Support of Pavement Management Systems

At The Delaware Department of Transportation

Prepared for

Delaware Transportation Institute

And

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Introduction

This is the final report of the Delaware Transportation Institute Project "Support of the Development of Pavement Management Systems, Part I" as prepared by the Center for Applied Demography and Survey Research (CADSR) at the University of Delaware. It describes research and analysis sponsored by the Delaware Department of Transportation (DELDOT) through the DELDOT Pavement Management Team.

Over the last few years, DELDOT has initiated substantial efforts to improve decision making in regards to the maintenance of the road network. These efforts include the improvement of historic databases on pavement structure and conditions, analysis of pavement condition rating schemes in use, and the development of multi-year prioritization tools for the development of a multi-year prioritization capability to determine the timing and types of pavement rehabilitation projects that would be most cost effective.

As part of these efforts DELDOT initiated contracts with Applied Pavement Technology, Inc (APTech) and the Delaware Transportation Institute (DTI). The DTI portion of the work conducted by CADSR supported the DELDOT Pavement Management Section and APTech in a multi-phased project to provide enhancements to pavement management systems at DELDOT. CADSR's work was focused in the following areas:

- A review of current practices in pavement management systems.
- A review of the data needed for PMS and its availability to support DELDOT initiatives.
- An evaluation of the current Overall Pavement Condition (OPC) rating used by DELDOT and its relationship to age, type, and other attributes of roads.
- Development of performance models for Sussex and New Castle counties based on the data provided by DELDOT.
- Examination of Sussex County surface distress data provided by automated means.
- Assistance with the development of pavement management databases and tracking systems.

This report describes CADSR's role and findings and is divided into three parts. Part I provides a background of pavement management systems and includes highlights of the research and literature review component of the project. Part II discusses the foundations of pavement management systems in terms of the data collection, modeling, and optimization that are involved. Part III discusses the specific work and analysis performed by CADSR in this project. A summary of findings by CADSR is provided at the end Part III.

PART I - BACKGROUND OF PAVEMENT MANAGEMENT SYSTEMS

Introduction of PMS

The term “pavement management systems (PMS)” originally came into use in the late 1960s. In 1966, the American Association of State Highway Officials (AASHO), now referred to as the American Association of State Highway and Transportation Officials (AASHTO), through the National Cooperative Highway Research Program, initiated a study to make new breakthroughs in the pavement management field. The intent was to provide a theoretical basis for extending the results of the AASHO Road Test. As a result, researchers at the University of Texas in 1968 began to look at pavement design anew, using a systems approach. Simultaneously, independent efforts were being conducted in Canada to structure the overall pavement design and management problem and several of its subsystems. A third concurrent keystone effort was that of Scrivner and others at the Texas Transportation Institute of Texas A&M University in their work for the Texas Highway Department. The work of these groups provides the overall historic perspective for pavement management systems.

The term *pavement management systems* began to be used by these groups of researchers to describe the entire range of activities involved in construction and maintenance of pavements. The initial operational or “working” systems were developed. One of the largest efforts was Project 123, conducted by the Texas Highway Department, Texas A&M University, and the University of Texas. A series of reports and manuals have resulted from this research, beginning with 123-1 in 1970. The project has produced many of the modern innovations in pavement analysis.

At present there is no universally accepted definition of a pavement management system. Haas and Hudson referred to it as the pavement functions “considered in an integrated, coordinated manner”. PMS was defined by the Organization of Economic and Cooperative Development (OECD) Expert Group as “the process of coordinating and controlling a comprehensive set of activities in order to maintain pavements, so as to make the best possible use of resources available, i.e. maximize the benefit for society”. (OECD report, 1987). In AASHTO’s *Guidelines for Pavement Management Systems*, PMS is “a systematic approach that provides the engineering and economic analysis tools required by decision makers in making cost-effective selections of Maintenance, Rehabilitation, and Reconstruction (MR&R) strategies on a network basis". Corresponding with this definition, pavement management today has become a concept that is mandated in federal legislation and implemented by state highway agencies, cities, counties, and airports throughout the world. It has evolved from a concept with little practical application into an established approach that can be used by engineers to make more informed decisions, resulting in more optimal use of resources.

Pavement management activities and system components are generally focused at two administrative levels termed the "network" and "project"(or individual) levels. Network level analysis is of greater interest to the decision makers and budget directors and is doubtless the most powerful of pavement management approaches, because it involves:

- Identification and ranking of candidate pavements for improvements;
- Network-level budgeting;
- Long range budget forecasts;
- Network-level pavement condition assessments;
- Forecast of future conditions.

The project level, on the other hand, is concerned with more specific technical management decisions for the individual projects. It involves:

- Assessing the causes of deterioration;
- Determining potential solutions;
- Assessing benefits of the alternatives by life-cycle costing;
- Ultimately selecting and designing the desired solutions.

Why is PMS important?

A systematic approach to pavement management is needed to provide factual information on the present state and evolution of pavement conditions, and logical procedures for evaluating repair options, taking into accounts as much as possible all of their economic advantages and disadvantages (Hass and Hudson, 1987). In this way, PMS assists with the technical problems of choosing optimal times, places, and techniques for repairing pavements and simultaneously, providing those in charge of maintaining and improving roads with the data and other technical justifications needed to secure political support for adequate road maintenance budgets and programs. As described in the most recent FHWA "Pavement Policy for Highways". "*The analysis and reporting capabilities of a PMS are directed towards identifying current and future* *needs, developing rehabilitation programs, priority programming of projects and funds, and providing feedback on the performance of pavement designs, materials, rehabilitation techniques, and maintenance levels."*

This systematic approach has advantages over the common approach of using rules of thumb and intuitive engineering judgment. In times of budget austerity, available resources must be put to their best use, which means that all the practical options should be quantitatively and economically evaluated to identify the best overall solution. A comprehensive pavement management system supported by computerized tools to examine in detail the estimated costs and benefits of various strategies can be very effective in making the best use of resources.

Experiences In Other States

While the initial introduction of PMS at the national level dates from the late 1970s and early 1980s, most DOTs continue to rely on the experience of their maintenance, material, and pavement engineers, rather than their PMS, to determine the performance of their maintenance treatments and strategies. However, experience in the United States, where PMS took root during the recent era of tight road budgets, shows that the benefits of systematic approaches to pavement management have proven themselves in practice (Smith, 1992):

- The Arizona Department of Transportation (ADOT) reports that PMS implementation to optimize pavement rehabilitation expenditures enabled ADOT to save approximately $300 million over a five-year period. These savings can be used to expedite the construction of other badly needed capital improvements.

- The California Department of Transportation (CALTRANS) reports that its priority program of pavement rehabilitation projects based upon objective criteria established by top management, has led to fewer instances where staff level (technical) decisions are overridden by elected representatives. CALTRANS has been able to show, to the satisfaction of its elected representatives, that the projects being funded are more viable than those that are not, and its PMS has resulted in improved communication between political and technical decision-makers.

- Minnesota has a comprehensive, flexible and operational PMS in place, tailored to its requirements. Among the key reasons for the successful development and implementation were careful pre-implementation planning; strong support throughout the department including senior management; a sound technical basis for the system in terms of the data base, models, programs, and reporting functions; and a commitment by those responsible for its systematic perspective.

- A number of other state road administrations were able to argue successfully for increases in their vehicle fuel tax rates, because they were able to show effectively and objectively that previous program funding levels were insufficient to keep up with deteriorating pavement.

These agencies employed different methods to improve the way they manage their pavements but they all experienced a similar outcome. Because of the sound technical foundation on which decisions were based, they were able to produce pavements with better performance from available resources and ensure more effective technical input into the political decision-making.

FHWA Pavement Policy for Highways

The Federal Highway Administration (FHWA) of the U.S. Department of Transportation has focused attention on the use of pavement management concepts for cost-effective use of highway funds. By co-sponsoring with the American Association of State Highway and Transportation Officials (AASHTO) and the Transportation Research Board (TRB), numerous conferences, workshops, and training activities have been conducted over the past 18 years.

The policy describes the scope and purpose of a PMS as providing the analysis and reporting capabilities to highway administrators and engineers that include the ability to identify current and future needs, develop rehabilitation programs, and prioritize programming of projects and funds. Decisions are made in consideration of historic performance of pavement designs, materials, rehabilitation techniques, and maintenance strategies. The policy advocates the inclusion of full network level performance and trend information, covering all rural and urban arterial routes under a transportation agency's jurisdiction. Certain data may be collected visually for lower-order systems, but some degree of objective measurements should be made for high-level systems. FHWA policy recommends that a state's PMS should address the following key areas:

1. Inventory – An accounting of the physical features (number of lanes, widths, and pavement type, shoulder information, functional classification, etc) of the roadway network is essential.
2. Condition Survey – Measurement of the pavement condition (ride or roughness, distress, structural adequacy, and surface friction) from which changes over time can be determined.
3. Traffic Data – Traffic loading data are key elements that enter into analyses of pavement performance and deterioration rates.
4. Database System – An effective, automated system for the storage and retrieval of roadway inventory, condition, and traffic data is a critical feature of a PMS. A means of linking data to physical locations is required to permit the incorporation of maintenance management systems data and other data sources (bridges, accidents, railroads crossing, etc.) into the PMS.
5. Highway Performance Monitoring System (HPMS) – Due to similar data needs, coordination between the PMS and HPMS activities are encouraged.
6. Data Analysis Capabilities – The ability to effectively manipulate and use the information in the database to produce useful reports for decision makers is probably the most important capability of a PMS. Reports such as traffic analysis, network trends, project programming, project ranking, and project selection strategy are examples of the type of output needed by decision makers. An operational PMS will enhance communication among planning, design, construction, maintenance, materials, and research activities. As data is added over a longer time period, a PMS can be used to develop evaluations of materials and designs in relation to traffic loading and environmental conditions.

The policy required each state highway agency to have an operational PMS within a reasonable time, not to exceed 4 years from the January 1989. The FHWA field offices periodically monitor implementation progress and assess adequacy of each state's PMS with regard to quality of data collected, reports produced, and use in strengthening the pavement program.

AASHTO Guidelines for Pavement Management Systems

AASHTO guidelines describe the various components of a PMS that are required for its development and implementation, and how the PMS products and reports can be used as strategic planning and programming tools. The guidelines suggest seven conditions necessary for the development, implementation, and operation of a PMS.

- Strong commitment from top management and coordination throughout the department.
- A steering committee that exclusively deals with organizational and political problems.
- PMS Staff including one person who will be the lead PMS engineer with full time responsibility for managing, coordinating, and operating the PMS.
- System selection or development including good data, good analysis, and effective communications.
- Demonstration of PMS on a limited scale.
- Full-scale implementation – The pavement management team established earlier is very important to successful implementation.
- Periodical review and feedback.

DelDOT PMS

DelDOT Division of Highways is responsible for the maintenance of 4,765 miles of public roads in Delaware. Of this mileage, 221 miles are multilane highways. Most of the necessary funds for construction, reconstruction, rehabilitation, and maintenance of these roads are allocated from the Delaware Transportation Trust Fund. This statewide roadway network represents a tremendous investment. The preservation and management of these facilities is vital to the economy of the state, and is a key responsibility of the Department. Increases in traffic, both in numbers of vehicles and in wheel loads, along with rising costs and reduced resources, results in significant challenges to administrative and engineering personnel.

A systematic approach to the management of the pavements is needed to provide engineering and economic analysis tools required by decision makers in making cost-effective selections of Maintenance, Rehabilitation, and Reconstruction (MR&R) strategies on a network basis.

DelDOT has recognized this need since 1980s and has made significant progress toward PMS development. In 1980, prior to the Federal guidelines, DelDOT management supported the concept of PMS and appointed a PMS Steering Committee. Recommendations from this committee led to improvements in data collection, the formation of a Pavement Management Unit within the Office of Planning and Programming (now Division of Planning), and the designation of a full-time Pavement Management Engineer. The Office of Planning and Programming, and the Pavement Management Unit were instrumental in the development of a priority process for selecting projects to be included in annual highway programs. However, the process did not include some of the important features of a PMS such as forecasting, graphic reporting, budgeting, and optimizing capabilities, and had some less desirable features:

- There was an inability to forecast pavement conditions and needs.
- The process was very labor intensive. Information for decision-making was located in different data files and the analysis required both manual and computer efforts.
- The process was based largely on more subjective evaluations of road condition, and rules of thumb. Rating and prioritization of projects was still a "worst first" approach with practically no consideration for preventive maintenance.

In 1991, in response to the requirements of Congress's Intermodal Surface Transportation Act, DelDOT contracted with the consulting firm PCS/Law, to conduct state-of-the-art engineering and economic analysis and to provide cost-effective management tools for the entire network of paved roads and streets under DelDOT's jurisdiction. The initial project concentrated on determining the specific DelDOT needs, desires, and objectives as they pertain to the PMS and the preparation of a work plan responding to these objectives. As the work plan advanced, DelDOT accepted PCS/Law's proposal to develop DelDOT PMS into multi-modal transportation facilities. This project lasted several years but was discontinued in 1996. Several issues were identified that needed to be addressed:

- Limited availability of fiscal resources and technical know-how to support PMS once implemented.
- The absence of an agency-wide data base system and a complete historical pavement database.

- Inadequate identification of the needs and anticipated costs and benefits derived from the project.
- Political disruption of the PMS's consistency and uniformity

In order to consistently maintain and rehabilitate the pavement network, DelDOT contracted with Applied Pavement Technology, Inc (APTech) and the Delaware Transportation Institute (DTI) to evaluate the information available for the development of PMS components and enhance the existing capabilities.

The first phase of the study conducted by APTech was completed in December 1997. The study (APTech report) concentrated on the following areas of interest:

- Data management – including the identification of the types of the data required to support the pavement management efforts, procedures for obtaining the information, and processes to ensure the consistency and quality of the data used.
- Pavement performance models – including enhancements to the existing condition rating methods, the development of agency-specific pavement performance prediction models, and the establishment of preventive maintenance and rehabilitation treatments, triggers, costs, and impacts.
- Implementation/training – including the integration of the tools into the operational processes that exist within DelDOT.

The findings from the first phase of the study will be further investigated in Phase II, during which APTech will work with DelDOT Pavement Management to further develop performance models and to implement pavement management computerized tools.

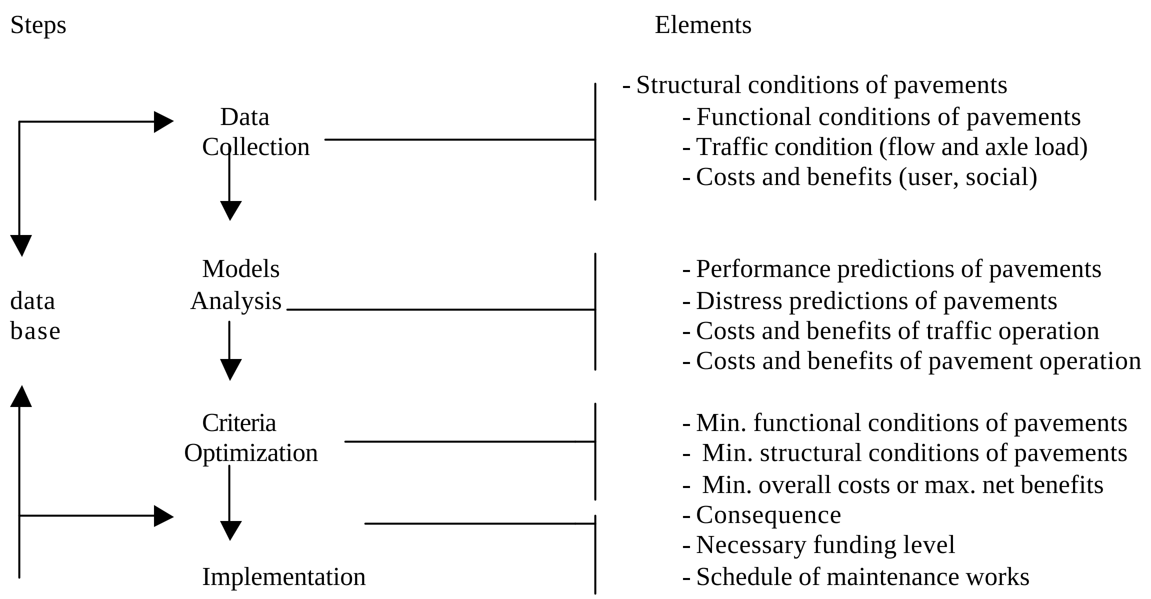
PART II - FOUNDATIONS OF PMS

A Framework of Pavement Management

Perhaps the most relevant research toward defining the components of a pavement management system was conducted by OECD (Organization of Economic and Cooperative Development) Expert Group's study, which laid the foundation for cooperative research across countries. The scope and objectives of PMS developed by OECD has been generally accepted by a number of countries in North America and Europe. Students of PMS from different countries all agree that the pavement maintenance procedure consists of four steps or processes as shown in figure 1.

1. Data collection
2. Models/analysis
3. Criteria /optimization
4. Consequences/implementation

Figure 1 PMS Framework



Data Collection

The objective of data collection is to keep track of the actual condition of roadways and record the condition in an objective and precise manner. Performance modeling depends on a database reflecting structural and functional conditions. When conducting the data collection procedure, the following elements are considered as important factors:

<u>Variability</u>

Variability of pavement surface distress measurements have always been an area of significant concern. When conducting evaluations of distress data manually (with raters observing the pavements in question, interpreting what they see and recording on paper) the data is subject to all of the human errors associated with such a process. To minimize the impact of such human errors on the important performance data, sophisticated equipment has been developed to eliminate as much of the human interpretation as possible.

The variability associated with distress data is dependent on such issues as season of collection, lighting, surface moisture, human experience and training as well as distress type, severity, and amount. To adequately quantify the precision and bias, a detailed experiment to evaluate the errors inherent in the different distress data collection methodologies is required. Examples of such experiments can be found in SHRP's *Distress Identification Manual for the Long-Term Pavement Performance Project* and *Guidelines for Pavement Management Systems* by AASHTO.

<u>Measurement Errors</u>

With any study, variables must be measured in order for analyse to be conducted and conclusions drawn. Measurement is always accomplished with a specified device or procedure, which will be referred to as an instrument (Carmines and Zeller, 1979). No matter what instrument is used, there is always some degree of error associated with it. Error comes from several sources including: the limits of precision of an instrument, idiosyncratic tendencies of the person conducting the rating, bias in the design of an instrument, and simple errors in the way a person uses the instrument. There are two types of errors, random error and bias. Random error occurs when errors are nonsystematic and are as frequently in one direction as any other, and thus values vary uniformly around the real or true score of the variable. Bias occurs when the errors tend to be in one direction more than another.

Random error causes data collected in a study to be less than precise. However, if one makes certain assumptions about the error component of measurement, one can use statistical procedures to circumvent this problem. Bias is far more problematic than random error. Since bias tends to be in one direction, there is no simple process to average out its effects. There may be instances in which it is possible to estimate the magnitude and direction of bias and to adjust for it.

Reliability

Reliability is a crucial characteristic of measurement and refers to the consistency of a measuring device or rater. In other words, questions can be asked like: (1) does the instrument always come up with the same score or number when the true value is the same? (2) Does the rater always have the same degree of visual accuracy of rating the object?

Validity

Validity of an instrument or procedure means that it measures what it is designed to measure. Validity is, in reality, complicated because raters are not always precise in their meanings of concepts and rarely have standards for comparison. A valid measure of pavement status would consist of a composite of structural and functional factors. But the question is how should they be combined? The definition of a pavement condition index is usually elusive. Generally an index is taken as part of a theoretical framework and establishes that certain hypothesized relationships exist between the examined indicator and other variables. As one finds that hypothesized relationships are supported, evidence for validity accumulates. Many agencies use the International Rating Index (IRI) mainly because IRI has been tested by AASHTO and has been accepted as a valid measurement. When none of the hypotheses are being upheld, either the instrument is invalid or the theories are wrong. Through the collection of evidence over time, a case is built for the validity of the measures, which are dependent upon theoretical models and hypotheses.

Frequency

The frequency at which a highway agency collects pavement condition data, depends primarily upon how often they need current data, budget restrictions, and the availability of trained personnel (Wang, 1998). Some pavement management systems require annual evaluation of pavement condition while others conduct pavement condition assessments once every two years. Nationally, it is common practice to inspect the Interstate pavements at least annually and other state maintained routes every other year.

However, the fact that the agency may collect pavement condition data every one, two, or three years does not necessarily mean that it inspects all of their pavements or inspects the entire length of a single pavement. Indeed, such a policy would often prove to be too time-consuming and too costly. A practical approach is to sample intervals along a pavement based on a statistical design aimed at achieving a prescribed level of confidence in the reported data as well as specifying which pavements should be inspected. For example, the following criteria to select pavements for inspection could be used:

1. Control sections which are tested every year to ensure consistency in the data;
2. Pavements with an index which exceeds a prescribed level on any of their failure mode listings for the previous year;
3. Sections requested for testing by the district personnel, because of specific distress conditions;
4. Pavements that have not been tested for a period of 3 years.

Pavement Condition Indicator

Whatever strategy is adopted for pavement management, it becomes important to assess the pavement's structural and functional qualities in a scientific, well-defined way. There are generally two philosophies of achieving that goal. One way is to combine attributes in a specific manner to determine a single pavement condition index universal to each section. By doing so, it is important to note that the index be objective and reflective of the real-world pavement status since the ultimate effectiveness of the decision is based upon the validity of this single index. Equally important, data should be updated on a periodical basis in order to be reflected in the index. The other philosophy is to use more than one condition indicator in decision trees, to prioritize and coordinate between difference indices and condition states, or to tabulate a pavement condition matrix. In this case there are usually several indices related to the extent of various types of surface distress.

While some agencies use multiple indexes to establish priorities between several pavements in need of repair, aggregation of pavement condition data into a single rating number is widely used to support project and network level decisions in pavement management. To characterize each pavement condition attribute and its time-decay relationship with traffic, age, climate, and other variables, various models have been developed. Table 1 introduces a number of condition indicators being adopted by several state agencies.

Table 1 Pavement Performance Condition Indicators

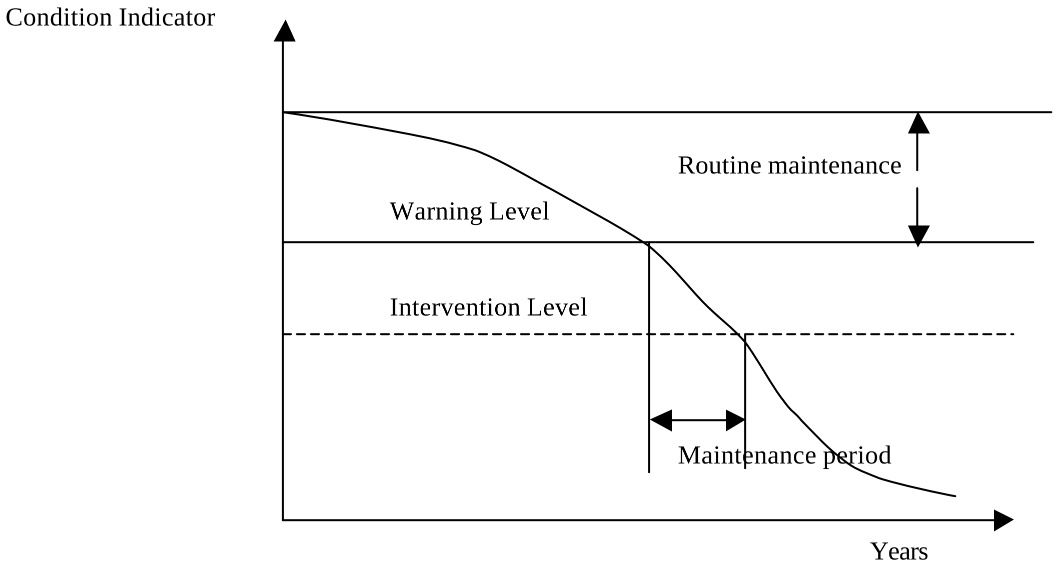
DOT	Index	Index Range	Models
Alaska	SCI	N/A	SCI=1.38(Rutting)2 + 0.01 (Alligator Craking +Full Width Patching)
Arizona	"Rate"	0-5	Rate=Cracking+0.2(Roughness)+2(Rutting)+0.0015(Average Maintenance Cost for last 3 years)
Canadian	DI	0-180	(1)DI=5(2(Severity of Raveling)+(Extent of Raveling)+Σ(2(Severity of Distress)+(Extent of Distress) (they are measured on a scale of 0 to 4) (2)DI=127+5.64Age-18.6(Percentage of Asphalt Cement Content in the Surface Course)-5.88$\log_{10}^{\text{Average Annual Daily Traffic}}$ (this is a prediction model)
Indiana	PSI	0-5	PSI=4.7-0.065(Age)-0.000006(Average Annual Daily Traffic)-0.46(Pavement Types-1 for Concrete 0 for Bituminous)
Pennsylvania	SDI	0-100	SDI=0.1(Excess Asphalt) +0.13(Raveling)+0.2 (Block Cracking)+0.25(Transverse/Longitudinal Cracking)+0.05 Edge Deterioration) +0.12 (Widening Dropoff)+0.15(Rutting)

Notes: DI --- Distress Index
PSI --- Present Serviceability Index
SCI --- Surface Condition Index
SDI --- Surface Distress Index

Performance Modeling

Performance modeling refers to the activity that patterns and predicts the deterioration of pavement conditions with accumulating use, based on comprehensive evaluation of the structural and functional characteristics of the pavement in service, deterministically and/or empirically. A typical performance curve, relating the pavement condition rating to the age of the pavement, is shown as an example in figure 2.

Figure 2 Performance Curve



Being able to predict the condition of pavements is the most essential activity to the management of pavements at the network and the project levels, both technically and economically. In fact, the models play a crucial role in several aspects of the PMS, including financial planning and budgeting as well as pavement design and life cycle economic analysis.

First, models are used to predict when maintenance should be required for individual road sections and how to prioritize competing maintenance alternatives. Second, by virtue of its prediction capability, the model enables the agency to estimate long-range funding requirements for pavement preservation and to analyze the consequences of different budgets on the condition of the pavement network. Third, because the models attempt to relate the influence of predicting variables to pavement distresses or to a combined performance index, they can be used for design as well as the life-cycle economic evaluation.

Pavements are complex physical structures responding in a complex way to the influences of numerous environmental and load-related variables and their interactions. A prediction model, therefore, should consider the evolution of various distresses and how they may be affected by both routine and planned maintenance. Such an approach is so highly complex that a compromise procedure combining a strong empirical base and a mechanistic approach is adopted to achieve a reliable model. The empirical base includes time-series pavement condition data compiled on pavements exposed to different environmental and loading conditions. With regard to mechanistic principles, interactions between traffic loading and pavement strength parameters, between loading and pavement deflections, and so on, are observed and included when significant. These considerations dictate the model form and provide guidance in the selection of the independent variables for inclusion in the prediction model.

Pavement Performance Prediction Methodologies

Performance is the "ability of a pavement to fulfill its purpose over time"(AASHTO Guidelines). A performance prediction method is "a mathematical description of the expected values that a pavement attribute will take during a specified analysis period" (AASHTO guidelines). Prediction models provide parameters to pavement management optimization so that they can base the selection of future MR&R programs on the forecasted conditions.

Several methods of studying performance have been used by state agencies in the past decade:

- Performance curves: A performance curve defines variations of pavement attributes over time. State agencies create performance curves for their particular conditions. A bituminous pavement with high traffic and low subgrade strength may have a different performance curve than a concrete pavement with low traffic and medium subgrade strength. A performance curve normally relates expected relationships between serviceability and age. These relationships are commonly estimated using regression, include structural capacity versus age, skid resistance versus age, and a measure of distress versus age.
- Nondestructive testing (NDT): O'Brien, Kohn and Shahin studied Prediction of pavement performance using NDT results. The NDT model was originally used by several states. Several variables were included in this model: pavement type, condition rating, NDT information, pavement construction, traffic information, and pavement layer thickness. The independent variables were pavement construction history, a weighted traffic variable, and NDT deflection parameters. The pavement construction history was reflected in three pavement layer age variables: time since

last overlay, time from construction to first overlay, and total pavement age. The NDT parameters were a normalized deflection factor given by the slope of the deflection basin and a measure of the deflection basin area. The traffic variable included in the prediction model is the natural logarithm of current traffic count weighted by traffic type. The relevant significance of each variable group was 60 percent for the age variables, 30 percent for the NDT variables, and 10 percent for the traffic variable.

- Regression Analysis: Regression Analysis is the approach that is most commonly used. A General Linear Model or polynomial model procedure is often used to develop a linear regression equation. In most regression analyses, the fit of the model is described by an R-square (R^2) value. The R^2 value is based on sample correlation coefficients that indicate the strength of the developed relationship between the dependent variable and independent variables when compared to the observed data. R^2 may then be interpreted as the proportion of total variability in the dependent variable that can be explained by the independent variables. The R^2 can range from zero to one with the higher number indicating a better fit of the model to the actual data.
- Empirical-Mechanistic Model: This model is based on the assumption that a prediction model should consider the evolution of various distresses and how they may be affected by both routine and planned maintenance. However, this approach is so complex that a compromise procedure combining a strong empirical base and a mechanistic approach is adopted to achieve a reliable model. The empirical base includes time-series pavement condition data compiled on pavements exposed to different environmental and loading conditions. With regard to mechanistic principles, interactions between loading and pavement deflections, and so on, are carefully observed and included when significant. The dependent variable is usually condition data (e.g. PCR, stands for Pavement Condition Rating). The selection of independent variables is based on experience suggesting that the prediction of pavement condition depends on: (1) period during which the pavement has been in service, age of the pavement; (2) traffic volume and weight, which are expressed in terms of years equivalent single-axle loads (ESALs); (3) thickness of last overlay in inches; (4) strength and condition of pavement structure represented by modified structural number.

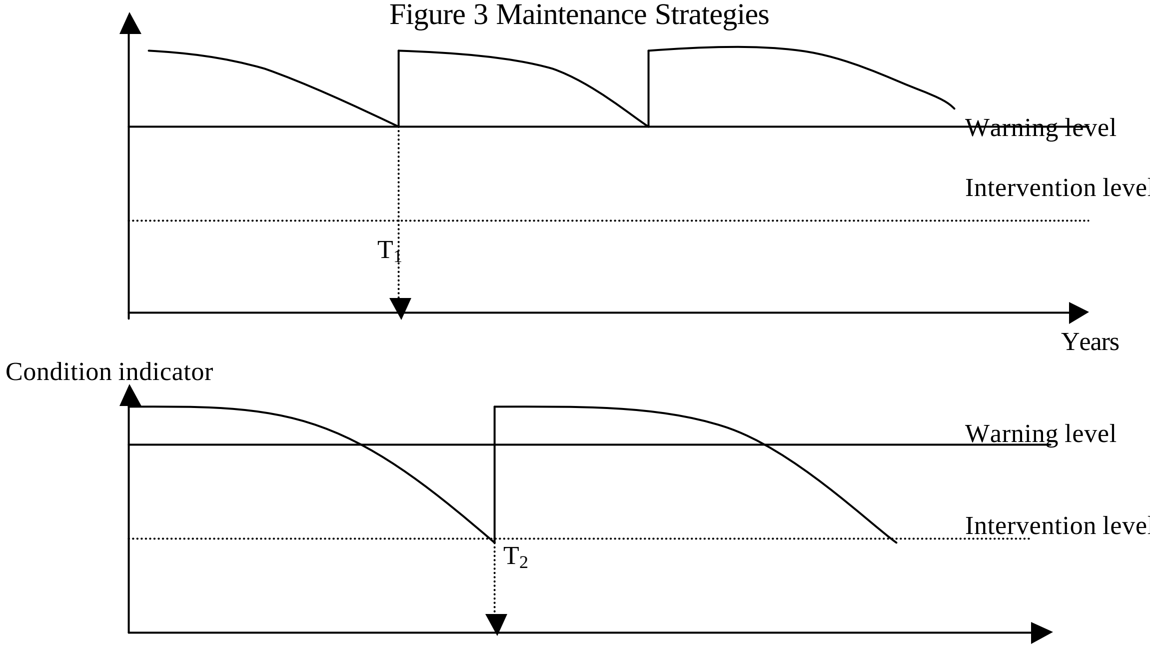
- Markov chain: The Markov chain is a probabilistic model that accounts for the uncertainties present with respect to both the existing pavement condition and future pavement deterioration. The underlying concept of this method is that a pavement section may be in one of several states or conditions and that unless maintenance or rehabilitation is undertaken, the condition of the pavement will worsen over time. The amount of pavement deterioration in a given period, such as a year, is a random variable depending only on the most recent state of the pavement and the amount and type of traffic loading that the pavement accrues during that period of time.

Optimization

When evaluating pavement conditions to decide on appropriate actions, it is necessary to define a set of intervention levels in accordance with the various types of data collected. Intervention levels could be defined based on a particular rating of pavement conditions to indicate the need for rehabilitation or preventive maintenance. Many different solutions are possible when the need for maintenance work arises, and each solution generates its own performance curve (according to the different criteria). Not only are many solutions possible, but also a tremendous number of different combinations are possible, when the timing, sequence or type of action are changed over an extended period (OECD, 1987). Figure 3 illustrates an example with two different maintenance strategies.

In the first case the maintenance work was made at a certain warning level, while in the second case the work was not carried out until the intervention level was reached. The cost of the maintenance work at time t2 may be greater than if the work had taken place at t1, or in other words, the actual cost of strategy two is higher than the first strategy. Potentially if the period of deferral lengthens, it causes much larger and non-economic expenditures when the remedial maintenance work is ultimately carried out.

Figure 3 Maintenance Strategies



By analyzing costs and benefits of all possible strategies for each road section within a set time frame, called the consideration period, the consequences of providing satisfactory pavement service can be estimated. Computer programs are available to assist with the complexity that arises when addressing thousands of roads at various stages in their life cycle.

Preventive Maintenance

Often pavement management is focused more on roads that are in need of major rehabilitation. As with many types of infrastructure it has been shown that there are cost advantages to addressing small problems before they become large ones. A preventive pavement maintenance strategy is an organized, systematic process for applying a series of preventive maintenance treatments over the life of the pavement to minimize life-cycle costs. Cost-effective preventive maintenance strategies are applied to pavements to minimize or prevent common pavement problems from occurring. To implement this strategy, a survey is made annually of the condition of each section of the pavement. Based on the results of that survey, the decision is made to perform the preventive maintenance activities or, if the pavement condition doesn't warrant it, to postpone the treatment for a year. Multi-year prioritization pavement management programs that consider preventive maintenance can be very complex and place even greater demands on data quality and the ability to accurately access and predict pavement condition.

Except for the simplest of circumstances, computer programs are necessary to examine all of the many options to optimize pavement condition at given levels of expenditure.

One of the earliest studies on preventive maintenance strategies, conducted by the Utah Department of Transportation in 1977, indicated that every $1 invested in a preventive maintenance treatment early in the life of a pavement, avoided the expenditure of approximately $3 later on in the cost of a major rehabilitation (Byrd 1979). In Kansas a strategy was implemented to treat the pavements in need of preventive maintenance before funding the reconstruction of poorer pavements (Byrd 1979). After the first 4 years, expenditures for both surface repairs and resurfacing of aggregate and asphalt pavements decreased progressively.

The Wisconsin Transportation Information Center at the University of Wisconsin-Madison conducted several simulations of pavement management strategies. One of the studies was conducted for a small city with a 68-mile roadway network and demonstrates the benefits of a preventive maintenance strategy. The pavement condition rating is on a scale of 1 to 10, with 10 equal to new pavement and 1 equal to failed pavement. The network initially had $2.4 million of work backlogged and an average condition rating of 5.88. The simulation demonstrated that the most beneficial strategy, which also results in the highest pavement condition rating, is to perform preventive maintenance on those pavements when and where preventive maintenance treatments are appropriate, and then to resurface and reconstruct those pavements where the condition has deteriorated below the point where preventive maintenance is effective (Geoffroy 1996). The least beneficial strategy is to allow a pavement to deteriorate until it needs to be resurfaced or reconstructed.

The table on the next page summarizes the results of applying alternative pavement strategies to a 1,000-mile network. The pavement is rated in five condition levels: Very Good, Good, Fair, Mediocre, and Poor. The analysis compares the number of lane miles in each condition level after 5 years with a do-nothing strategy, a worst-first strategy funded at $8.0 million annually, and two preventive maintenance strategies, one funded at $8.0 million annually and one at $6.4 million annually. This example demonstrates the cost-effectiveness of preventive maintenance. The network condition after 5 years is approximately the same for the worst-first strategy funded at $8 million annually and the preventive maintenance strategy funded at $6.4 million annually for an annual savings of $1.6 million or 20 percent.

Table 2 Example Comparison of the Effect of Alternative Strategies for maintaining a road network

Pavement Condition	Year 0	Do-Nothing	Worst-First $8 Million Annually	Preventive Maintenance Annual Funding at $8 Million	Preventive Maintenance Annual Funding at $6.4 Million
Very Good	200	66	334	352	294
Good	280	48	124	146	132
Fair	370	100	140	175	170
Mediocre	100	68	80	101	100
Poor	50	711	321	225	303

PART III SUPPORT OF DELDOT PAVEMENT MANAGEMENT SYSTEMS ENHANCEMENTS

Introduction

In addition to conducting research into current practices in pavement management as previously described in this report, the Center for Applied Demography and Survey Research's (CADSR) assisted the DelDOT Pavement Management Team and Applied Pavement Technologies Inc. in addressing the following questions.

- What is the state of current pavement management systems at DELDOT?
- How is the Overall Pavement Condition (OPC) index derived and will it support road surface performance modeling?
- What are the appropriate factors that should be considered for derivation of an OPC and for performance modeling, and what is the current availability and accuracy of data for Delaware?
- What are appropriate performance models? How can pavement management systems be implemented?

This part of the report describes the work done by CADSR to find answers to these questions and is divided into three sections, one that discusses the study and evaluation of OPC, a second describes the development of pavement performance models, and a third summarizing the findings of CADSR's analysis. A number of data tables and figures were selected from the analysis to illustrate findings.

Section One: Evaluation of OPC

The primary focus of analysis in support of pavement management system enhancements was to evaluate the current Overall Pavement Condition (OPC) rating currently in use by DELDOT, and to examine how OPC related to age and other factors that could be used in performance models. As the dependent variable in all performance models, OPC, and surface distress and condition ratings in general, are the most important data component of pavement management systems. In order to specify the current condition of roads and to model future conditions, it is necessary to have a very reliable measure of pavement condition.

Determination of OPC

DelDOT uses Overall Pavement Condition (OPC) to reflect the general conditions of Delaware roadway networks and to determine rehabilitation decisions. OPC is a composite and subjective index. It combines the human estimation of the attributes of fatigue cracking, environmental cracking, surface defects, and patching into one indicator. The extent of these distresses (low, medium, high) is recorded in the field for each road. OPC is obtained via windshield survey conducted by each District. To rate a certain road, District raters drive over each pavement section in their District and assign a value between 0 and 5 to represent the overall condition of the pavement section. A "5" represents a new road or newly rehabilitated pavement, and a "0" represents the absolute worst pavement condition. OPC has been used, in its current format, for two years.

While in general OPC is a subjective combination of distresses, DelDOT's policy for rating road sections that are less than 6 years old relies on a table related to estimated life (see Table 3). Pavements that need some type of rehabilitation in the year of inspection (remaining life of 0) are assigned an OPC of 2.5. Pavements that have a remaining life of more than 1 year are assigned higher values and those that should have received some type of rehabilitation prior to the inspection are rated lower than a 2.5.

Table 3 OPC Scoring Based on Remaining Life

Pavement Type	0 year	1 year	2 years	3 years	4 years	5 years
Asphalt Concrete	2.5	2.6	2.7	2.9	3.0	3.1
Composite	2.5	2.7	2.9	3.1	3.3	3.6
Concrete	2.5	2.6	2.7	2.8	2.9	3.0
Surface Treated	2.5	2.9	3.3	3.7	4.1	4.5

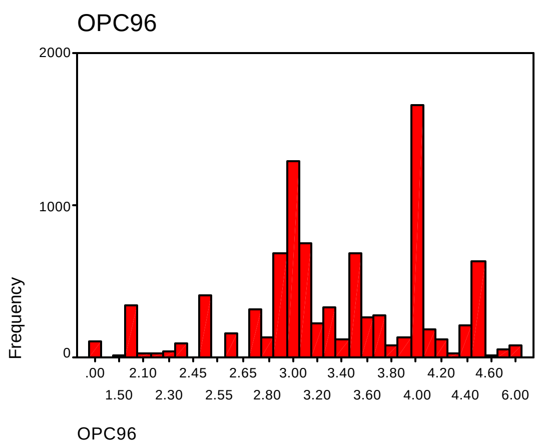
The District personnel have been trained in the determination of the OPC rating and are comfortable with the ratings scheme because of its simplicity. There is some confidence with the rating scheme from a value of 3 and below. However at the upper end of the scale (greater than 3 and less than 5) there is less understanding of remaining life and the DELDOT Pavement Management team found that assigning an OPC was more difficult.

OPC then is directly related directly to an estimate of remaining life and a fixed deterioration curve for each of the three pavement families, Asphalt, Composite, and Concrete, where estimated life is 5 years or less. Where the estimated life is greater than 5 years, OPC is a subjective measure based on a review of surface distresses, and is not generated by a composite index calculated on the basis of the distress information collected.

Variability

To view the distribution of OPC, a bar chart of the frequency of OPC was plotted (figure 4). The minimum value of OPC is 0 and the maximum is 6. Periodically, DelDOT has used an OPC rating of 6.0 to indicate a pavement section that is receiving rehabilitation that should not be considered in the development of the next paving list.

Figure 4 Distribution of OPC



The graph shows that the variability of OPC is very low with the majority of points clustering around 3, 3.5, 4, and 4.5. This implies that for a subjective rating, the rater might have difficulties in differentiating the road conditions simply from human observations. Very few values fall below 2.5 because pavements with remaining life of 0 were rated 2.5.

Errors and Outliers

By running a scatter-plot of OPC and age (see figure 5), a number of suspected errors in the data sets were identified.

1) There are numerous data points for low age with low OPC and, high age with high OPC, forming a square shape in the scatter-plot shown in figure 5.
2) The age ranges from 0 to 25 for OPC values of 5 and 4.5. Similarly, for age values of 0, OPC ranges from 1.5 to 5, between which almost any values are possible.
3) Older roads might have higher OPC due to, for example, minimal traffic volume or insignificant weather degradation. However, the inclusion of erroneous data from the windshield survey might also, if not primarily, contribute to the older-age-higher-OPC scenario.

Figure 5 Scatter-plot of OPC and Age (flexible family)

4) Among roads that have OPC equal to 5, thirty-one percent have estimated remaining life of 0 or 1 year as shown in Table 4:

Table 4 Distribution of Estimated Remaining Life for OPC equal to 5.

ESTLIFE

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	0	7	11.9	12.1	12.1
	1	11	18.6	19.0	31.0
	5	7	11.9	12.1	43.1
	6	33	55.9	56.9	100.0
	Total	58	98.3	100.0	
Missing	System	1	1.7		
Total		59	100.0		

Yearly Difference

The three OPC surveys in 1998, 1997, and 1996 in the South District were determined differently as the process was refined. The OPC 1998 was believed to be more reliable because of its better quality control. Statistical differences among the three-year measures were examined. Two dummy variables, d_1 and d_2, were created to represent three groups of comparison as listed below. OPC98 is base group when both d_1 and d_2 are equal to zero.

The equation for a third-order polynomial regression model is as follows[1]:

$$OPC = a_0 + a_1x + a_2x^2 + a_3x^3 + a_4d_1 + a_5d_1x + a_6d_1x^2 + a_7d_1x^3 + a_8d_2 + a_9d_2x + a_{10}d_2x^2 + a_{11}d_2x^3$$

The coefficients in Table 5 indicate that all the t statistics are significant (significant level less that 0.05 when a confident level of 95% was selected). That means the base group (OPC98), d_1 group (OPC97), and d_2 group (OPC96) all contribute to the pooled model. In other words, the OPC measures for the three years are statistically different.

Table 5 Statistical Summary for OPC Year Testing

Coefficients [a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	4.043	.033		121.980	.000
	AGE	-.147	.013	-1.059	-11.248	.000
	AGE2	7.36E-03	.001	1.153	5.591	.000
	AGE3	-1.2E-04	.000	-.474	-3.404	.001
	D1	-.332	.042	-.218	-7.884	.000
	D1AGE	7.00E-02	.017	.386	4.081	.000
	D1AGE2	-6.1E-03	.002	-.563	-3.489	.000
	D1AGE3	1.29E-04	.000	.269	2.756	.006
	D2	-.290	.039	-.191	-7.340	.000
	D2AGE	7.06E-02	.016	.404	4.352	.000
	D2AGE2	-6.4E-03	.002	-.710	-3.870	.000
	D2AGE3	1.47E-04	.000	.419	3.348	.001

a. Dependent Variable: ALLOPC

Table 6 Statistical results from South District

OPC Year	R^2
1998	0.387
1997	0.336
1996	0.329

Comparing the statistical results in Table 6 for the three years of OPC, the 1998 survey has the best fitness model with the highest R^2 value. 1997 is the next and lastly, 1996 survey. This confirmed the suspicion that the reliability of OPC affects the fitness of the model.

Comparison with automated measures of Districts

In the 1998, automated surface distress data was obtained through Roadware's Automated Road Analyzer (ARAN). Three data sets for roads in Sussex County, Delaware were examined with the primary goal being to examine the level of correlation between DelDOT's OPC and objective, automated measures. Another objective was to investigate the possibility of employing automated means in the future for the determination of overall pavement condition index. The data included measures for surface distress on asphalt pavements, surface distress on concrete

[1] The reason for using third-order polynomial model is explained in Part IV of this report.

pavements, and a third data set for ride and roughness across all roads in the sample (see Table 7).

Table 7 ARAN Data Description

Flexible Pavements	Concrete Pavements	Joint Ride
Percentage of Transverse Cracking at each severity level (% area) Percentage of Fatigue Cracking at each severity level (% area)	Transverse Cracks at each severity (% slabs) Longitudinal Cracks at each severity (% slabs) Joint Spalling at each severity (% joints) "D" Cracking at each severity (% joints)	Average roughness ---IRI (inches/mile, left and right wheel path) Ride Number

Surface distress and ride information provided in the automated data sets at every tenth or hundredth of a mile, were aggregated and averaged over the large road segments addressed in PMS databases. As a result, values of OPC, pavement family, pavement age, and pavement structure from pavement history file could be related to automated distress data. Since there was not enough data for concrete pavements, only asphalt pavements were analyzed.

For asphalt pavements, the extent of cracking is recorded as area percentages of three levels of cracks, low, medium and/or high. In other words, the total value of three levels of cracks for one road segment should not be greater than or less than 100%. Those values which are not equal to 100 as well as OPC values greater than 5 were considered as errors and thus were also removed from the data sets.

Using two-tailed Pearson correlation, all the distress types showed statistically significant correlation with OPC at 99% confidence level (see Appendix B). Scatter-plots of OPC with transverse cracking and fatigue cracking were also generated and shown in figure 6 and 7.

Figure 6

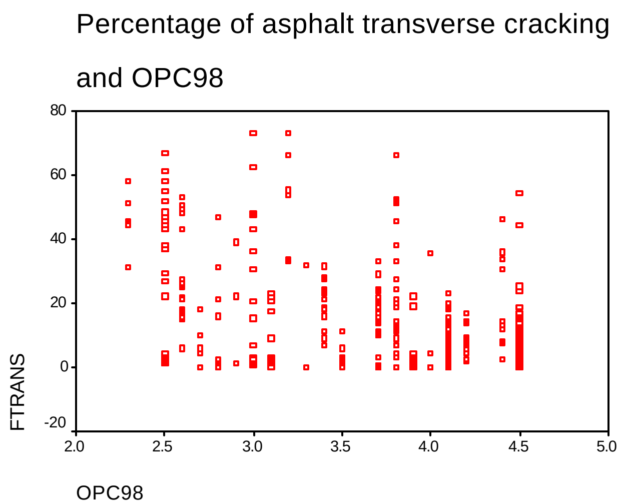
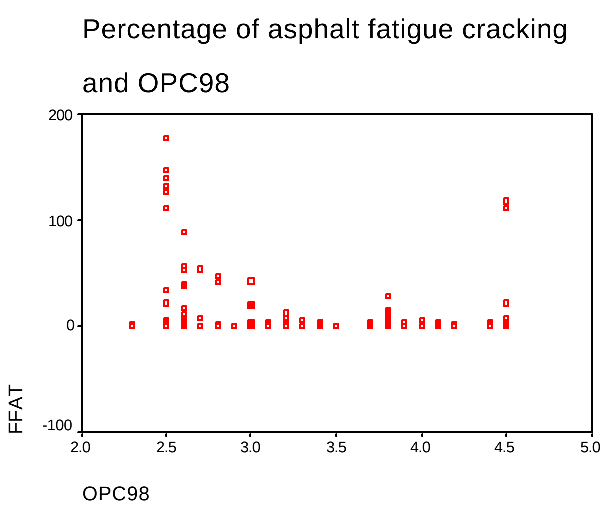


Figure 7



After outliers were investigated and removed from the data sets, the distress types were then included in a linear multiple regressions as independent variables to show how much they relate to OPC. Since cracks at different levels highly correlate with the overall measure of this crack, only the overall measurements were considered in the model. Table 8 shows that the coefficients of average roughness, percentage of fatigue cracking, and percentage of transverse cracking are all negative, demonstrating an inverted linear relationship with OPC. In other words, the higher the OPC, the lower the distress measurements, as would be expected. All the independent variables are statistically significant.

Table 8 Coefficients of Distress Types

Coefficients [a]

Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.
1	(Constant)	4.360	.076		57.515	.000
	percentage of fatigue cracking	-4.2E-03	.002	-.140	-2.400	.017
	average roughness	-3.1E-03	.001	-.220	-4.102	.000
	percentage of transverse cracking	-1.7E-02	.003	-.396	-6.749	.000

a. Dependent Variable: OPC98

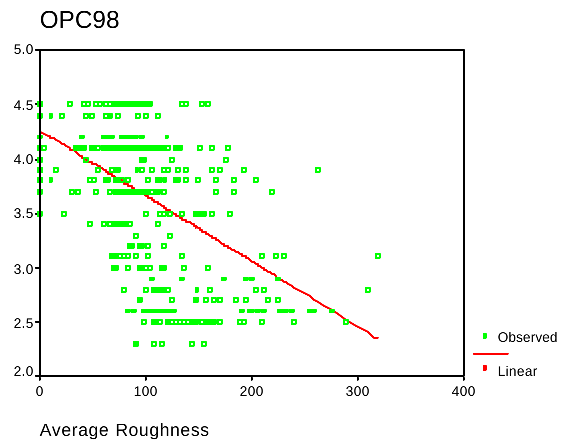
The correlation of roughness to OPC was also examined. Roughness is determined by response or profile measure. It can be expressed in several forms. The International Roughness Index (IRI) is a measure of roughness expressed in inches/miles that can be determined from either method of measurement and has been recognized by the FHWA. The IRI value has a minimum value of 0 inches/miles and has no maximum value because it is expressed as a measure unit. It is defined, according to the International Road Roughness Experiment held in Brazil in 1982, as the average rectified slope of a standard quarter-car simulation traveling 80 kilometers per hour. FHWA has selected the IRI as the most suitable pavement roughness statistic for incorporating pavement roughness into the Highway Performance Monitoring System (HPMS) database. Roughness condition ranges have been suggested by the FHWA to classify the IRI measure into appropriate condition categories, as shown in the Table 9.

Table 9 IRI and Roughness Category

IRI Range (inches/mile)	Roughness Category
0 – 190	Smooth
190 – 320	Medium
> 320	Rough

Using a least-square fitness curve to represent the most likely trend of the data points as shown in figure 8, the relationship between the OPC and roughness figure was revealed as linearly inverse correlation. There is some indication that as roughness values go beyond 200, an OPC value of 2.5 can be could be seen as a trigger value to take rehabilitation action.

Figure 8 OPC and Roughness



$R^2 = .27$

Another roughness index is the computed Ride Number (RN). The RN is a ride/roughness statistic with values from 0 to 5 where 5 indicates a very smooth pavement. The RN uses the form:

$$RN = f(PI)$$

$$PI = \left\{\left[RMS(P_r)\right]^2 + \left[RMS(P_1)\right]^2\right\}^{0.5}$$

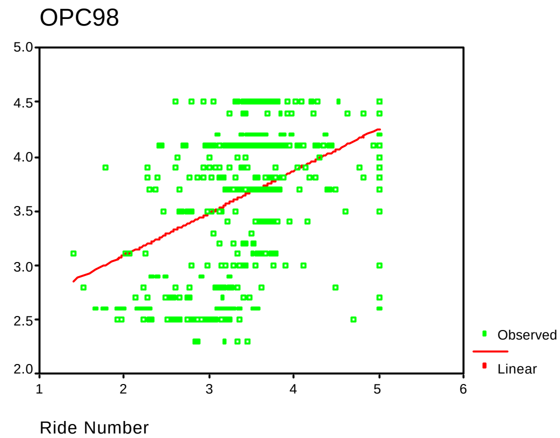
Where RMS = room mean square of vertical acceleration

P_r = measured displacement amplitude of right wheel path for pavement wavelengths 1.6 ft to 8 ft.

P_1 = measured displacement amplitude of left wheel path for pavement wavelength 1.6 ft to 8 ft.

As the higher ride number represents a smoother road, the correlation between ride number and OPC is expected to be a positive linear relationship. DelDOT's OPC with the ARAN ride data are plotted in figure 7. A correlation exists but the plot also reveals many variations within the data points and the curve only explains 20% of the variances.

Figure 9 OPC and Ride Number



$R^2 = .20$

Analysis described concerning comparison between DelDOT's OPC and automated distress measures were limited to examining whether there were correlations with particular distresses and roughness measures. Another approach would be to determine a method of combining the distress measurements into an overall condition index. In Baladi's study, he introduces the methods of creating an overall Pavement Quality Index (PQI) or Pavement Condition Index (PCI) on the basis of individual distress indices. After obtaining Categorized Evaluation Indices (CEI) such as surface distress index, drainage index, structural index, etc, a relative weight factor can be assigned to each index category. The PQI or PCI can then be calculated by summing the products of each CEI and the appropriate weight factor. A threshold value of the PCI/PQI can be established below which a pavement section is rendered unacceptable and in need of repair. Because of the difficulty in establishing the proper weights for each distress, an overall index was not formulated for the DelDOT data.

Section Two: Pavement Performance Modeling

Factors Used to Predict Performance

Independent variables used for predicting pavement performance are derived from one or more of the following factors:

1) Period during which the pavement has been in service
2) Traffic volume and weight, expressed in terms of yearly equivalent single-axle loads
3) Thickness of last overlay, in inches
4) Surface deflection
5) Construction quality
6) Climate factors such as temperature and precipitation
7) Pavement Material Type
8) Drainage

The DelDOT pavement management database is composed of pavement data attributes covering pavement identification, functional classification, surface type, layer material properties, and traffic records. Data for two counties, New Castle and Sussex, representing the North District and the South District, respectively, were available for this study. In the databases, each pavement attribute or set of related attributes is associated with a variable length segment of pavement by specifying beginning and ending mile-points. Through discussion with APTech and a review of the local conditions in Delaware, DelDOT decided to take into consideration the following factors to predict OPC: age, pavement type, and structure number.

Age

Age is significant because; it is a common factor in the estimation of both cumulative traffic loads and environmental loads over the life-cycle period; age can be determined for any pavement and would be expected to be a good predictor; and age can be a surrogate for the cumulative effect of many detrimental factors, such as thermal effects, subgrade movements, freeze-thaw effects and bitumen aging. To closely reflect the roads service time on a life-cycle basis, the age of a road was defined as the number of years since the road was last improved. In modeling the relationship of age with OPC, the age of the road segment at the time that the OPC rating was taken was used.

Pavement Type

Pavement material type is also critical to pavement performance. The preliminary investigation of the data from the South District resulted in the groupings of 23 different pavement families based on surface type. Among these 23 families, only five families contained enough data to conduct regression analysis using pavement type. Therefore, the data was then regrouped into more general families --- rigid, composite, flexible, surface treatment, unimproved, and unconventional. Surface treatments were excluded from the modeling because their rehabilitation needs are determined on a cyclic basis, rather than on conditions. Unimproved and unconventional types --- including graded and drained, soil, grave, stone, bricked, and other combinations were not considered in the study. The distribution of the data for each family is shown in Table 10. The groupings of the many surface types that exist for Delaware roads into the above families are listed in detail in Appendix D.

Table 10 Family Distributions

family classfication

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	rigid	1194	12.5	12.5	12.5
	composite	3418	35.7	35.7	48.1
	flexible	3175	33.1	33.1	81.3
	surface treatment	1615	16.9	16.9	98.1
	unimproved	131	1.4	1.4	99.5
	unconventional	36	.4	.4	99.9
	unknown	14	.1	.1	100.0
	Total	9583	100.0	100.0	

Structure Number

For flexible pavements, the structure number is expressed by the thickness of each of the pavement layers through the use of layer coefficients as given by:

$$SN = a_1D_1 + a_2D_2 + a_3D_3$$

Where: SN = structural number representing the structural capacity of the pavement; D_1, D_2, D_3 = layer thickness; a_1, a_2, a_3 = layer coefficients

The layer coefficients are empirical parameters relating the layer thickness to the structural number and expressing the relative ability of a material to function as a structural component of the pavement. Theoretical layer coefficients for any material can be developed using multi-layer elastic analysis and comparing strain and stress levels within the pavement layer structure. Materials that are not assigned AASHTO coefficients are assigned a structural number based on coefficients (recommended by Materials and Research) multiplied by the thickness of the pavement layers.

According to AASHTO road tests, the road structure, as indicated by the structure number, influences the deterioration of flexible pavements with and without overlay. Composite and overlaid pavement equations include asphalt surface thicknesses as well. Structure number is believed to be an indicator of mechanistic parameters of how a pavement performance is effected by stress, strain, and deflection. Theoretically, a pavement with better materials has a higher structural number than a pavement with less resilient materials. Similarly, if two pavements are made with the same materials, a thicker pavement would have a higher structural number than a thinner pavement. Structure number is also used when designing pavements to meet expected loads and usage.

Model Procedure

Groupings of Highway Sections

Many factors may influence pavement performance and each has a distinctive effect over time. Ideally, a pavement model could be constructed to reflect the unique characteristics of each road. However, developing performance models for each road section requires extensive historical databases and therefore in practice proves to be very difficult. Instead, a method of categorizing pavements based on similar characteristics is often chosen to account for the wide variety of factors on a network-level basis, assuming that pavements with the same grouping will perform similarly throughout their lives.

Early in the research, data for roads were studied in 23 groupings corresponding to various pavement types. Further detail was introduced by looking at different functional classifications of roads within pavement types. Because of sparse data in many of the groups, and because of the great variation in the data for OPC and age (see ApTech Phase I report), a more general grouping was selected. Pavement sections with similar characteristics were finally grouped into three families, rigid, composite, and flexible, and the development of performance models was focused on each of these groups.

Screening Procedure

Errors were identified as those pieces of data in which a mistake was suspected when gathering, coding, or entering the data. Inaccurate data can be found where basic system rules are broken. One example is where OPC values are greater than 5 when the OPC scale is from 0 to 5. The data was sorted by group, time since pavement was built or last rehabilitated, and OPC. For each family type, scatter-plots were run to display the data distribution between OPC and age. Obvious problems such as OPC greater than 5 or less than 0, or remaining life less than or equal to 1 and OPC greater than 4, were eliminated from the database. However, to ensure appropriate model building, further examination of the data for any unusual observations was performed.

Unusual data values can have substantial impact on model development. To identify these extreme cases, the deviations from predicted values of OPC were subjected to residual analysis. Residuals are calculated as the difference between the observed value and the value predicted by a linear regression model. If the observations are normally distributed about the regression equation with constant variance, then the residuals should be approximately normally distributed. To check this, histograms of residuals were plotted (figure 10 shows an example). A normal plot of residuals should approximate a bell shape about 0. The standard deviation of the residuals is used as a measure of spread to observe the relative magnitude of any particular residual. If an observation has a residual that is several standard deviations below or above 0, it is an outlier and should be checked. The probability that a deviation in either direction will exceed three standard deviations is close to zero. Therefore, any deviation larger than three standard deviations was assumed to be out of the expected values and the case was listed as an outlier (see Table 11 for an example).

Figure 10 Histogram of Residual

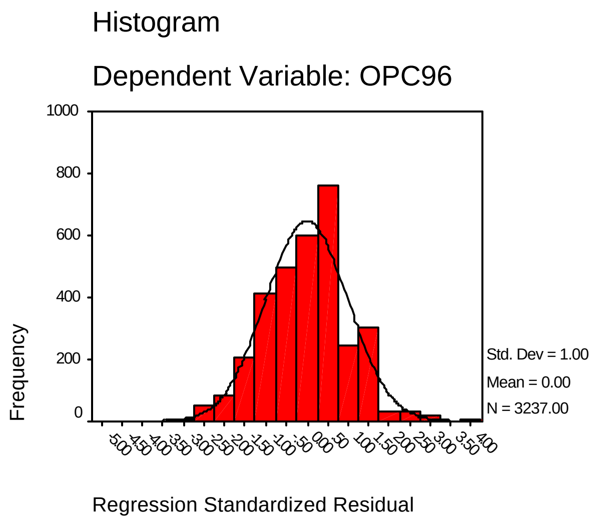


Table 11 Sample Outliers

Casewise Diagnostics[a]

Case Number	Std. Residual	OPC96	Predicted Value	Residual
148	-3.391	1.50	3.3685	-1.8685
1048	-4.844	1.00	3.6690	-2.6690
1163	-3.066	2.10	3.7893	-1.6893
3974	-3.247	2.00	3.7893	-1.7893
6503	3.834	5.00	2.8876	2.1124
6504	3.943	5.00	2.8275	2.1725
6505	3.943	5.00	2.8275	2.1725
6506	3.943	5.00	2.8275	2.1725
6507	3.943	5.00	2.8275	2.1725
6508	3.943	5.00	2.8275	2.1725
7796	-3.247	2.00	3.7893	-1.7893
7797	-3.247	2.00	3.7893	-1.7893
7798	-3.247	2.00	3.7893	-1.7893

a. Dependent Variable: OPC96

Linear Regression Analysis

After errors and outliers were eliminated from the data file, the first method used in developing prediction curves was a linear regression analysis. This method used age as a single independent variable (suggested by DELDOT and ApTech as a first approach) in making the prediction. The data plots in figure 11, 12 and 13 show the data points and the linear model. Linear models for rigid, composite, and flexible models explain only about 17%, 27%, and 19%, respectively, of the variance. For any given age there is a wide range of OPC values. The data plots of the flexible family and the composite family distribute in a visible square shape that contains unexpected relationships of low age with low OPC and high age with high OPC. The slope of the regression lines indicates a slower decrease in OPC with age than would be expected. The flatter slope is expected with data that has such variability. Also the intercepts at Age = 0 indicate an OPC less than 4.0 which does not correspond to the definition of OPC where OPC = 5 for a new road. Therefore, the linear models for the three families were not satisfactory.

Figure 11 Linear Model for Rigid Family

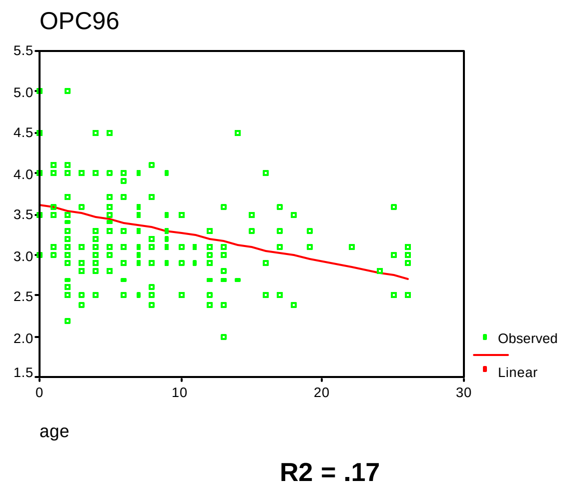


Figure 12 Linear Model for Composite Family

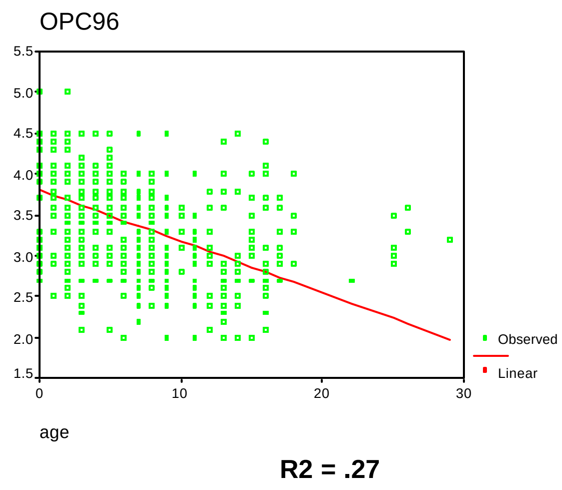
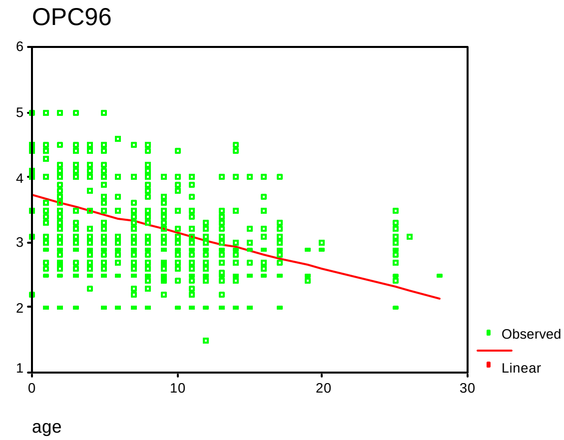


Figure 13 Linear Model for Flexible Family



R2 = .19

<u>Non-linear Regression Analysis</u>

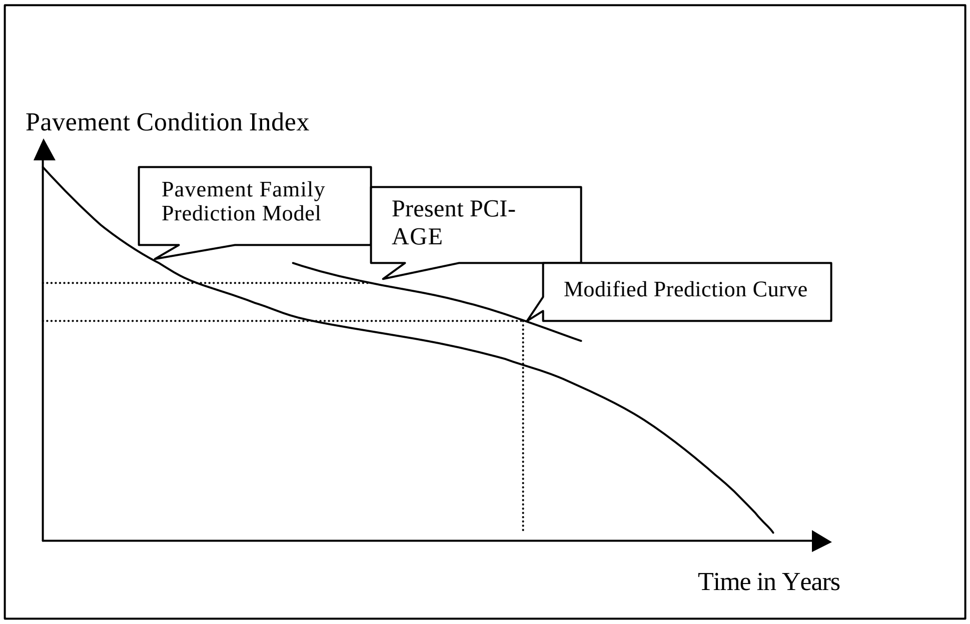
One of the assumptions of pavement performance modeling is that a section of pavement deteriorates with time at different rates during the life of the pavement; therefore, an appropriate model would be a curvilinear relationship between OPC and age. In Nunez and Shahin's study in 1986, a third-order polynomial regression model was successfully developed to predict the pavement condition when a single condition indicator was used. The study concluded that pavement condition forecasting could be accomplished by customizing the prediction for each individual road section depending on its condition in relation to the prediction model curve for the pavement family. A typical performance curve is shown in Figure 14. In this model, to predict the future pavement condition, the model curve is translated to pass through the present PCI-AGE point, which is parallel to the prediction model curve for the pavement family. The PCI can then be determined at the desired future AGE by reading from the adjusted curve. A similar model was used in the DelDOT project with PCI/LAW.

Pavement performance models already developed from other sources revealed that the equations developed as a result of this model take the form of the constrained least-square equation:

$$\text{OPC} = p_0 + p_1 * x + p_2 * x * x + p_3 * x * x * x$$

where x is the age, p_0, p_1, p_2, and p_3 are the coefficients

Figure 14 Pavement Condition Forecasting Model



Two approaches were used to model non-linearity. In the first of these, a cubic function, a curvilinear function having two bends was used to find the best-fit curve. The second approach used a mathematical transformation of the age variable into square and cubic terms such that each of these three variables is linearly related to the dependent variables. The second approach is helpful in finding the intercept and coefficients.

Table12 Statistical Parameters of First-order Linear Prediction Models (South and North districts)

Type of Pavement	Regression Coefficient	R^2
Rigid	P0 = 3.615 P1 = 0.0345	0.17
Composite	P0 = 3.813 P1 = 0.0633	0.27
Flexible	P0 = 3.722 P1 = 0.0564	0.18

Table13 Statistical Parameters of Third-order Polynomial Prediction Models (South and North)

Type of Pavement	Regression Coefficients	R^2
Rigid	P0 = 4.077 P1 = -0.290 P2 = 0.029 P3 = -0.0009	0.30
Composite	P0 = 4.053 P1 = -0.224 P2 = 0.0018 P3 = -0.0005	0.35
Flexible	P0 = 4.013 P1 = -0.211 P2 = 0.018 P3 = -0.0006	0.23

Non-linear models were plotted as shown in figures 15 through 22, to reflect the relationship between OPC and age for the three families in the North Districts, South Districts and the pooled data combining the North and the South. Comparing third-order polynomial models with first-order linear models as shown in Table 12 and Table 13, the prediction models of third-order polynomial fit better than linear models in terms of intercepts, slope and R^2 values. For all three families, nonlinear models explain significantly more variance than do linear models. Nonlinear models also show a varying rate of deterioration along the life of the pavements with a negative slope as the start, a positive slope next, and larger negative slope in the end. However, the nonlinear models still have difficulties in reflecting the expected degradation of the road surface, compared with theoretical models. The intercepts for the three families were all around an OPC of 4. At age = 0, when a road is new or newly rehabilitated, an OPC of at least 4.5 is expected. Also the slopes prove to be very flat with OPC values fluctuating around 2 to 4.

It is obvious in looking at the figures that these models perform poorly in modeling the performance of the roads. There are features in the data that limit the types of models that can be generated and the degree to which the physical realities will be reflected. Most notably are portions of the curve at about the 10-year range that would indicate improving road condition with age as the slope of the curve becomes positive. One explanation of the problem might be that by the time most roads reach this age they have reached a condition that warrants rehabilitation. The data points that are left are those roads that for some reason are in better condition at higher age, therefore distorting any models generated from the data. There is a general problem at higher age values of a lack of data, and a lack of representative data. There is also a problem of a low number of high values for OPC (4.5 to 5) for low age, forcing a low intercept.

Another factor affecting the fitness of the model is the scale of OPC. The use of the 0-to-5 scale, in addition to the fact that the evaluation of OPC is subjective, restricts the raters' ability to provide a comprehensive and accurate reflection of the real road condition. The range of OPC as reflected in the data is really from 2.0 to 5.0. With such a small range, high variability, and obvious problems with the data particularly for the high age portions, the ability to formulate realistic models is impossible.

Figure 15 Rigid Families in the North District

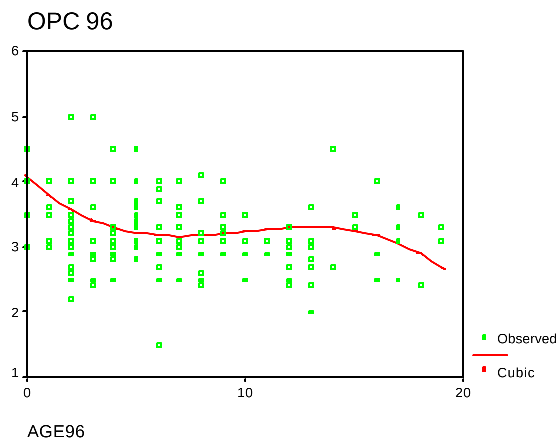


Figure 16 Composite Families in the North District

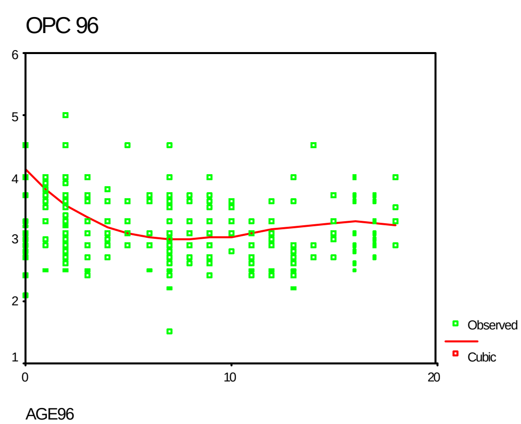


Figure 17 Flexible Families in the North District

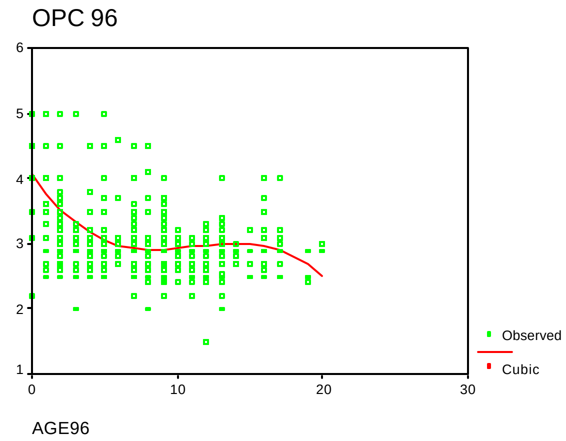


Figure 18 Composite Families in the South District

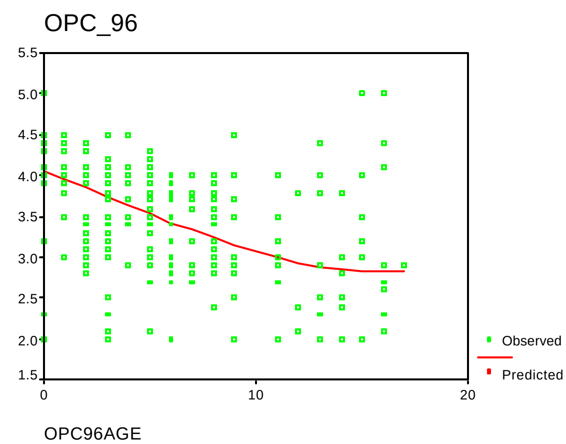


Figure 19 Flexible Families in the South District

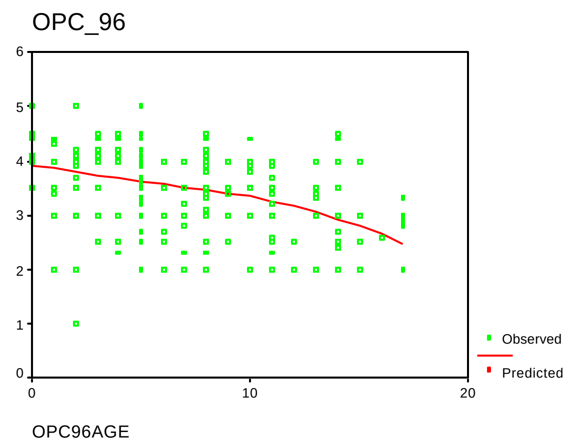


Figure 20 Rigid Families in pooled data

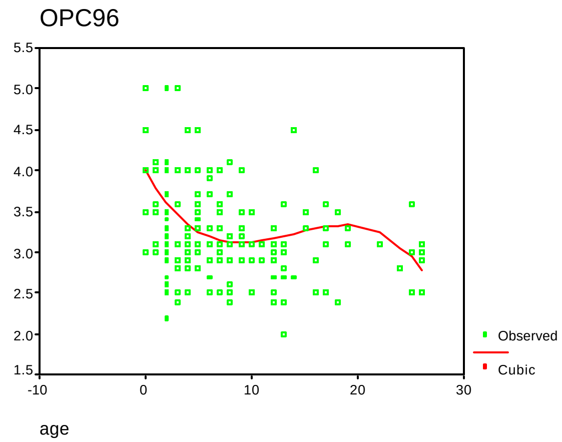


Figure 21 Composite families in pooled data

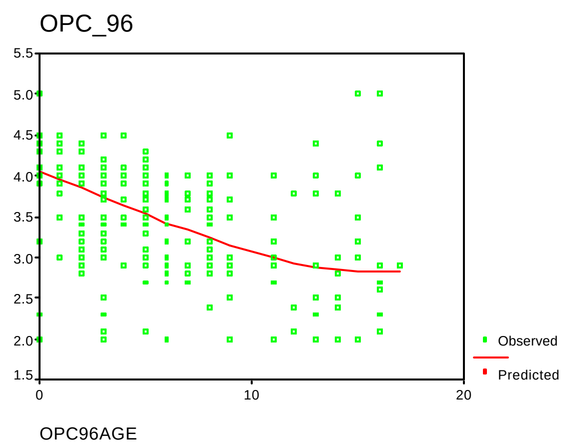
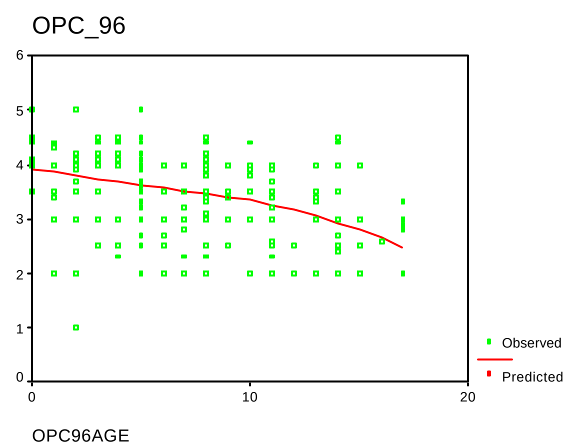


Figure 22 Flexible families in pooled data



Inclusion of Structure Number

Structure number was included in the linear models of OPC and age. Roads were viewed in the three families; Rigid, Composite, and Flexible. Linear models for the three pavement types addressed were determined to be:

Rigid

$$OPC = 2.124 + .159 * S - .015 * A$$

Composite

$$OPC = 3.99 - .04 * S - .075 * A$$

Flexible

$$OPC = 3.77 + .094 * S - .066 * A$$

Where S = structure number, A = age

Differences were evident between the three pavement families. With rigid pavements the age variable is weak with structure strong. For composite pavements structure is weak and the age effect much stronger. Composite and flexible pavements are similar for aging but very different with respect to structure. While the models showed significant effects of both age and structure number, this method was believed to be inappropriate because: (1) The equations reflect that thicker pavements are in better condition than thin pavements, even at an age of zero. This contradicts with the principle that the highest rating (in this case a 5) reflects the condition of a pavement in its initial construction state. (2) Since the structural number does not change over time unless rehabilitation is applied, the model is only reflecting the deterioration of the OPC due to age, while restricting the highest possible OPC for a pavement at age zero based on its structure number.

In order to test the effects of structure number, the model was then revised to take the structure number out of the equation and instead, use it to further divide the pavement family. Pavements were grouped by surface type, and these families were further divided into categories based on structure numbers with at least two categories defined to represent strong/weak or thick/thin pavements. Data from the North District did not include structure number, so only the South District data was examined in this manner.

A cross tabulation of structure number with pavement type (See Appendix D) indicates the correlation of structure number with the three surface type families. Because the road sections clustered around several structural numbers, each of which has a number of observations less than 50, the production of any reasonable model classified by different groups of structure numbers was not possible. It was recognizable, however, that a structure number of 6.4 is a dividing line between the composite family and flexible family. Anything below 6.4 in the composite family was treated as outliers and thus was not included in the modeling.

In order to test the hypothesis that family categorization by structure number contributes to different models and thereby should be individually treated based on family, two dummy variables were created in a third-order polynomial regression model shown below:

Table 14 Dummy Variables for Family Classification

	S_1	S_2
Flexible (sn=0~6.4)	1	0
Composite (sn=6.4~10.2)	0	1
Composite (sn=10.2~20.6)	0	0

In the model, the base group for comparison was the one where $S_1 = 0$ and $S_2 = 0$, that is, structure number falls in the category 10.6 ~ 20.6. S_1 group represents flexible, and S_2 group represents composite with structure numbers from 6.4 to 10.2.

The data tested was from the South District with OPC98 as the dependent variable. OPC98 was believed to be the most reliable reflector of the road conditions in the three indices. The following is the statistics summary.

Table 15 Model Summary of Family Testing

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.527[a]	.278	.275	.5900013

a. Predictors: (Constant), S2XC, S1XC, S2, OPC98AGE, S1, S2X, S1X, AGE98S, AGE98C, S1XS, S2XS

Table 16 Coefficients of Family Testing

Coefficients [a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	4.415	.110		40.206	.000
	OPC98AGE	-.226	.053	-1.614	-4.241	.000
	AGE98S	1.46E-02	.007	2.167	2.100	.036
	AGE98C	-4.4E-04	.000	-1.549	-1.778	.076
	S1	-.376	.124	-.271	-3.021	.003
	S2	3.85E-02	.121	.027	.318	.750
	S1X	.153	.057	1.101	2.689	.007
	S1XS	-1.4E-02	.007	-1.602	-2.012	.044
	S1XC	4.61E-04	.000	1.029	1.822	.069
	S2X	-1.2E-02	.056	-.087	-.221	.825
	S2XS	-5.5E-04	.007	-.066	-.077	.938
	S2XC	1.75E-04	.000	.492	.694	.488

a. Dependent Variable: OPC_98

The final equation from the above model was:

$$Y = 4.415 - 0.226x + 0.014x_2 - 0.004x_3 - 0.376S_1 + 0.153S_1x - 0.014S_1x_2 + 0.0005S_1x_3 + 0.038S_2 - 0.012S_2x - 0.0005S_2x_2 + 0.0002S_2x_3$$

Where Y represents OPC, x is age.

Note that in the Table 17, all the t statistics of coefficients in the S_2 group (composite family with structure numbers from 6.4 to 10.2) are not significant and those of S_1 group (flexible family) are significant. It signifies that the inclusion of flexible family into a composite-based model **does** make a difference.

The next step was to test if division of structure number within one family makes a difference. In order to do that, a dummy variable, c was created. When c = 0, it represents thin pavements whose structure numbers are from 6.4 to 10.2; when c = 1, it represents thick pavements whose structure numbers are from 10.2 to 14. Remember structure numbers greater than 6.4 are considered as composite family.

The modeled equation with dependent variable OPC98 is:

$$OPC98 = 4.436 - 0.230*age + 0.014*age^2 - 0.0003*age^3 + 0.079*c + 0.024*c*age - 0.009*c*age^2 + 0.0003*c*age^3$$

Major statistics summary was also generated:

Table 17 Model Summary of Structure Number Testing

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.664[a]	.441	.438	.5004864

a. Predictors: (Constant), CXC, OPC98AGE, C, AGE98C, CX, AGE98S, CXS

b. Dependent Variable: OPC_98

Table 18 Analysis of Variance of Structure Number Testing

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	280.714	7	40.102	160.096	.000[a]
	Residual	356.443	1423	.250		
	Total	637.157	1430			

a. Predictors: (Constant), CXC, OPC98AGE, C, AGE98C, CX, AGE98S, CXS

b. Dependent Variable: OPC_98

Table 19 Coefficients of Structure Number Testing

Coefficients[a]

Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.
1	(Constant)	4.436	.054		81.901	.000
	OPC98AGE	-.230	.023	-1.691	-9.896	.000
	AGE98S	1.43E-02	.003	1.908	5.324	.000
	AGE98C	-3.2E-04	.000	-.747	-3.534	.000
	C	7.89E-02	.088	.055	.900	.368
	CX	2.38E-02	.043	.133	.550	.583
	CXS	-9.1E-03	.006	-.666	-1.587	.113
	CXC	3.12E-04	.000	.359	1.496	.135

a. Dependent Variable: OPC_98

Note that the t statistics of variables c, cx, cxs and cxc are not significant. This means that our breakdown of structure number into thin pavements and thick pavements does not make a statistical difference. An identical investigation into flexible family, as shown below, discovers that by dividing the family into two separate groups, 0.5~1.5 and 1.5~6, the t statistics of those independent variables relating to the dummy variable B, which is composed of the classification of the two groups, are also not significant (the significant levels are larger than .05).

Table 20 Coefficients Statistics of Flexible Family

Coefficients [a]

Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.
1	(Constant)	4.211	.102		41.209	.000
	OPC98AGE	-.172	.048	-1.072	-3.595	.000
	AGE98S	1.23E-02	.006	1.380	2.009	.045
	AGE98C	-3.9E-04	.000	-.733	-1.756	.079
	B	.199	.186	.137	1.072	.284
	BX	-5.8E-02	.081	-.345	-.719	.472
	BXS	9.33E-03	.010	.701	.925	.355
	BXC	-4.0E-04	.000	-.451	-1.114	.266

a. Dependent Variable: OPC_98

Within one district, the families divided by surface types seem to show statistical difference between each other, whereas the effects of further division by structure number within individual families are minimized. Therefore, the deterioration pattern seems to be affected by contributions of different material types. The results of this analysis indicated that grouping roads by ranges of structure number (generally thick and thin pavements) offered no statistical significant improvement in models.

Improvements on Pavement Management Databases

The availability of a reliable pavement management database is the foundation of any pavement management system and any attempts at performance modeling. Throughout the project, the DELDOT Pavement Management Team worked to put together pavement history data on age and structure of roads through a detailed and often difficult review of hard copy project files in DELDOT archives. For the first time, a pavement history database was developed for all roads maintained by DELDOT for all counties. The data includes original construction information, materials, dates and details of follow-on rehabilitation. A number of corrections and refinements to the data were made during the course of the project. The DELDOT Pavement Management Team has been active in department wide efforts to better coordinate and improves data collection efforts.

Previous pavement management initiatives at DelDOT in the early 1990's suffered for a lack of data. Also, while previous computer software was well grounded in current theory, DELDOT personnel had difficulty in updating and working with road databases. Since then a number of personal computer based tools for managing data have become available such as Microsoft Access and Microsoft Excel. DELDOT Pavement Management personnel feel comfortable working with such tools and are enthusiastic about having more capabilities of constructing and analyzing their data. With some assistance from CADSR, they initiated the creation of a Microsoft Access application to capture information from their rehabilitation projects.

Part III, Section Three, Summary of Findings

The work done by the Center for Applied Demography and Survey (CADSR), through the Delaware Transportation Institute, in support of DELDOT's 1997 Pavement Management System (PMS) Enhancements was focused on the following tasks.

- A review of current practices in pavement management systems.
- A review of data needed for PMS and availability of data at DELDOT.
- Evaluating the current OPC and how it relates to road degradation through the life of the roads.
- Assistance in examining how the current OPC could be used in the construction of road performance models.

What follows is a summary of findings related to these tasks.

A review of current practices

A number of the State initiatives have demonstrated the success and importance to pavement management of providing information on the current and future state of pavement conditions, and systematic procedures for evaluating rehabilitation options while taking into account as much as possible the relative economic advantages and disadvantages. PMS assists with the technical problems of choosing optimal times, places, and techniques for repairing pavements and simultaneously, providing those in charge of maintaining and improving roads with the data and other technical justifications needed to secure political support for adequate road maintenance. These agencies employed different methods to improve the way they manage their pavements, but they all experienced a similar outcome. Because of their pavement conditions surveys and data analysis schemes, they were able to produce better-maintained pavements from available resources and ensure more effective technical input into the political decision-making process.

Perhaps the most relevant research toward defining the components of a pavement management system was conducted by OECD (Organization of Economic and Cooperative Development) Expert Group that suggests that the pavement maintenance procedure consists of four steps.

- Data collection
- Models/analysis
- Criteria /optimization
- Consequences/implementation

AASHTO guidelines suggest seven conditions necessary for the development, implementation, and operation of a PMS.

- Strong commitment from top management and coordination throughout the department.
- A steering committee that exclusively deals with organizational and political problems.
- PMS Staff including one person should be the lead PMS engineer with full time responsibility for managing, coordinating, and operating the PMS.
- System selection or development including good data, good analysis, and effective communications.
- Demonstration of PMS on a limited scale.
- Full-scale implementation – The pavement management team established earlier is very important to successful implementation.
- Periodical review and feedback.

In regards to the development of pavement performance models, promising work by Nunez and Shahin in 1986 provides an example and demonstration of the application of a third-order polynomial regression model to predict the pavement condition. The suggested model relates well to what is known about the pattern of degradation of roadways, and the study suggested methods of adapting a network level model to the prediction of a particular road's performance.

<u>A review of data needed for PMS and its availability</u>

The literature suggests the following types of data to be used as predictors for pavement management systems:

- Pavement condition measures
- Surface distress measures
- Period during which the pavement has been in service (age, time since last rehabilitation)

- Traffic volume and weight, expressed in terms of yearly equivalent single-axle loads
- Thickness of last overlay, in inches
- Surface deflection
- Construction quality
- Climate factors such as temperature and precipitation
- Pavement Material Type(s) and thickness of layers
- Drainage

DELDOT is in the process of constructing a pavement history database for all State maintained roads in Delaware. The data includes the pavement age or last date of rehabilitation, OPC measures, and the material type(s) and thickness(s) that make up each road. DELDOT Pavement Management Team made considerable efforts over the last year to compile this information from hard copy as-built records and contracts in DELDOT archives. They have initiated procedures and built computer-based tools to maintain the data. Accurate and current data are crucial to any type of multi-year prioritization of pavement projects and these efforts have yielded considerable progress over past efforts. Efforts should also be made to include traffic volume and traffic weight (ESALs) in the database. As the database is continually refined and maintained, its value will increase in its ability to support a better understanding of the current and future condition of roads. Eventually given improved pavement condition data a history of individual road performance over several years will be available. At this point, overall pavement condition ratings are only available for 1996, 1997, and 1998.

It is recommended that the data go through continual review and quality control with particular emphasis on understanding why many roads have low OPC values with low age, and why there numerous roads that have high OPC values with high age (greater than 10 to 15 years).

Evaluating the current OPC and how it relates to age

The following points summarize the evaluation of the OPC rating used at DelDOT and its relationship to age.

- OPC is a subjective measure for the upper end of the five-point scale and for this portion of the scale is based on examining the extent of four surface distresses.
- Roads that are within 5 years of needed rehabilitation are assigned OPC values by referencing

a fixed table for each pavement type. OPC then is constrained to a fixed relationship with age and directly related with a subjective estimate of remaining life.

- OPC results from two very different subjective rating methods.
- OPC values generally are assigned to half points of the scale, i.e. 2.5, 3.0, 3.5, 4.0, 4.5, indicating that OPC is not a true continuous variable and takes on a limited set of values owing to the raters difficulty in quantifying in more detail the overall condition of roads.
- Plots of OPC versus age show trends of decreasing OPC with increasing age but there does not appear to be a systematic relationship that would be indicated by what is known about the degradation of pavements. In an examination of OPC as it relates to the time a road was last rehabilitated (age), there exists great variability in the values of OPC at a given age. Values of OPC less that three are common even after a few years since rehabilitation. OPC values of 5 are found even after 10 years of pavement life. These "low age - low OPC" and "high age - high OPC" data points would seem to signal problems with the data, and at a minimum suggest the need for a closer look at the data to find an explanation.
- Statistical analysis indicates a significant difference in the OPC measures for 1996, 1997, and 1998. The 1998 survey has the best fit with 3rd order polynomial models using age as the independent variable. This would support the DelDOT Pavement Management Team's statement that each year OPC ratings were more reliable and were subject to more quality control.
- OPC is correlated with measures taken by automated means for individual surface distress measurements that included transverse cracking, fatigue cracking, the International Roughness Index (IRI) and Ride Number. As OPC is an overall condition index, it would be necessary to develop methods to combine individual automated surface distress measurements into an overall surface distress index for the purpose of further examining the validity of the OPC rating. Many of the difficulties in modeling the performance of roads in Delaware are attributable to the lack of an objective measure of pavement condition. CADSR concurs with APTech Inc.'s recommendation that DELDOT determine whether distress information obtained by automated means would be sufficient to develop a new OPC rating that would be objective and more comprehensive.

<u>The development of pavement performance models</u>

Data within the DelDOT Pavement History databases was used to develop performance models. DelDOT OPC rating for the years 1996, 1997, and 1998 provided data for the dependent variable, and age, pavement type, structure number were the factors investigated as independent variables. The analysis can be summarized as follows.

- As the DelDOT Pavement Management team is focused on the network level, and because of the lack of historical data on pavement condition, it is appropriate to develop models for groupings of roads rather than addressing roads individually. The initial attempt at dividing roads into 23 families by pavement type was not effective in that there was minimal data for all but 6 of these families and because of the great variation of OPC for any given age. When roads were grouped into the three families; Flexible, Rigid, and Composite, the modeling was simplified. Statistical analysis indicated that pavement performance models of these three families were significantly different from each other.
- The high variation of OPC for a given age, the limited scale of OPC, the low values of OPC with low age, data gaps, and questionable data at age greater than about 10 years, all contribute to unsatisfactory, inapplicable performance models.
- 3rd order polynomial models are indicated as the most likely form for performance models rather than linear or other forms. Even with polynomial models that would best correspond to the expected pattern of degradation of roadways, the deficiency in the available data and the problems with the subjective measure of OPC result in models that can not be used to support multi-year prioritization of projects or preventive maintenance forecasting.
- Analysis indicated that grouping roads by ranges of structure number offered no statistically significant improvement over grouping by Composite, Flexible, and Rigid types.

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Appendix A

Correlation of OPC with Distress Types (Asphalt Pavements)

Correlations

		OPC98
OPC98	Pearson Correlation	1.000
	Sig. (2-tailed)	.
	N	254
average roughness	Pearson Correlation	-.343
	Sig. (2-tailed)	.000
	N	254
percentage of transverse cracking at low level	Pearson Correlation	.251
	Sig. (2-tailed)	.000
	N	254
percentage of transverse cracking at medium level	Pearson Correlation	.235
	Sig. (2-tailed)	.000
	N	254
percentage of transverse cracking at high level	Pearson Correlation	-.319
	Sig. (2-tailed)	.000
	N	254
percentage of transverse cracking	Pearson Correlation	-.510
	Sig. (2-tailed)	.000
	N	254
percentage of fatigue cracking low	Pearson Correlation	-.061
	Sig. (2-tailed)	.332
	N	254
percentage of fatigue cracking medium	Pearson Correlation	-.112
	Sig. (2-tailed)	.073
	N	254
percentage of fatigue cracking high	Pearson Correlation	-.401
	Sig. (2-tailed)	.000
	N	254
percentage of fatigue cracking	Pearson Correlation	-.361
	Sig. (2-tailed)	.000
	N	254

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

Source: Center for Applied Demography and Survey Research

Appendix B

OPC Rating Guides

OPC SCORE

(Based on Remaining Life)

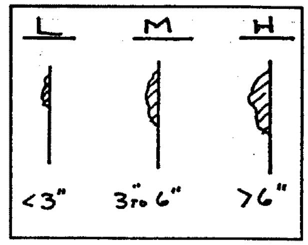
Pavement Type	0 yrs	1 yr	2 yrs	3 yrs	4 yrs	5 yrs
Asphalt Concrete	2.5	2.6	2.7	2.9	3.0	3.1
Composite	2.5	2.7	2.9	3.1	3.3	3.6
Concrete	2.5	2.6	2.7	2.8	2.9	3.0
Surface Treated	2.5	2.9	3.3	3.7	4.1	4.5

Source: Deleaware Department of Transportation

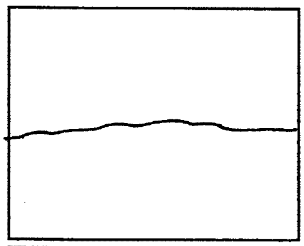
"Cheat Sheet for Concrete Pavements"

Joint Deterioration:

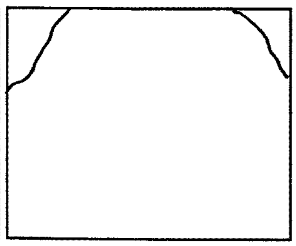
Low:	Spalls less than 3 inches wide
Medium:	Spalls from 3 to 6 inches wide
High:	Spalls greater than 6 inches wide



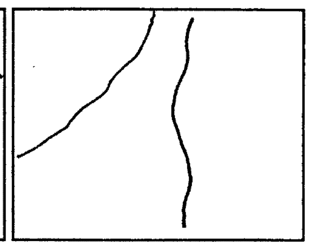
Cracks at Mid-Slab:



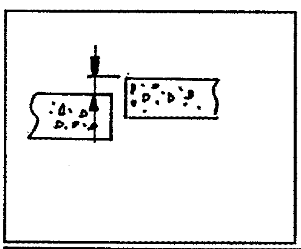
Corner Breaks:



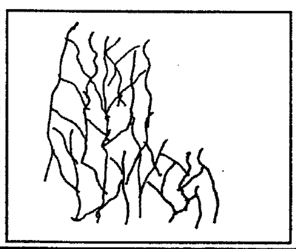
Slab Cracks:



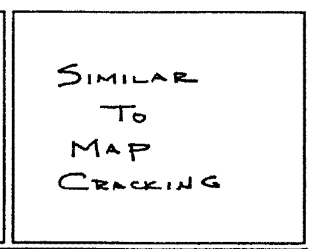
Faulting:



Map Cracking:



ASR:



Remaining Life	0 yrs	1 yr	2 yrs	3 yrs	4 yrs	5 yrs
OPC SCORE	2.5	2.6	2.7	2.8	2.9	3.0

Source: Delaware Department of Transportation

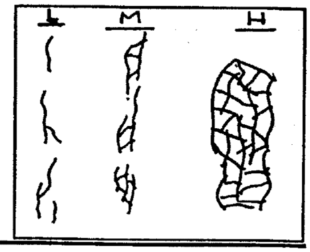
"Cheat Sheet for Asphalt Concrete Pavements"

Fatigue Cracking:

Low: Single Crack with few or no connecting cracks; Little or no spalling; no pumping

Medium: Interconnected cracks forming a pattern; may have slight spalling; no pumping

High: Interconnected cracks forming a complete pattern; moderate to severe spalling; possible pumping, potholes, and/or depressions

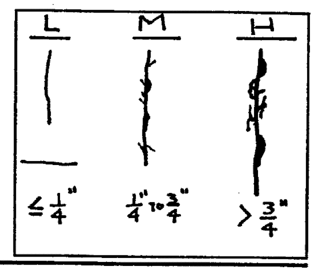


Environ. Cracking:

Low: Single Cracks ≤ 1/4 inch wide with little or no spalling ; Sealed cracks in good shape

Medium: Cracks between 1/4 and 3/4 inches wide: moderate spalling; Adjacent low severity random cracks; Sealed cracks in bad shape

High: Cracks greater 3/4 inches wide: severe spalling; Adjacent medium to high severity random cracks;

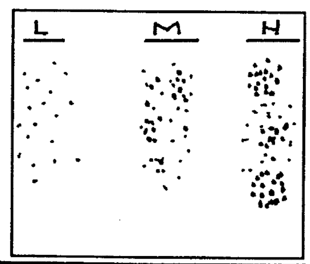


Surface Defects:

Low: Aggregate and binder has begun to wear away but has not progressed significantly. Some loss of fine aggregate.

Medium: Aggregate and binder worn away and surface is rough and pitted. Loss of fine agg. and some coarse agg.

High: Surface texture is very rough and pitted; loss of coarse aggregate; looks like concrete scaling.

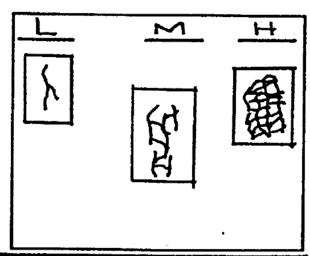


Patches:

Low: At most, low severity distress of any type.

Medium: At most, medium severity distress of any type.

High: Has high severity distress of any type.



Remaing Life	0 yrs	1 yr	2 yrs	3 yrs	4 yrs	5 yrs
OPC SCORE	2.5	2.6	2.7	2.9	3.0	3.1

Source: Delaware Department of Transportation

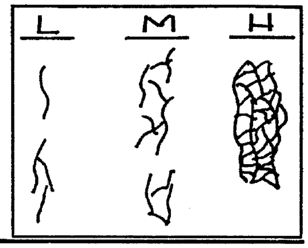
"Cheat Sheet for Composite Pavements"

Fatigue Cracking:

Low: Single Crack with few or no connecting cracks; Little or no spalling; no pumping

Medium: Interconnected cracks forming a pattern; may have slight spalling; no pumping

High: Interconnected cracks forming a complete pattern; moderate to severe spalling; possible pumping, potholes, and/or depressions

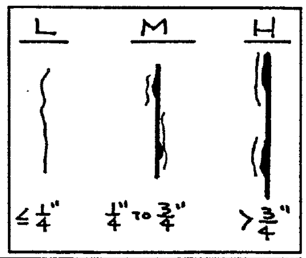


Jt. Reflection Cracking:

Low: Single Cracks ≤ 1/4 inch wide with little or no spalling ; Sealed cracks in good shape

Medium: Cracks between 1/4 and 3/4 inches wide: moderate spalling; Adjacent low severity random cracks; Sealed cracks in bad shape

High: Cracks greater 3/4 inches wide: severe spalling; Adjacent medium to high severity random cracks;

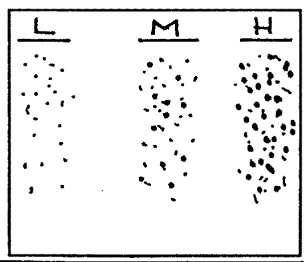


Surface Defects:

Low: Aggregate and binder has begun to wear away but has not progressed significantly. Some loss of fine aggregate.

Medium: Aggregate and binder worn away and surface is rough and pitted. Loss of fine agg. and some coarse agg.

High: Surface texture is very rough and pitted; loss of coarse aggregate; looks like concrete scaling.

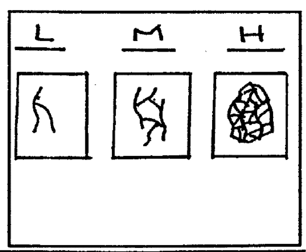


Patches:

Low: At most, low severity distress of any type.

Medium: At most, medium severity distress of any type.

High: Has high severity distress of any type.



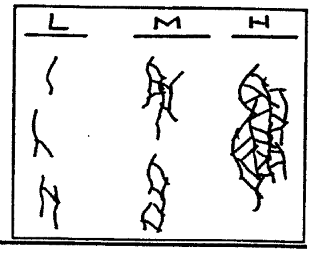
Remaing Life	0 yrs	1 yr	2 yrs	3 yrs	4 yrs	5 yrs
OPC SCORE	2.5	2.7	2.9	3.1	3.3	3.5

Source: Delaware Department of Transportation

"Cheat Sheet for Surface Treated Roads"

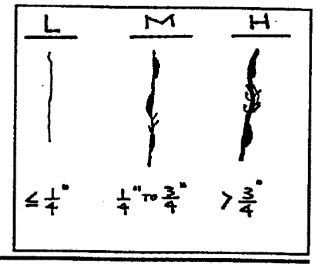
Fatigue Cracking:

Low:	Single Crack with few or no connecting cracks; Little or no spalling; no pumping
Medium:	Interconnected cracks forming a pattern; may have slight spalling; no pumping
High:	Interconnected cracks forming a complete pattern; moderate to severe spalling; possible pumping, potholes, and/or depressions



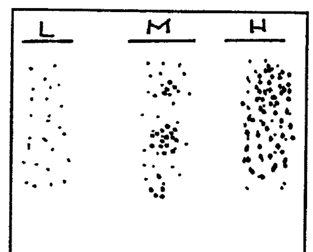
Environmental Cracking:

Low:	Single Cracks ≤ 1/4 inch wide with little or no spalling ; Sealed cracks in good shape
Medium:	Cracks between 1/4 and 3/4 inches wide: moderate spalling; Adjacent low severity random cracks; Sealed cracks in bad shape
High:	Cracks greater 3/4 inches wide: severe spalling; Adjacent medium to high severity random cracks;



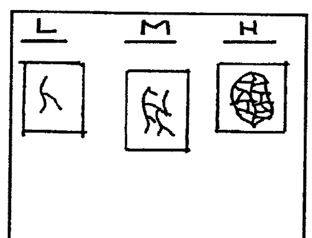
Surface Defects:

Low:	Aggregate and binder has begun to wear away but has not progressed significantly. Some loss of fine aggregate.
Medium:	Aggregate and binder worn away and surface is rough and pitted. Loss of fine agg. and some coarse agg.
High:	Surface texture is very rough and pitted; loss of coarse aggregate; looks like concrete scaling.



Patches:

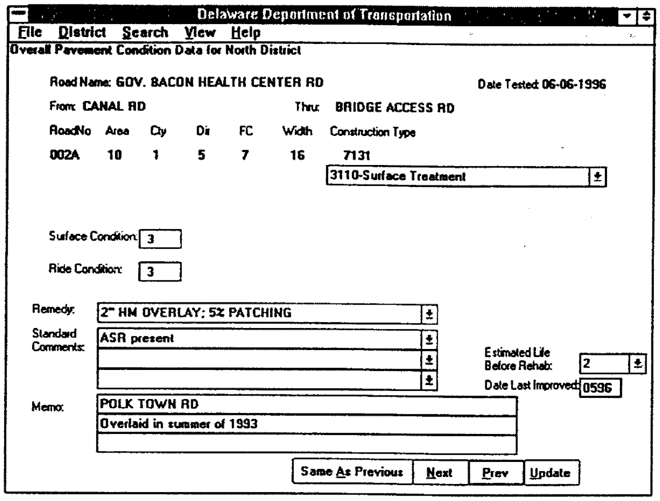
Low:	At most, low severity distress of any type.
Medium:	At most, medium severity distress of any type.
High:	Has high severity distress of any type.



Remaing Life	0 yrs	1 yr	2 yrs	3 yrs	4 yrs	5 yrs
OPC SCORE	2.5	2.9	3.3	3.7	4.1	4.5

Source: Delaware Department of Transportation

LOCAL SCREEN



STEP 1. Change Construction Type, if necessary, by using the list box.

STEP 2. Click on **Same As Previous** button. NOTE: If the current road segment and the previous road segment use the same Data Entry screen (i.e., if they are both local segments), entries from the previous data screen are copied to the current screen. If not, you receive the message **Local and Nonlocal Segments Cannot Share Values.**

OR

Enter a numerical rating for the Surface Condition.

STEP 3. Enter a numerical rating for the Ride Condition.

STEP 4. Enter the Estimated Life Before Rehab in years (i.e., 0 to >5).

STEP 5. Select a Remedy using the list box.

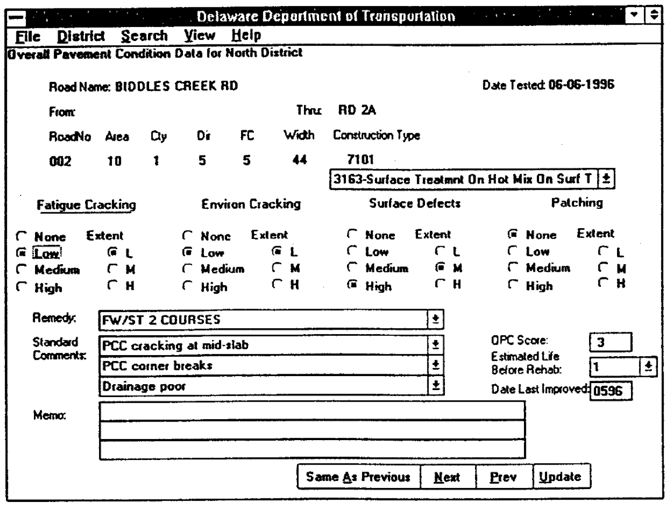
STEP 6. Select up to three Standard Comments using the list boxes, if desired.

STEP 7. Enter text in the Memo field if desired.

STEP 8. Press **UPDATE** to save entries. Data Entry screen for next road segment appears.

Source: Delaware Department of Transportation

NONLOCAL SCREEN



STEP 1. Change Construction Type, if necessary, by using the list box.

STEP 2. Click on **Same As Previous** button. NOTE: If the current and previous road segments use the same Data Entry screen (i.e., if they are of the same pavement type), entries from the previous data screen are copied to the current screen. If not, you receive the message **Pavement Types Different, Same As Previous Canceled.**

OR

Rate the road conditions presented in dialog boxes using the radio buttons. You can tell which dialog box is active by the underscore of the name of the dialog box. Use the arrow keys to move between buttons; the <**TAB**> key to move between boxes. NOTE: If you use a rating other than **NONE**, you must select an Extent rating as well.

STEP 3. Enter the OPC Score.

STEP 4. Enter the Estimated Life Before Rehab in years (i.e., 0 to >5).

STEP 5. Select a Remedy using the list box.

STEP 6. Select up to three Standard Comments using the list boxes, if desired.

STEP 7. Enter text in the Memo field, if desired.

STEP 8. Press **UPDATE** to save entries. If the screen is complete, the Data Entry screen for next road segment appears. If not, you receive an error message, e.g., **OPC Score Missing** or **Not All Ratings Have Been Chosen**.

Source: Delaware Department of Transportation

Appendix C

Correlation of Pavement Family with Surface Type

Correlation of Family with Surface Type

surface type * family classfication Crosstabulation

Count

		family classfication					
		rigid	composite	flexible	surface treatment	unimproved	unconventional
surface type	graded and drained/unimproved					3	
	soil surface graded and drained/unimproved					128	
	surface treatment				1555		
	surface treatment on hot mix on surface /unconventional						22
	surface treatment on hot mix on soil cement bas/unconvention						10
	surface treatment on soil cement				46		
	low type bituminous/ surface treatment				9		
	hot mix on soil surface/flexible			226			
	hot mix on waterbound base of stone/flexible			719			
	hot mix on surface treatment/flexible			1662			
	hot mix on low type bituminous or sand asphalt/flexible			392			
	hot mix on soil cement base/flexible			42			
	hot mix on concrete/composite		3418				
	hot mix on brick			122			
	unknown	1194					
	surface treatment on concrete/unconventional						4
	how mix on surface treatment/flexible			10			
	concrete alongside surface treatment/surface treatment				5		
	concrete alongside hot mix/flexible			2			
Total		1194	3418	3175	1615	131	36

APPENDIX D

Crosstabulation of Structure Number and Pavement Type

Crosstabulation of Structure Number and Pavement Type

STRUCTUR * 1= rigid, 2= composite, 3= flexible Crosstabulation

Count

		1= rigid, 2= composite, 3= flexible			Total
		1	2	3	
STRUCTUR	.00000	1		30	31
	.32000			3	3
	.40000			1	1
	.60000			16	16
	.66000			2	2
	.80000		10	256	266
	.90000			10	10
	1.00000			12	12
	1.06000			1	1
	1.20000		18	566	584
	1.26000			7	7
	1.30000			3	3
	1.40000			5	5
	1.46000		9	15	24
	1.48000			4	4
	1.60000			95	95
	1.80000			1	1
	1.86000			12	12
	1.90000			3	3
	2.00000		5	32	37
	2.02000			1	1
	2.04000			13	13
	2.10000			9	9
	2.26000			9	9
	2.40000		1	36	37
	2.44000			5	5
	2.48000			14	14
	2.56000			7	7
	2.62000			8	8
	2.66000			18	18
	2.80000			21	21
	2.84000			4	4
	3.04000			1	1
	3.06000			6	6
	3.20000			6	6
	3.24000			4	4
	3.52000			35	35
	3.60000			1	1

	3.68000		8		8
	3.76000			10	10
	3.92000			13	13
	4.00000			13	13
	4.08000			9	9
	4.24000			32	32
	4.32000			4	4
	4.44000			12	12
	4.56000			1	1
	4.64000			10	10
	4.88000			7	7
	5.12000			14	14
	5.20000		1		1
	5.64000			2	2
	5.68000			29	29
	5.76000			1	1
	6.40000			8	8
	6.80000		1		1
	7.00000		7		7
	7.20000		17		17
	7.60000		4		4
	7.80000	15	48		63
	8.00000	8	26		34
	8.20000		114		114
	8.22000		8		8
	8.40000		64		64
	8.60000		22		22
	8.80000		55		55
	9.00000	27	127		154
	9.20000		145		145
	9.40000		216		216
	9.42000		1		1
	9.60000		37		37
	9.80000	36	40		76
	10.00000		55		55
	10.20000		154		154
	10.22000		5		5
	10.40000		36		36
	10.52000		5		5
	10.60000		85		85
	10.80000		19		19
	11.00000		6		6
	11.12000	15			15
	11.20000		8		8
	11.40000		69		69
	11.60000		47		47
	11.80000		1		1
	12.00000		8		8
	12.20000		4		4

	12.90000		1		1
	13.20000		10		10
	13.80000		25		25
	17.60000		3		3
	20.60000		6		6
Total		102	1531	1437	3070