DEVELOPING PAVEMENT PERFORMANCE PREDICTION MODELS AND DECISION TREES FOR THE CITY OF CINCINNATI

Final Report

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Abstract:

This report presents the details of a study conducted to develop pavement performance prediction models and decision trees for various families of pavements, using the data available with the City of Cincinnati. Required data was acquired from the city’s pavement inventory database. The road network was divided into two classifications namely, major roads and minor roads. These roads were further grouped based on their structural makeup. Statistical regression models were developed for each group. A decision tree was developed to suggest appropriate maintenance and rehabilitation activities based on the condition of the pavement. The city engineers can use these models in conjunction with their pavement management system to predict the future condition of the highway network in Cincinnati and to implement cost effective pavement management solutions. Using the methodology developed in this study, the engineers can also further improve the accuracy of the models in the future.
ACKNOWLEDGMENTS

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DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Ohio Department of Transportation or the federal Highway Administration. This report does not constitute a standard, specification or regulation.
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1. INTRODUCTION

1.1 Overview of Pavement Performance Prediction Models and Decision Trees

Pavement performance prediction models are used to predict future pavement conditions of the highway network as part of the agency’s pavement management activities. The models must reflect the best possible representation of the pavement deterioration. Predicting pavement performance is an essential activity of a pavement management system. Within a pavement management system, the prediction models are an important component for a multi-year analysis for the types of activities listed below [1]:

- Estimating the type and timing of maintenance and/or rehabilitation as part of a multi-year improvement program;
- Predicting the length of time until a lower limit of acceptable pavement condition is reached (remaining service life);
- Optimizing the combination of projects, treatment, and timing to achieve agency goals;
- Evaluating the long-term impacts of various program scenarios;
- Providing a feedback loop to the pavement design process; and
- Estimating pavement life-cycle costs.

Deterministic models are one of the most common types of models used for a multi-year pavement management analysis. These models may be either empirical (based on data from in-service pavements) or mechanistic-empirical, calibrated using regression techniques that
statistically develop relationships between two or more variables. Development of deterministic models requires a variety of data on factors that affect the rate of deterioration namely, traffic loads, pavement layer thicknesses, materials, subgrade strength, environmental factors, and construction techniques.

One of the primary uses of pavement performance prediction models is in the selection of an appropriate Maintenance and Rehabilitation (M&R) treatment. Selecting an optimum M&R strategy is often a complex process. Some researchers have suggested a “decision tree” approach. The decision trees have been used primarily to select appropriate repair strategy based on the existing pavement condition. The decision trees assist the pavement engineers to select the most feasible M&R treatment considering roadway information – distress type, severity level and extent of distresses, pavement type, and traffic level. In other words, decision trees will provide directions and rationale for the selection of M&R strategies.

1.2 Cincinnati’s Pavement Management Practices

The City of Cincinnati’s Department of Transportation and Engineering (DOTE) is responsible for the design, operation and maintenance of the City’s street rehabilitation program. The DOTE coordinates with its Division of Engineering to generate quantitative and qualitative data on the City’s street network, including its current and future performances. This information base is used to link technical analysis, decision making and budgetary processes.

The street rehabilitation program includes all the activities involved in the planning and programming, design, construction, maintenance and rehabilitation of street pavements in Cincinnati. The street network has approximately 850 miles (or 2655 lane miles) of pavements. In 1996, the city established a structured pavement management system to aid the management in planning network-level budgets and developing multi-year plans for the network. The system
developed by the Infrastructure Management System (IMS) was operational till 1999 [2]. During this period, the IMS consultants collected a large amount of performance data for the city, which included visual observation of surface distresses, automated roughness and deflection data. An internal review of the system in 2000 indicated that the pavement conditions predicted by the program did not relate to actual conditions observed by the engineers [3]. This may have been due to the use of generic performance evaluation procedures instead of developing specific procedures/models for the conditions that existed in the city of Cincinnati. Further, the program was not capable of performing multi-year prioritization. As a result, the city decided to discontinue the use of the IMS pavement management system and developed a simple condition rating system on a four point scale (excellent, good, fair, and poor), based on visual observations only. This procedure termed Visual Pavement Evaluation and Recording System (ViPERS) [4], however, limited the use of pavement condition data for single year (year-to-year) programming without the ability to do multi-year prioritization. During this period, more often than not, pavements in ‘fair’ and ‘poor’ categories were selected for maintenance and rehabilitation. No consideration was given to using the condition data to predict the probability of moving from one condition to another. No consideration was given to using the condition data to predict the probability of moving from one condition to another. In 2004, the city initiated steps to develop and implement a new pavement management system. After a thorough review of several options, late in 2005, the city decided to adopt Micro PAVER pavement management system.

Micro PAVER was developed by the U.S. Army Corps of Engineers and adopted by the American Public Works Association in 1979 [5]. This is the most widely used software for pavement management among city governments and airport authorities. However, very few State agencies have adopted micro PAVER. Excellent documentation is available on the
developmental and operational aspects of the program. The program is user friendly, versatile and customizable [6].

Among many features, Micro PAVER has built-in algorithms to help the users develop performance prediction models using historic data of pavement condition for group of pavements that exhibit similar attributes. The pavements are first classified into different families based on surface type, construction, and functional type. Fourth degree polynomial constrained least squared regression models can then be developed to predict performance. A typical model is as follows:

\[ PCI = 0.1 \times 10^3 - 0.86 \times 10^1 \times AGE + 0.79 \times AGE^2 - 0.32 \times 10^{-1} \times AGE^3 + 0.43 \times 10^{-3} \times AGE^4 \]

In the above equation, ‘PCI’ is defined as Pavement Condition Index and represents the overall pavement condition on a 0 to 100 scale, obtained as a composite index of surface distresses. The term ‘AGE’ refers to the number of years since construction or last major rehabilitation.

Performance prediction is a key part of pavement management system because it reflects on how well the planning, design, and construction objectives have been satisfied. In other words, performance prediction models developed using historic data from the City’s road network would ensure the appropriateness of the pavement management decisions. In conjunction with their decision to implement a new pavement management system, the city engineers desire to develop pavement performance prediction models using data collected over many years. The primary objectives of this initiative are: (i) to develop and use reliable performance prediction models, instead of using generic algorithm provided in the pavement management software program, and (ii) to explore an opportunity to integrate these models in the new pavement management software.
1.3 Role of Ohio Department of Transportation in the Current Study

The City of Cincinnati is a large metropolitan city in the State of Ohio. The Ohio Department of Transportation (ODOT), through its various programs, works with the local governments to develop and foster transportation infrastructure in Ohio. Three such programs related to the current study are:

• Urban paving program
• Ohio Partnered Research Exploration Program (OPREP)
• Pavement management – local pavement condition rating

1.3.1 Urban Paving Program

According to the Ohio state law, cities in Ohio are required to pave the U.S and state routes within their boundaries. However, this is an expense most cities find it difficult to fund. In response to this issue, in January 2000, the ODOT Urban Paving Program was established to fund and evenly distribute state urban paving funds throughout Ohio [7]. This program sets new standardized policy for paving U.S. and state routes in municipalities and aids in establishing an equitable funding program. In this program, ODOT will provide 80 percent of the paving funds, while the municipalities must provide a 20 percent match. By aiding cities equally, the department can ensure a quality statewide transportation system. Such programs encourage the local governments to develop systematic pavement management programs and policies. Needless to say, a structured pavement management system can assist local governments to develop plans, and better interact with ODOT to present their specific needs.
1.3.2 Ohio Partnered Research Exploration Program (OPREP)

The Ohio Partnered Research Exploration Program is administered through ODOT’s Office of Research and Development [8]. This program helps local agencies leverage research funds and resources. Some of the significant benefits of this program are that, by getting involved in this program, the local agencies can directly interact with the experienced pavement management specialists at ODOT, access ODOT’s resources, and obtain technical and financial support to conduct research that can lead to development and implementation of sound pavement management practices.

1.3.3 Pavement Management- Local Pavement Condition Rating

The Pavement Management Division of ODOT’s Office of Pavement Engineering collects pavement performance data annually on all state owned and maintained pavements. This includes U.S. and state routes in municipalities. In addition, through the ‘Local PCR Program’ the department personnel collect condition data on selected local and secondary systems [9]. This is a unique system that can bring the state and local agencies together and further encourage the local governments in Ohio to collect condition data on the rest of the network, and thereby establish a pavement management system.

In summary, the state and local governments in Ohio have developed programs that can help them better interact and to develop a unified pavement management system throughout the state. The current study has been undertaken jointly by the University of Cincinnati and the City of Cincinnati. ODOT has provided technical and financial support for this project.
2. **PRESENT STUDY: OBJECTIVES AND SCOPE**

The specific objective of the present study is to develop pavement performance prediction models and decision trees for various families of pavements, using data available with City of Cincinnati. The report outlines a concise review of the published literature, the data sources, statistical models and complete description of various tasks performed in this study.

3. **BACKGROUND AND SIGNIFICANCE OF WORK**

A pavement performance model is a mathematical expression that can be used to predict future pavement condition, based on the present pavement condition and a host of factors that contribute to the change in condition. Performance models are indispensable for many processes of decision making as they are useful in establishing answers to questions: ‘what’, ‘where’, and ‘when’ with respect to managing pavements. In other words, the performance models enable the engineers to determine type of treatment required, the portions of network requiring treatment, and the timing of treatments. Used at the network level, pavement forecasting models are helpful in planning, programming, and budgeting. At the project level, forecasting models are used to design pavements, to perform life-cycle cost analyses, to select optimal designs with least total costs, and in trade-off analyses in which the annualized costs of new construction, maintenance, rehabilitation, and user costs are considered for a specific pavement design [10].

Several approaches are employed for their development. They include regression analysis using field performance data, mechanistic modeling based on pavement response parameters, and models that combine both field data and response parameters, which are aptly called mechanistic-empirical models. There are four basic criteria that should be followed to develop reliable performance models at any level within the transportation agency. These include the following items [1, 11, 12]:

i. An adequate database;

ii. The inclusion of all significant variables that affect performance;

iii. An adequate functional form of the model; and

iv. The satisfaction of the statistical criteria concerning the precision of the model.

It is important that the data needed to develop model be available and continue to be updated as changes occur. The data must be representative of the pavements for which the model is being developed. Every possible variable that may affect the performance of pavement should be considered. The functional form of the model, or the way in which the variables are arranged, can only be determined through consideration of the actual relationships between the variables and the trends from the data on plots. Statistics should be used when all forms are considered to adhere to the boundary conditions and other physical principles that govern the variable being modeled are considered. One of the important boundary conditions is Initial Condition Rating. Several studies, including the previous study by ODOT, have reported that, when pavements are rehabilitated, the condition rating of the rehabilitated pavement section is usually in the range of 90 to 98 based on a scale of 0 to 100 [13]. The initial condition rating depends on the type of pavement, type of activity performed and construction techniques. In developing pavement performance models, due consideration must be given to identify the initial condition rating, initial slope, and overall trend of the model.

Because of the large number of variables involved in a regression analysis, performance models are developed by grouping pavements into families that have common characteristics such as surface type, functional classification, traffic levels, and geographic location. The family approach has been used successfully by agencies. This approach is based on the assumption that
each pavement section within a family has a similar deterioration pattern. The pavement performance model developed for the family represents the average deterioration pattern for all sections in that family. When families of pavement sections with similar characteristics are developed, the regression analysis need only analyze pavement condition in terms of age, greatly reducing the number of variables in the regression equation.

Recently, ODOT has initiated a similar research to develop performance prediction models applicable to interstate, U.S. and state routes [14]. The present study complements ODOT’s ongoing study by developing performance models for an urban pavement network.

4. REVIEW OF CINCINNATI’S PAVEMENT CONDITION DATABASES

As outlined earlier, pavement condition data was collected in Cincinnati during two distinct phases – first between 1996 and 1999 by IMS consultants and later by the City between 2000 and 2003. A description of the databases, termed IMS Database [2] and ViPERS Database (Visual Pavement Evaluation Recording System) [4], is provided below:

4.1 IMS Database

The IMS database consists of pavement inventory and condition report for each pavement segment that was surveyed. To begin with, the road network in Cincinnati was divided into four zones. Pavement sections in each zone were divided into homogeneous sections based on several factors including, functional classification and surface type. The required data was collected by the consultants on all pavements in only one zone, each year. Thus, during the four year period, all the pavements in the City were surveyed once. The condition data includes the following:
4.1.1 Deflection Data

Deflection data was collected using Dynaflect. One set of readings was recorded in each homogeneous pavement section. Deflection data was collected using five geophones, spaced at 12 inch intervals. The geophone readings were recorded in milli-inches and were labeled $W_1$ through $W_5$ where $W_1$ is closest to the load. The data was processed to obtain Dynaflect Maximum Deflection ($DMD$), Surface Curvature Index ($SCI$), Bending Curvature Index ($BCI$), and Spreadability ($SP$). These terms are defined below:

- $DMD = W_1$
- $SCI = W_1 - W_2$
- $BCI = W_4 - W_5$
- $\%SP = 100 \times (W_1 + W_2 + W_3 + W_4 + W_5) / (5 \times W_1)$

Using the above parameters, a Dynamic Condition Number (DCN) was calculated for each pavement section. DCN is a composite index of the above four parameters and varies from 10 to 100.

4.1.2 Surface Condition Data

The surface condition data was acquired using a Laser Road Surface Tester (RST). RST is a self-contained automated device for measuring and storing detailed objective data about the pavement surface. The RST consisted of eleven lasers mounted on a vehicle that enabled measurement of surface data. The data collected included rut depth measurements, ride quality in terms of International Roughness Index (IRI), and cracking. This information was combined to form a Surface Condition Number that ranged from 10 to 100.
4.1.3 Pavement Condition Number

Using the processed deflection and surface condition data, along with an environmental factor, an index termed Pavement Condition Number (PCN) was generated. PCN is analogous to ODOT’s Pavement Condition Rating (PCR) number and varied from 10 to 100. Unlike ODOT’s PCR which is derived solely based on subjective evaluation of visual distresses (and varied from 0 to 100), PCN is obtained as a function of many parameters such as deflection, ride quality, surface condition and environmental factor. The development and computational aspects of PCR is well documented in ODOT’s PCR Manual [15]. However, such details are not available with respect to PCN.

4.2 ViPERS Database

The ViPERS data consists of condition data collected on all pavements in the city, each year. The data collection procedure consisted of rating pavements on a 4-point scale as excellent, good, fair, and poor. This system did not include collection and recording additional related to severity and extent of individual distresses although the raters occasionally noted additional comments about the distresses. No attempt was made to convert this rating into a number index. As a result, this database was not used for the development of performance prediction models.

5. MODELING PAVEMENT PERFORMANCE

5.1 Model Variables

Development of pavement performance prediction models requires a careful consideration of dependent and independent variables. The dependent variable is always a pavement condition indicator. The choice of a dependent variable is often made based on the type of data collected and the condition indicator established by the agencies. Some examples of pavement condition indicators include Present Serviceability Index (PSI), Pavement Condition Rating (PCR), pavement
Index (PCI), and International Roughness Index (IRI). In the current study, Pavement Condition Number (PCN), established by the IMS consultants as part of their pavement management system was considered as the dependent variable. PCN is a composite condition index and is obtained as a function of structural, surface and environmental characteristics.

The list of independent variables should always be comprehensive enough and be able to describe the performance of highway sections in all respect. The variables should encompass various categories deemed important in rating highway sections. Generally, a host of factors are considered as independent variables. Typically they include: age of the pavement, traffic, pavement type, functional classification, material type and properties, environmental conditions, and construction and maintenance histories. Many highway agencies have incorporated combinations of these variables depending on their relative importance (as perceived by them) and availability of data. In the present study, a careful review of IMS database was made to select appropriate independent variables.

The IMS database consists of the following group of information for each pavement segment surveyed:

- Location – Zone Number, Street Name, From, To
- Functional Classification – Eight classifications
- Traffic- Average Daily Traffic and truck traffic
- Pavement Type – AC for asphalt surface, PC for Concrete surface
- PCN – Pavement Condition Number as an aggregate index of structural, surface and environmental characteristics.
- PCN Year - Year when PCN was recorded
The pavement sections are predominantly (98%) asphalt surfaced. Reliable traffic data was not available for all segments. However, the functional classification assigned to each segment was recorded.

Age of pavement is a variable of paramount importance. Most performance models have incorporated age either as a sole independent variable or in combination with other independent variables. Age can adequately describe changes in pavement condition with time due to several factors that affect performance of pavements.

In this study, to begin with, two independent variables namely, functional classification and age were considered in the development of performance prediction models. Here, age is defined as the number of years since construction or last major rehabilitation. It was decided to combine all the pavement segments into two families (functional classifications) namely, major and minor roads.

5.2 Data Acquisition

A typical performance model is shown in Figure 1. In this figure, the curve represents a general pattern of deterioration of a group of pavements that exhibit similar characteristics. To develop a model of this type, it is necessary to obtain performance data collected over a number of years on a large number of pavement sections, along with date of construction or last major rehabilitation. However, this information was not recorded in the IMS database. The city engineers then assembled two databases listing construction records, one for major roads and the other minor roads.
The next step was to link the IMS database with the construction database. Pavement location parameters in terms of street name, from and to were used as key variables. However, there were no matching records between the two databases. This was because the limits used for paving did not correspond to the limits used in the IMS database for performance monitoring. As such, there was no common attribute in the two databases and this resulted in a null database. Additional efforts made using city’s GIS (Geographic Information System) database and later by manually reconciling the limits did not prove successful either.

Subsequently, another database maintained by the city for the urban paving list was made available for major roads. This database consisted of pavement condition data collected by ODOT
along with the construction history required to establish the age of pavement sections, for 100 pavement sections. In this database, the condition rating system used was ODOT’s PCR (Pavement Condition Rating). Since the urban paving list database consisted of all the required information and sufficient number of records, it was decided to use this database to develop performance models for major roads.

At this juncture, the researchers reviewed ODOT’s database for Hamilton County, collected through the local pavement management program. The information contained in this database for minor roads was, however, insufficient for performance modeling. Unlike the urban paving program, ODOT’s local program is very limited in scope. ODOT surveys a small percent of minor road network, limiting the evaluation to the roads in the vicinity of major roads.

City’s database of construction history for minor roads consisted of 3000 records for all the secondary roads in the city. When this file was joined with the IMS database, adequate information to develop models, including pavement condition (PCN) and age of pavement sections was available for 409 records.

Thus two different databases became available, one for major roads and the other for minor roads. These databases offered two different condition rating indicators namely PCR and PCN. PCR is derived using visual observation of surfaces distresses and ranges from 0 to 100. PCN, on the other hand, is derived as a function of deflection, surface profile and environmental characteristics, on a 10 to 100 scale. Following a series of meeting with the city engineers, a decision was made to proceed with the development of performance models using the available data.
5.3 Data Validation

The data contained in the two databases for major and minor roads was subjected to validation. Data validation is defined as inspection of all the collected data for completeness and reasonableness, and elimination of erroneous values. This step transforms raw data into validated data. The validated data are then processed to develop models. Typically, validation is done by performing a range of tests, or by manually reconciling suspect values.

There are essentially two parts of data validation – data screening and data verification. Data screening uses a series of validation routines to screen all the data for suspect (questionable and erroneous) values. Data verification requires a case-by-case decision on what to do with the suspect values – retain them as valid, reject as invalid, or replace them with redundant valid values (if available). This part is where judgment by a qualified person is needed.

In this study, each data element was subjected to range tests. The data was compared to upper and lower limiting values. As a result of this effort, the major roads database yielded 91 records while the minor roads database yielded 279 records.

5.4 Development of Performance Models

5.4.1 General

Pavement performance models developed can be either linear or non-linear, depending on whether or not the relationship among the variables can be defined in terms of a straight line. Regression is one of the most widely used and powerful analysis techniques available for constructing performance models. A nonlinear regression is used when the relationship between the dependent and independent variables is not linear. In these instances, polynomial regression is frequently used. The common S-shaped deterioration curve is a result of a polynomial
regression. The best equations to use to predict the value of Y from some value of X is one that minimizes the differences between the regression line and the actual data.

In this study, regression analysis was performed on the validated data by considering several shape functions that included linear, polynomial, logistic, exponential, power function and a few user defined shapes. The best fit was determined based on the coefficient of determination, $R^2$ value.

5.4.2 Models for Major Roads

This group included pavements on arterial highways, state highways and freeways passing through the city. A total of 91 pavement sections were available for performance modeling. Since more than 95% of these pavements belonged to AC type, pavement type was not considered as an independent variable. Cincinnati’s major rehabilitation generally includes milling existing asphalt layer and construction of two inch thick new asphalt overlay. Hence, the type of activity performed was not considered as an independent variable. Thus, all these pavement sections were grouped into one family, i.e., major roads.

Figure 2 shows a scatter plot of age vs. PCR for major roads along with a best fit model. The model can be represented by the following equation:

$$PCR = \frac{60}{1 - (0.4 \times e^{-0.07 \times \text{age}})}$$
At $age = 0$, this model calculates PCR equal to 100 and thus satisfies the initial boundary condition value. Although several linear and polynomial models have been developed by various agencies, the author of this report considers an S-shaped curve would best represent pavement performance with time. In the above figure, there is one point at $age = 30$ indicating a downward trend and the possibility of developing an S-shaped curve. However, such an effort resulted in a very low $R^2$ value. It should be realized that the shape of the best fit model is governed by a cluster of points rather than individual points. In developing the model, all data points were considered without eliminating any as outlier.
The $R^2$ value describes how well the regression line represents the data. The regression analysis for major roads yielded a value equal to 0.51. A value of 0.51 implies that 51% of the variation is accounted for by the regression equation. An $R^2$ value from 0.4 to 0.6 is generally considered moderate correlation by most researchers, while a value ranging from 0.6 to 0.8 is deemed strong correlation.

### 5.4.3 Models for Minor Roads

Minor roads consisted of secondary and residential streets. A total of 279 pavement sections were available for performance modeling. The surface type was predominantly AC type. Type of rehabilitation did not vary either, as in the case of major roads. Figure 3 shows a scatter plot of age vs. PCR for minor roads along with the best fit model. The model can be represented by the following equation:

$$PCN = 85 - 0.75 \times \text{age}$$

In this equation, PCN, the predictor variable, is the condition indicator. A cursory look at the figure reveals a wide scatter of points. Various functional forms were tried to obtain the best fit. The linear model yielded the highest $R^2$ value of 0.2, indicating a weak correlation between the two variables. Since the PCN is a combination of deflection, surface profile and environmental characteristics, a low $R^2$ can be expected as the variability in PCN is a combination of the variability of the individual factors.

PCN is a combination of deflection, surface profile, and environmental characteristics. A low $R^2$ can be expected since the variability in PCN is a combination of the variability of the individual factors.
In an effort to improve the $R^2$ value, discussions were held with the city engineers and the minor roads database was further investigated. Investigation of the IMS database revealed additional information about pavement classification based on the structural makeup. The pavements were classified into five categories as below [2]:

- Flexible
- Flexible Deep Granular
- Stabilized
- Stabilized Deep Granular
- Rigid
Flexible pavements are asphalt pavements over a granular base. Flexible deep granular pavement is flexible pavement over a deep (greater than two feet) granular subbase. Stabilized pavement is asphalt pavement over a semi-rigid base material. The base material normally consists of a pozzolonic (lime/fly ash) aggregate mixture or cement stabilized aggregate mixture. Stabilized deep granular pavements are stabilized pavements over deep granular layers as in flexible pavement. Rigid pavement is Portland cement concrete pavement. Asphalt overlaid concrete pavement is also considered rigid.

The minor roads database was subdivided into five groups, according to the pavement type classification. The number of pavement sections available in each group was as follows:

- Flexible - 101
- Flexible Deep Granular - 41
- Stabilized - 31
- Stabilized Deep Granular - 28
- Rigid - 78

Performance models were developed for the individual group of pavements. Figures 4 through 8 show the scatter plots along with best fit model for each pavement type. A summary of the models and $R^2$ values is provided in Table 1. It can be seen that adequate data was available from statistical standpoint to develop models for each pavement type. However, there was either no improvement or marginal improvement in $R^2$ values as a result of this effort.
Minor Roads - Flexible

\[ PCN = 87 - 1.04 \times \text{Age} \]
\[ N = 101, R^2 = 0.2 \]

Figure 4. Performance Model for Minor Roads – Flexible Type

Minor Roads - Flexible Deep Granular

\[ PCN = 85 - 1.27 \times \text{Age} \]
\[ N = 41, R^2 = 0.3 \]

Figure 5. Performance Model for Minor Roads – Flexible Deep Granular Type
Figure 6. Performance Model for Minor Roads – Stabilized Type

\[ PCN = 90 - 4.89 \times \text{Age} \]

\[ N = 31, R^2 = 0.2 \]

Figure 7. Performance Model for Minor Roads – Stabilized Deep Granular Type

\[ PCN = 87 - 0.99 \times \text{Age} \]

\[ N = 28, R^2 = 0.3 \]
PCN = 87 -0.5 x Age
N = 78, R² = 0.2

Table 1. Summary of Performance Models

<table>
<thead>
<tr>
<th>Family</th>
<th>Performance Model</th>
<th>N</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major Roads</td>
<td>PCR = 60 / (1 - (0.4 x e(^{-0.07xAge})))</td>
<td>91</td>
<td>0.51</td>
</tr>
<tr>
<td>Minor Roads</td>
<td>PCN = 85 - 0.75 x Age</td>
<td>279</td>
<td>0.2</td>
</tr>
<tr>
<td>Minor Roads-Flexible</td>
<td>PCN = 87 - 1.04 x Age</td>
<td>101</td>
<td>0.2</td>
</tr>
<tr>
<td>Minor Roads-Flexible Deep Granular</td>
<td>PCN = 85 – 1.27 x Age</td>
<td>41</td>
<td>0.3</td>
</tr>
<tr>
<td>Minor Roads-Stabilized</td>
<td>PCN = 90 – 4.89 x Age(^{0.46})</td>
<td>31</td>
<td>0.2</td>
</tr>
<tr>
<td>Minor Roads-Stabilized Deep Granular</td>
<td>PCN = 87 – 0.99 x Age</td>
<td>28</td>
<td>0.3</td>
</tr>
<tr>
<td>Minor Roads-Rigid</td>
<td>PCN = 87 – 0.5 x Age</td>
<td>78</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Figure 8. Performance Model for Minor Roads – Rigid Type
The format for the database provided in the IMS software is generic, meaning it was not developed specifically for the pavements in Cincinnati. Classification of pavements is normally done by taking core samples followed by a thorough review of historic construction records. No report is available to indicate such an effort by the consultants while setting up the database. By asserting correct pavement type for each pavement section in the minor roads database, it may still be possible to obtain better $R^2$ values and increase the accuracy of models.

5.4.4 Validation of Performance Prediction Models

Model validation using statistical techniques is an important step in the model building sequence. Often the process of validation consists of citing the $R^2$ value from the fit, which measures the fraction of the total variability in the response that is accounted for by the model. There are many statistical tools for model validation, but the primary tool of model validation is graphical residual analysis, i.e., through an assortment of plots of differences between the observed data and the predicted value from the model. Graphical methods have an advantage over numerical methods for model validation because they readily illustrate a broad range of complex aspects of the relationship between the model and the data. Numerical methods for model validation tend to be narrowly focused on a particular aspect of the relationship between the model and the data, and often try to compress that information into a single descriptive number or test result. Graphical analysis of the residuals is the single most important technique for determining the need for model refinement or for verifying that the underlying assumptions of the analysis are met. The residuals are the differences between the responses observed and the corresponding prediction of the response computed using the regression function. Examining residuals is a key part of statistical modeling. Residuals can be thought of as elements of variation unexplained by the fitted model. Since this is a form of error, the same general
assumptions apply to the group of residuals that is typically used for errors in general: it should be roughly normal and approximately independently distributed with a mean of 0 and some constant variance. These are the assumptions behind classical regression analysis. This means that a regression model should err in predicting a response in a random fashion; the model should predict values higher than actual and lower than actual with equal probability [15].

Figures 9 through 14 show the residual plots for the major and minor road models. The residuals for the $i$th observation, $e_i$, are calculated as:

$$e_i = \text{PCR}_{\text{observed},i} - \text{PCR}_{\text{calculated},i}$$

As seen in these figures, for each model, the distribution of residuals is random, with no definite pattern. Moreover, for each model the number of positive residuals is about the same as the number of negative residuals. Since the residuals appear to behave randomly, it suggests that the models developed fit the data well. On the other hand, if non-random structure is evident in the residuals, it is a clear sign that the model fits the data poorly. The reference line at 0 emphasizes that the residuals are split about 50-50 between positive and negative. There are no systematic patterns apparent in the plots. The residual plots explain if the assumptions made during the model development (normality of the data) are valid. It does not explain how good the fit is. Thus, in conclusion, the models presented represent the best-fit for the data used in their development.
Figure 9. Residual Plot for Major Roads

Figure 10. Residual Plot for Minor Roads – Flexible Type
Figure 11. Residual Plot for Minor Roads – Flexible Deep Granular Type

Figure 12. Residual Plot for Minor Roads – Stabilized Type
Minor Roads - Stabilized Deep Granular

Figure 13. Residual Plot for Minor Roads – Stabilized Deep Granular Type

Minor Roads - Rigid

Figure 14. Residual Plot for Minor Roads – Rigid Type
6. **DECISION TREE**

The objective of this task was to develop a decision tree to assist in the selection of a reasonable maintenance or rehabilitation alternative for each project in the road network, based on the condition of pavement and future expected performance. First, using a thorough review of literature and practices followed by Ohio agencies, an exhaustive list of alternative treatments was prepared. Then these alternative treatments were grouped into three categories namely, preventive maintenance, minor rehabilitation, and major rehabilitation. A decision tree was prepared, as illustrated in Figure 15.

It should be recognized that the decision tree presented can only assist the engineers at the network level analysis, so as to assess total budget required to maintain the network at the desired level. This should be followed by a project level analysis to determine the specific needs of a pavement or group of pavements.
Figure 15. Proposed Decision Tree for Selection of M&R Alternatives
7. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

The primary focus of this study was to develop pavement performance prediction models for the City of Cincinnati. In addition, a decision tree was developed to suggest appropriate maintenance and/or rehabilitation activities, based on the current condition of pavements.

The study began with an extensive review of literature designed to identify the factors that affect the pavement condition, types of prediction models, modeling techniques and the structure of decision trees developed by various highway agencies. Next, the data required to develop performance models and the decision tree was acquired from the City of Cincinnati’s pavement inventory database. Based on a review of the data, initially the following variables were considered:

- Age of the pavement sections
- Functional classification of the roads
- Pavement type and composition

Age was calculated for each pavement section as the number of years since construction or last major rehabilitation. The entire data obtained from the city’s records was divided into two classifications: major roads and minor roads. Major roads are arterial highways, state highways and freeways passing through the city. These roads are typically funded and periodically monitored by ODOT. Minor roads consist of secondary and residential streets. The functional classification also reflects the type and amount of traffic carried by the roads: major roads subjected to medium to heavy traffic while minor roads generally receive low and occasionally medium traffic.
While extracting the pavement condition data vital for the development of the performance models, it became evident that there was a basic incompatibility between the condition rating data for the two functional classifications. That is, the available pavement condition data for major roads—which was collected by ODOT—was in terms of Pavement Condition Rating (PCR), while the condition data for the minor roads—collected by Cincinnati’s private consultant—was expressed as a Pavement Condition Number (PCN). Unfortunately, there was no way of relating these two different summary statistics. Hence, regression analysis was performed and two pavement performance models were developed (one for each type of functional classification) using available data, with age as the independent variable and the condition indicator being the dependent variable. A moderate correlation was obtained for the major roads. However, the model for minor roads yielded a low value of $R^2$ indicating a weak correlation. In order to improve the accuracy of the model, it was decided to further investigate the effect of pavement type and composition. The results are presented in section 4 of the report.

In conclusion, this study resulted in a set of pavement performance prediction models for the city of Cincinnati based on the available historical data. A decision tree has been developed to identify the appropriate maintenance and rehabilitation activities based on the condition of the pavement. The city engineers can use these models in conjunction with their pavement management system to predict the future condition of the highway network in Cincinnati and to implement cost effective pavement management solutions. Using the methodology developed in this study, the engineers can also improve the accuracy of the models in the future by updating the database.

An important finding of this study is an understanding of data collection needs by the local agencies in Ohio and type of interaction required between ODOT and the local agencies.
Cincinnati and similar agencies have been collecting systematic pavement condition data for many years. Often, the agencies use private consultant services to establish a pavement management system, data collection procedures and even to collect data and maintain the database. In such cases, the pavement management systems are proprietary products and are not necessarily compatible with ODOT’s or other agencies in Ohio. In the event a city replaces the consultant as it happened in Cincinnati, there will be no compatibility between the existing and new system, resulting in non-utilization of previous work. Currently, ODOT has been collecting a fair amount of data on all major roads in the State and selected minor roads through their local program. However, these efforts are not truly coordinated with the cities. As a case study, it can be seen that Cincinnati’s efforts were not compatible with ODOT’s. The state roads were monitored for condition evaluation by both ODOT and the city, but in different ways. To make these efforts more productive it is recommended that the State and all local agencies in Ohio establish an improved communication and a uniform pavement management practice, so it can significantly benefit all agencies in general and ODOT’s urban paving program in particular.

8. IMPLEMENTATION PLAN

This research presents a set of pavement performance prediction models designed to predict future pavement conditions for the urban highway network in the City of Cincinnati. The models have been developed using historic data available with the city and hence represent Cincinnati’s past and near future pavement management practices. When integrated with a pavement management system, these models can help City’s engineers and planners to perform various tasks including remaining life estimation, life-cycle-cost analysis, detailed inspection scheduling, planning of needed works, development and optimization of budget plans and
optimization of network pavement condition. In essence, the prediction models can assist the engineers and planners to predict condition of individual pavement section and subsequently the entire network in future years, leading to efficient pavement management decisions.

The first step in the implementation is the development of a database from which data can easily be accessed. The database should be designed in such a way that identification of pavement family, age of pavement, type of surface, functional classification of road, type of maintenance treatments provided in the past, and other relevant information about pavement sections can easily be identified. It is important that the information about pavement sections be kept current and be frequently updated. Next, the performance models need to be integrated with City’s pavement management system. Cincinnati has recently acquired the services of a private consultant to set up a pavement management system. A meeting should be held with the pavement management engineers, construction engineers and the consultants to exchange and discuss the integration of performance models. Such an interaction would allow the city and the consultants to identify the changes to be made in the software package. Many pavement management system software packages provide default models and coefficients for use in cases where models may not be available. The use of prediction models developed in this study in place of default models or coefficients is expected to result in more reliable predictions.
REFERENCES


3. Miscellaneous Correspondence with the City of Cincinnati, 1998-2003

4. Visual Pavement Evaluation and Recording System, a system developed and implemented by the City of Cincinnati, 2000


6. Software Catalog of Selected Pavement Management Software for Local Transportation Agencies, January 1997


Oxford, MS, in partial fulfillment of the requirements for the degree of Doctor of philosophy.


14. *Pavement Forecasting Models*, Research in Progress conducted by the University of Toledo for the Ohio Department of Transportation