the family modeling approach to establish the deterioration rate for a portion of the entire network, such as a sub-network. These sub-networks could be established very simply, using factors such as surface type; or they could be more complex, using a combination of geographic location, surface type, functional classification, and freight volume. The key is to establish families that have similar performance characteristics so the family model is representative of the rate of deterioration for each section included in the family.

The degree of sophistication of the factors used in creating the families depends on the quality and the degree of sophistication of the pavement management database. Therefore, a major advantage of the family modeling approach is the use of certain performance variables to *classify* pavement sections into families, rather than relying on the accuracy of the values for *predicting* future performance.

Performance models are created for each pavement family by plotting the condition and inspection age of the sections (e.g., the number of years since major rehabilitation at the time the inspection is performed) for each pavement section that meets the family definition. Regression techniques are then applied to predict the behavior of the data based on the age of the pavement, as discussed in Section 5.3.

Pavement families can be very simple or quite complex. Since performance models have to be developed for each family and each condition index, the number of families generated has a significant impact on the complexity of the pavement management system. For example, an agency that has three pavement types, three condition indices for each pavement type, and three traffic levels will have to develop and maintain twenty-seven different performance models (e.g., 3 * 3 * 3). Therefore, agencies should use some restraint in defining families in too much detail. In general, a family model should be comprised of data representing a range of pavement conditions and pavement ages. If a family does not have a full range of data available, it may be temporarily combined with a family displaying similar deterioration characteristics until more data become available.

When using the family modeling approach with historical condition data, it is important to store the family characteristics with the historical condition ratings so that each inspection point can be grouped with the correct family as models are being developed. If this step is not taken, the historical data could be pulled into the wrong family if a treatment has been applied at some point. For instance, if a concrete road is overlaid with hot-mix asphalt at some point in time, it is important that the data associated with the concrete ratings are kept with the concrete pavement families and those associated with the composite pavement are grouped with the composite families.

5.4.2 Site-Specific Models

Some agencies prefer using the unique characteristics of each pavement section to predict future conditions. Multiple variable regression equations are an example of site-specific models in which the predicted performance is based on the specific data stored in the database for that section. The predictions are considered to be site-specific because two pavement sections with identical condition information will not be expected to deteriorate at the same rate if other variables used in the model are different (e.g., climate, pavement thickness, or traffic).

Most agencies that use site-specific models require that at least three to five data points be available for the pavement section or an alternate model must be used. For example, the Colorado Department of Transportation requires at least five inspection points after a rehabilitation treatment has been applied before a site-specific model can be used (Keleman et al. 2003) while the Minnesota Department of Transportation requires that three inspection points exist and that agency-established rules for a reasonable rate of deterioration are satisfied before its site-specific models are used (FHWA 2008c). For instance, if overlays are expected to perform adequately for 5 to 10 years, a site-specific curve will be used if the predicted conditions fall within that range, otherwise the default family model will be used.