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Article

Prediction of Pavement Maintenance Performance Using an Expert System

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Abstract: The pavement experiences deterioration due to traffic and environment, i.e., unsatisfactory riding quality and structural inadequacy, over time. Thus, predicting pavement performance over time is one of the key elements of any pavement maintenance management system (PMMS). It can be used as an efficient tool to program/schedule the maintenance applications and expenditures, and thus the necessary funds can be allocated. Using a combination of independent variables for any selected pavement section can generate section-wise condition assessment and prediction models. Moreover, these models can be used to select the most cost-effective maintenance alternative to be applied to that pavement section. The present study developed an expert system based on pavement performance models which combines the available maintenance data with the knowledge acquired from the experts of the General Administration of Operation and Maintenance in Riyadh, Saudi Arabia. Eight regression models were first developed for four maintenance and rehabilitation (M&R) strategies, i.e., no maintenance, routine maintenance, overlay, and reconstruction for low and high traffic. Then, a practical expert system was developed to aid pavement maintenance engineers in finding the most effective and efficient M&R strategies and suitable time for the application. The regression models revealed that the effect of routine maintenance and reconstruction is greater in low traffic than in high traffic, while the effect of overlay is greater in high traffic than in low traffic. Based on this initial system, another improved one can be developed using the machine learning technique.

Keywords: pavement maintenance management system; expert system; pavement performance; cost-effective maintenance alternatives

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1. Introduction

1.1. Background

The City of Riyadh, Saudi Arabia, has seen very rapid development over the past two decades. The city area expanded from 75 km^2 to more than 1600 km^2. The General Directorate of Operation and Maintenance of Riyadh Municipality is the agency responsible for maintaining a street network exceeding in length 10,000 km [1]. It was not possible to maintain the roads of a city with this huge street network without a pavement maintenance management system (PMMS).

PMMS is a program to maintain and preserve the pavements of the road network at an acceptable level of safety, quality, and performance and minimize their lifecycle costs as a major component of a comprehensive pavement management system (PMS) [2]. The basic purpose of a PMMS is to achieve the best value possible for the available public funds and to provide safe, comfortable, and long-lasting transportation infrastructure [3].

An essential element of any PMMS is a reliable and accurate way to predict pavement performance. A typical way to predict the performance of the pavement is by developing pavement performance models, which can be used to determine the future maintenance needs and the required maintenance budget and to set maintenance priorities based on the available budget. Pavement performance models are imperative for a PMMS and perform a function similar to that of a car engine. Based on these models, the future pavement condition can be forecasted and can be used as an input to the maintenance policy to predict the required maintenance and rehabilitation (M&R) activities. Therefore, the PMMS assists top management in finding optimum strategies for providing and maintaining pavement in a serviceable condition [1].

A pavement performance curve describes the relationship between pavement conditions with pavement age or traffic level. The performance of the pavements was assessed to determine whether they were good or poor [4,5]. Pavement conditions can be determined through performance indicators such as pavement distresses, riding quality, structural adequacy, and skid resistance. These performance indicators can be combined into one index, e.g., the pavement condition index (PCI) has been widely utilized to allocate pavement maintenance strategies [6]. As shown in Figure 1, PCI values are computed based on visual assessment and indicate the types of distress, magnitude, and quantity present on the pavement surface [5]. The PCI provides the evaluation of the pavement's state, with scores ranging from 0 (failed) to 100 (excellent), as illustrated in Figure 2.

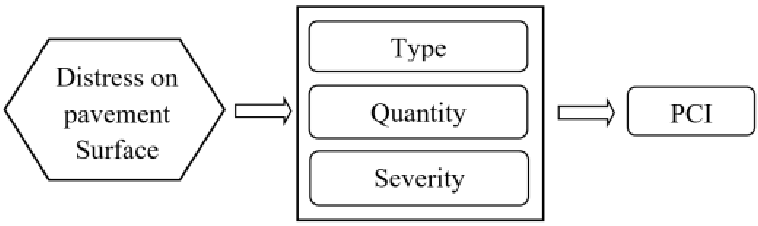

Figure 1. The procedure of the pavement condition index (PCI).

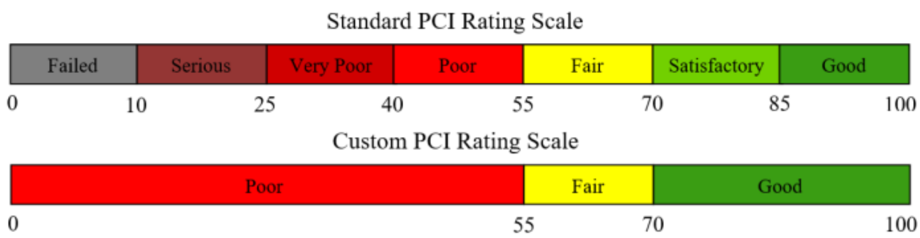

Figure 2. Pavement condition index (PCI) rating.

Maintenance activities are used to prevent pavement deterioration or reduce the rate at which the pavement deteriorates. The effect of M&R can be represented as the improvement in the pavement condition. This effect can be evaluated based on the change in the slope of the pavement condition curve or as the change in the level of pavement condition before and after performing a maintenance strategy. In some cases, the effect is measured by the frequency of the maintenance applied to extend the pavement's service life. The concept of pavement maintenance's effect on pavement condition is illustrated in Figure 3.

One technique to evaluate the effects of different M&R strategies is by building performance models. The procedure of modeling the M&R effect starts by determining the factors that may influence the pavement condition. These factors may include the pavement construction details, maintenance age, traffic level, availability of drainage system, maintenance age, environmental factors, etc. Once all the possible factors that may influence pavement condition are determined, pavement sections can be grouped based on the type of maintenance they received. The maintenance models can then be developed to predict pavement conditions under each maintenance strategy.

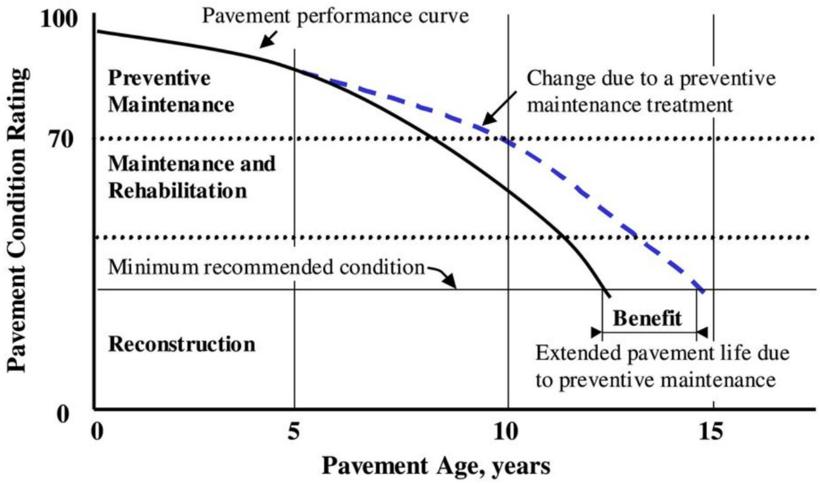

Figure 3. Expected effects of maintenance strategies on pavement condition.

The main element in pavement condition evaluation is to define performance measures. Pavement condition is then evaluated based on variables that affect pavement performance. A typical performance measure is the PCI. The evaluation of pavement condition was conducted for main streets only in the present study. The urban distress index (UDI), which represents the PCI, was a combined index of fifteen pavement distresses. This index is calculated using the type, severity, and quantity of each distress in a specific sample. The pavement section can be qualified based on UDI using the following ratings [1]:

- Poor: 0–39
- Fair: 40–69
- Good: 70–89
- Excellent: 90–100

1.2. Factors Affecting Pavement Condition

Some important factors that usually affect flexible pavement conditions are discussed briefly below.

a. Pavement Age

Over time, the hardening of asphalt increases, thus making it more brittle and susceptible to cracking. In pavement performance prediction, pavement age is measured from the date of construction or from the date of the last major maintenance application.

b. Pavement Maintenance Types

The type and timing of maintenance have a direct impact on the condition of the pavement. In the present study, the types of maintenance strategies to be evaluated were restricted to four only. These M&R strategies were no maintenance application, basic routine maintenance, overlay, and reconstruction.

c. Traffic Level

Pavement deterioration is highly affected by traffic volume and vehicle types. The traffic level is usually expressed as the average daily traffic (ADT). To evaluate the M&R performance, road sections were categorized based on traffic level into two classes, high and low. A section of low traffic is receiving traffic of fewer than 3000 vehicles per lane per day (v/d), while a section of traffic that exceeds 3000 v/d is classified as high traffic.

Predicting pavement performance is fundamental for appropriate resource allocation at the network level [7]. Reducing the prediction error of pavement deterioration aids transportation organizations to save money [8,9]. Several data-driven pavement performance models have been developed. A popular approach in pavement performance is the model of Markov prediction. To predict pavement performance, several statistical regression models are commonly utilized [10–12].

A knowledge-based expert system is one of the results of applications of artificial intelligence (AI) research to software programming. AI is a branch of computer science that studies ways of enabling computers to perform tasks that appear to require human intelligence. Expert systems are named for their essential characteristic: they provide advice for problem-solving that is derived from the knowledge of experts [13]. Expert systems typically use a set of rules and facts to make inferences that are reported as conclusions. The inference process relies heavily on theories of logical deduction. The objective of an expert system is to help the user choose among a limited set of options, within a specific context, from information that is more likely to be qualitative than quantitative.

Expert systems or machine learning have become popular recently and have been successfully applied in many fields. The framework for an expert system primarily consists of the knowledge base, inference engine or inference machine, context or working memory, explanation module, and user interface. The collection of facts, rules and computational procedures for manipulating the information in the knowledge base to reach conclusions is called the control mechanism, or the inference engine. The objective of the inference engine is to find one or more conclusions for a sub-goal or a main goal of the consultation. It searches the facts and rules in the knowledge base and identifies and stores conclusions to use in new facts for subsequent inference. The context or working memory contains all the information derived from the inference process. This information describes the problem being solved, the rules that have been "fixed," and the conclusions derived from them. The explanation module contains explanations for every inference made or piece of advice given. The user interface provides for dialogue between humans and machines.

Knowledge acquisition and representation are the most difficult parts of building an expert system. They often require the knowledge engineer to interact intensely with one or more experts in the application domain. Not all problems are suitable for expert systems. For a successful application, there must be an expert or expert in the domain, and the problem should be specialized. The expert selected must be able to articulate the special knowledge needed to solve problems in the domain. If solving the problem involves the use of rules of thumb or symbolic reasoning, then an expert system might be appropriate and helpful [14].

There is a considerable turnover in the ranks of maintenance management; in addition, much-experienced personnel is now retiring. However, many maintenance decisions are made by the unit's foremen, sub-district superintendents, or field supervisors, based on their judgment. If they do not have ample experience, expert systems can help fill the gap. To illustrate, maintenance needs estimation through visual inspection requires foremen not only to correctly assess the road condition but also to convert the road condition information into workloads. Although the foremen can be trained to assess the road condition, workload estimation demands considerable experience and know-how. There is inherent uncertainty in the unit foreman's translation of distress information into the type and number of activities to be performed. A knowledge-based expert system could be applied to take care of the uncertainty in the estimation process. It provides a tool for estimating the activities in the absence of an expert. The knowledge base can be tested and altered over time to improve its performance. Since the computer stores the expert system, it can become a part of a larger cost estimation system for the entire road network [15].

The expert system involves base knowledge, facts gathered through time, and a set of rules for each situation shown in the program. Additions to the knowledge base can improve advanced expert systems. A 'tool' or a 'shell' is a type of developing software that may be used to create an expert system. As shown in Figure 4, a shell is a comprehensive development environment for creating and managing knowledge-based applications [16,17].

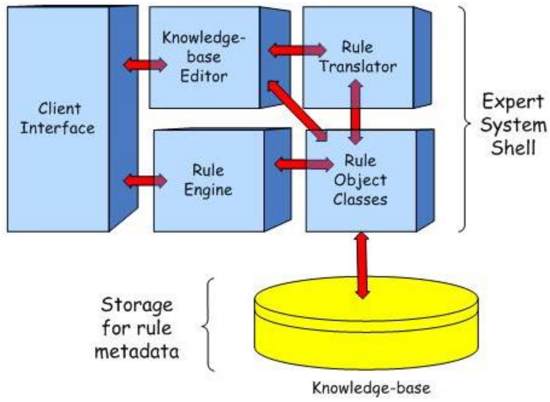

Figure 4. Expert system architecture.

There are some examples of expert systems developed for highway [18,19] developed a knowledge-based expert system to assist the New Mexico State Department, and there were 278 rules in the PARES rule base.

Sharaf E. and Kotob A. [20] designed a pavement maintenance management expert system for developing countries. The system consists of two programs: the first is an algorithmic program and the second program is an expert system. EXPSYS shell was used to develop this program. The input data of this expert system included many variables, such as section code, branch code, sample unit number, and condition survey. A two-fold system has been developed to assist highway agencies that lack in-house experts in the evaluation of asphalt pavement and assessment of maintenance and rehabilitation needs. First, the evaluation subsystem is an interactive algorithmic computer program, the output of which was PCI calculated from distress data. Secondly, the M&R subsystem is an expert system that simulates a consultation between the engineer and an expert in the field. The system has been developed and verified using data from portions of the Egyptian road network, where comprehensive visual inspection data were available.

2. Objectives

The main objective of the present study is to develop a pavement maintenance performance expert system to evaluate the different strategies based on the effectiveness and cost of each strategy. The expert system was based on several maintenance performance models, which were built from actual data in addition to the knowledge acquired from the experts in the field.

3. Data Collection

The developed database included information that describes the roadway classification based on traffic, pavement condition, and pavement maintenance. The main source of the collected data was Riyadh Municipality, represented by the General Directorate of Operation and Maintenance (GDOM). The actual data comprised the available pavement condition survey, while the expertise data were collected using a questionnaire, which was filled out by the experts from the GDOM.

3.1. Data Required for Developing the Pavement Performance Models

The data required for the development of the pavement performance models greatly depend upon the approach and the technique. In general, the following data were necessary for building these models:

1. Pavement characteristics: pavement type, strength, layer thickness, materials' properties, and age.
2. Traffic data: traffic volume, traffic composition, and loading.
3. Environmental conditions: seasonal temperature variations, rainfall frequency, and intensity, subgrade soil condition, and other regional factors.

4. Pavement condition: distress type, extent, severity, roughness, structural capacity, and skid resistance.
5. Maintenance data: maintenance techniques, expected maintenance service life, and maintenance unit cost.

3.2. Data Collected for Building the Performance Models

Two types of data used to build the maintenance performance models were: the available recorded maintenance performance data and the expertise data.

The available maintenance performance data for specific sections were collected from the GDOM of Riyadh Municipality. These sections were then categorized based on the initial PCI values (recorded before applying the maintenance). The criterion on which these sections were selected was the availability of recorded PCI values from at least ten years ago. The obtained information was only for the sections treated by basic routine maintenance and overlay.

To fill the gap of unavailable data, the study attempted to capture the knowledge of the experts in the pavement maintenance field. To attain this goal, a questionnaire was designed for this purpose and distributed to the experts working with GDOM.

3.3. Recorded Maintenance Performance Data

The pavement condition evaluation data were stored in computer files for the basic routine maintenance and overlay. A separate file was used for each year. Some important parameters included in these files were:

- Section number
- Street name
- Traffic class
- UDI date
- UDI value
- Maintenance type
- Maintenance application date

Conforming to the objective of the research to capture the knowledge of the experts in the field of pavement maintenance, a questionnaire was designed to fulfill this goal. However, the designed questionnaire has the following additional benefits:

To overcome the shortage of actual recorded maintenance data; for example, no data are available for a maintenance age of ten years.

To study the behavior of pavement performance when different strategies of maintenance are applied; for example, in real practice, the GDOM does not maintain sections using overlay if the UDI value is 80 or above, while for the research needs, this case should be considered and evaluated based on the experts' prediction.

Such a questionnaire requires deep knowledge and experience in the field of pavement maintenance, and this urged us to select the best experts in the GDOM to complete the questionnaire. The filled questionnaires were collected and analyzed to complete the database for the pavement maintenance performance model.

4. Maintenance Strategies

The performance of a pavement is mainly affected by the type, time of application, and quality of the maintenance it receives. Preventive routine maintenance slows the rate of pavement deterioration due to traffic and environmentally applied load. Failing to apply the preventive maintenance at a suitable time leads to an increase in the rate at which the pavement deteriorates, and consequently the quantity of defects and their severity that the pavement shows so that when they are to be corrected, the cost of repair is great. Continued deferring of maintenance actions shortens the time between the overlays and reconstruction, and thus considerably increases the lifecycle costs of the pavement. The different maintenance strategies used are briefly discussed below.

4.1. No Maintenance

This strategy implies that no maintenance has been carried out on the pavement since the reconstruction or major rehabilitation.

4.2. Basic Routine Maintenance

Basic routine maintenance activities were generally carried out to slow the rate of pavement deterioration and keep the pavement in safe and operational conditions. The pavement deterioration, in this case, is mainly due to the presence of localized distresses, such as cracks and potholes. The required routine maintenance includes preliminary maintenance activities such as crack sealing and patching. This alternative would be applied to pavements having a value of PCI greater than the critical value. The critical PCI is defined as the value below which the pavement condition rapidly deteriorates, and should ideally be determined from performance models. However, based on experience in the Riyadh Municipality and ongoing pavement condition evaluation, a value of 70 was adopted as the critical PCI for the Riyadh roads network. Adoption of this alternative alone, however, implies that the pavement is structurally sound (which is usually the case) and no overlay is needed. Basic routine maintenance is also classified into three maintenance levels: low, normal, and high.

4.3. Structural Overlay

The overlay alternative may be applied to the pavement below or above the critical PCI. However, the structural overlay is dependent on the structural adequacy of the pavement section and is normally applied when the pavement condition is below the critical UDI value. In some cases, where the pavement is structurally sound, but the serviceability is poor, a thin overlay is applied to improve the riding quality (as preventive maintenance). The falling weight deflectometer (FWD) measurements were utilized using the ELMOD algorithm to determine the required overlay thickness and the residual pavement life. An overlay is applied after the necessary routine maintenance is carried out. High overlay thickness (>7.5 cm) should not be adopted since reconstruction might be more cost-effective.

4.4. Reconstruction

A reconstruction alternative is adopted when the PCI is far below the critical value, where the pavement is in a poor condition and is structurally inadequate. Alternatively, reconstruction may be applied when the required overlay thickness is greater than 7.5 cm.

5. Data Analysis

The available data were analyzed, and the performance models were built. For the constraints of time and data availability, the following factors and assumptions were considered:

1. UDI used by the GDOM would be used to represent the PCI.
2. Uniform pavement sections with homogenous pavement characteristics were used.
3. Pavement age of a road section was defined as the number of years since the last maintenance application.
4. Four types of M&R strategies were considered, which were: no maintenance, routine basic maintenance, overlay, and reconstruction.

5.1. Sorting and Building the Model Database

To build the model database, it was necessary to sort and categorize the data; therefore, it was practical to eliminate some confusing data, which would not help design the model. Examples of these data were section number, street name, maintenance percent, many sections for one street, repeated data for one type of maintenance, and one traffic level for the same pavement.

The important data were:

- Highway class (main street),

- Traffic level (low, high),
- M&R strategy (no maintenance, basic routine maintenance, overlay, and reconstruction),
- Pavement age (years).

5.2. Modeling Techniques

Several techniques were used for the development of pavement performance. These techniques include the empirical (regression) model, probabilistic model, expert system, mechanistic model, and the mechanic-empirical model. Since the available data lacked some important factors, regression models were found very suitable for this project. Regression analysis was very practical, simple, and easy to develop. For these reasons, this technique has been adopted in the analysis to obtain pavement performance curves.

5.3. Empirical (Regression) Models

This analysis was used to establish an empirical relationship between two or more variables. Each variable was described in terms of its mean and limits of minimum and maximum variation. The regression technique is the most popular method for developing a deterministic empirical model. In the regression models, pavement condition was condition (PCI) was considered as the dependent variable, while the selected set of factors were the independent variables. A statistical technique was used to select the factors that should be included as independent variables. The regression models could be linear or non-linear depending on the relationship between the dependent and independent variables.

5.4. Expert Systems

An "Expert System" is a computer program that attempts to capture the knowledge and experience of one or more human experts to make such experience available on-demand to the user of the program. It operates in much the same manner as a human expert. It has a store of knowledge consisting of both facts and rules about those facts. This store is referred to as the knowledge base. By asking the right questions and then considering the user's reply, it decides which elements of its knowledge, i.e., which facts and/or rules, to use as the basis for further questioning until a goal is reached. This goal might be how to fix a piece of machinery, how a pavement maintenance activity may be applied, or whatever specialized information you may want your expert system to provide. As it is based on a human expert, an expert system knows the right questions to ask based on its general store of facts and rules as well as on user responses to pertinent queries.

5.5. Building Regression Models Using the Available Database

Various factors can affect pavement performance. The factors considered in the present study were roadway class, present pavement condition, pavement age, traffic level, and maintenance type. They are briefly discussed below.

a. Roadway Class

Riyadh Municipality classifies the roadways into two classes, main and secondary streets. Roadway class can affect the maintenance policy and criteria to a high extent, for example, the critical serviceability for main streets may be higher. In this project, a pavement performance model was developed for main streets only.

b. Pavement Age

The deterioration of paved roads is partly related to pavement age. Over time, the hardening of asphalt increases, thus making it more brittle and susceptible to cracking. In the pavement performance model development, pavement age was measured from the date of construction or from the date of the last major maintenance.

c. Traffic Level

Pavement deterioration is highly affected by traffic volume and vehicle types. Riyadh Municipality categorizes highways based on the traffic levels into two levels: high and low.

d. Maintenance Type

The type of M&R performed affects the pavement performance. Four maintenance strategies were considered in this project: no maintenance, basic routine maintenance (low, normal, and high), overlay, and reconstruction.

5.6. Development of Riyadh Pavement Performance Model

In developing the pavement maintenance performance model for Riyadh roadways, the following methodology was adopted. All the available data were sorted and classified based on the following:

- Traffic levels,
- Maintenance strategy type,
- Maintenance age,
- Initial PCI value (at the start of maintenance application).

- Data in each homogeneous group were plotted using a scatter plot. The data were then analyzed, the outliers were eliminated, and further analysis was conducted.
- For each group, a regression model was developed, as the drop in the PCI value for each traffic level and PCI initial value, while the other factors were used as the predictors for each group of homogeneous sections.
- The regression curves of the same maintenance and traffic group were compared to combine them into one model if possible.
- The regression coefficients in the final models were used in the expert system for easy application.

Figures 5 and 6 show the regression performance models for the no M&R strategy for a low- and high-traffic case, respectively. Performance models for routine maintenance are shown in Figures 7–10 show the overlay strategy for low and high traffic, respectively. Finally, Figures 11 and 12 show regression performance models for the reconstruction strategy for low and high traffic, respectively.

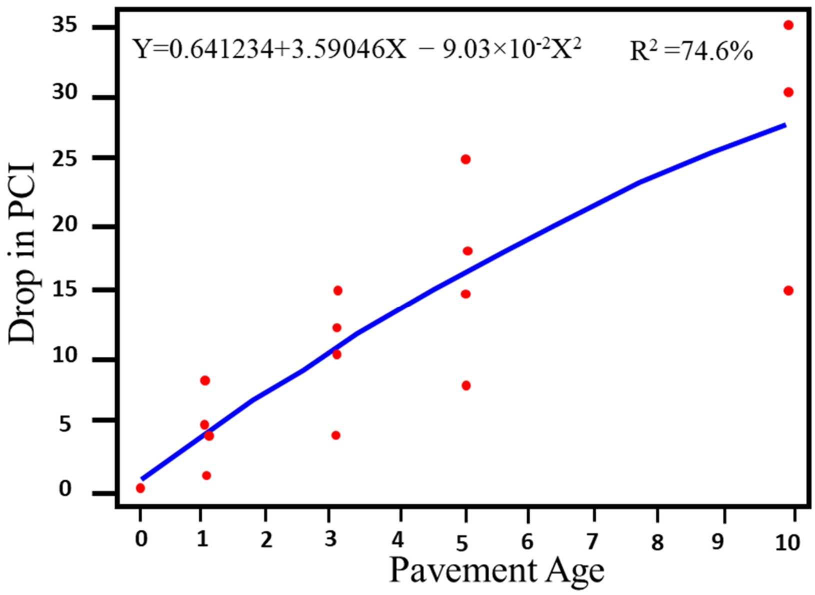

Figure 5. Effect of the no maintenance strategy on the deterioration of PCI for low traffic.

As indicated in the above figures, the effect of routine maintenance and reconstruction is greater in low traffic than in high traffic, whereas the effect of overlay is greater in high traffic than in low traffic.

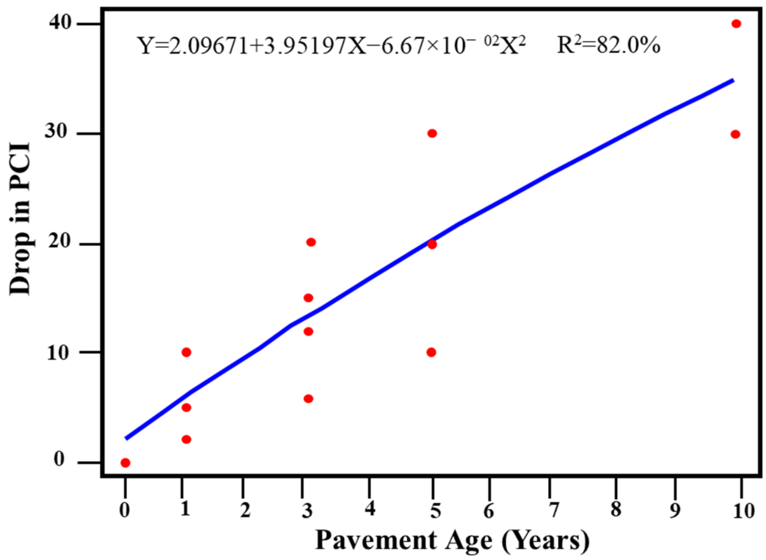

Figure 6. Effects of the no maintenance strategy on the deterioration of PCI for high traffic.

Figure 7. Effect of routine maintenance on the deterioration of PCI for low traffic.

Figure 8. Effect of routine maintenance on the deterioration of PCI for high traffic.

Figure 9. Effect of the overlay on the deterioration of PCI for low traffic.

Figure 10. Effect of the overlay on the deterioration of PCI for high traffic.

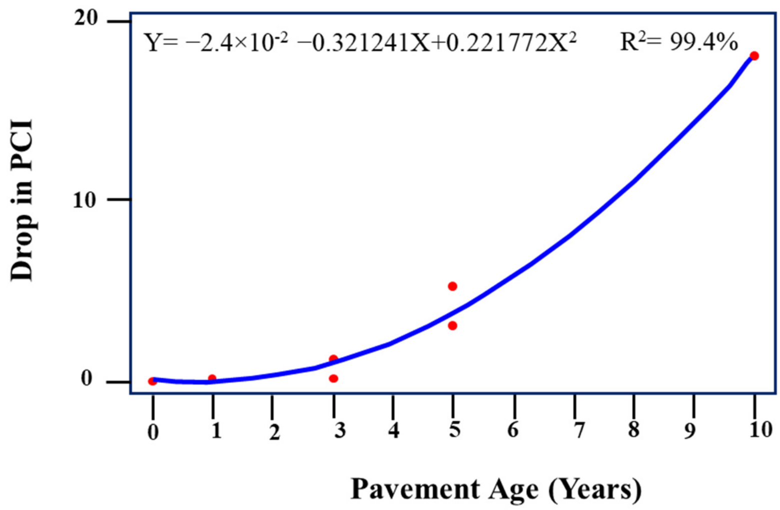

Figure 11. Effect of reconstruction on the deterioration of PCI for low traffic.

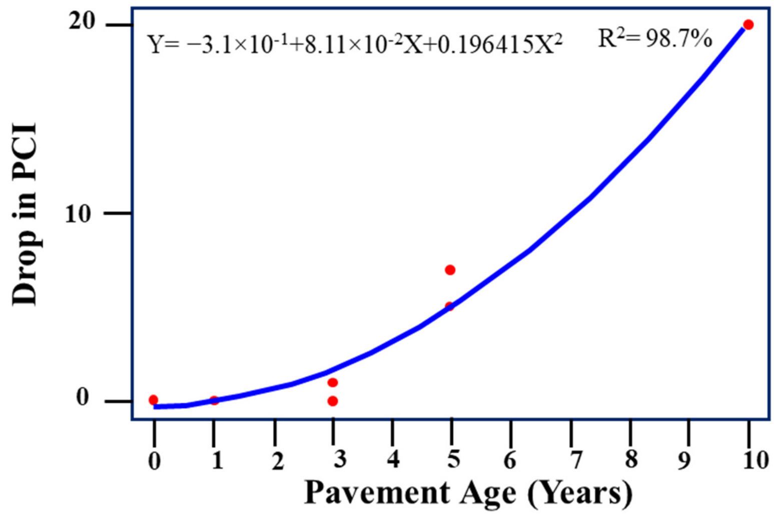

Figure 12. Effect of reconstruction on the deterioration of PCI for high traffic.

5.7. Pavement Maintenance Performance Expert System

The expert system developed using eight regression performance models is easy to operate and self-explanatory. The steps to run the program are listed below:

1. From the MS-DOS prompt, type "PMPEXP" and press the <Enter> key. This will start the program, which will show a description screen.
2. To produce a printable text file, press the <Y> key followed by the <Enter> key and then input the file name.
3. Section description: this is an optional field, which may include the road/section name for reference.
4. The following inputs are mandatory to run the program:
    - Present PCI for the section: This represents the PCI at the start of the analysis. It could be any value between 0 and 100.
    - Critical PCI value: This represents the minimum allowable PCI value, below which the pavement condition is not allowed to fall. It is used as the main criterion in evaluating the maintenance strategies. It could be any value between 0 and 100.
    - Analysis Period: this is the period (in years) along which the maintenance strategies are evaluated, and the cost is calculated for each strategy.
5. After the above inputs are entered, the user will be shown the maintenance activities available along with their preset costs. The user will be prompted to change an item's cost if necessary. Next, the user will be introduced to the M&R strategies, which can be suggested by the user.
    - Maintenance strategy: A maintenance strategy is a combination of the letters: X, A, B, C, P, O, and R, separated by the "+" sign. Each strategy represents the sequence of maintenance activities that the user proposes. For example, if the user inputs the following combination: "C+O+A", this means that he intends to first carry out the basic routine maintenance (high level) until the pavement condition index falls to or just above the terminal PCI value, and then a structural overlay will be applied; after that, the pavement will be lifted until it reaches the terminal PCI value, and at that time, the basic routine maintenance (low level) will be applied.
    - The user should enter at least one M&R strategy to continue running the program, and a maximum of five.
    - The maintenance strategies should be entered using letters separated by the "+" sign without any spaces or quotation marks. A maximum of five combinations (letters) is allowed.

- Periodic maintenance is not available.

After entering the M&R strategies, the program will produce the actual strategies that can be implemented throughout the analysis period along with their costs and details.

The program file to be run is named: "PMPEXP.EXE". It reads a configuration file called: "PMPEXP.CFG", which must exist in the same directory as the program. The expert system is written in a manner such that the applied maintenance models and initial costs can be changed without any programming effort. The coefficients of the performance curves and initial costs are stored in the configuration file (up to three coefficients, i.e., cubic equation). It must be noted that the format of the configuration file should not be changed to correctly run the program.

6. Conclusions and Recommendations

The pavement deteriorates with time as a result of traffic and the environment, resulting in poor riding quality and structural inadequacies. As a result, one of the most important aspects of any PMMS is the ability to anticipate pavement performance over time. PMMS is an effective tool for planning and scheduling maintenance applications and expenditures, allowing for the proper use of funds.

Segment-wise condition assessment and prediction models can be created using a combination of independent variables for every specified pavement section. Furthermore, these models may be utilized to determine the most cost-effective maintenance option for that particular pavement section.

A practical expert system was developed to aid novice pavement maintenance engineers and work teams in deciding the most feasible M&R strategy and the suitable time for application. The program starts by asking the user some questions, which will control the analysis of the pavement section and the evaluation of the M&R strategies proposed by the user. The expert system will then analyze the different maintenance activities based on the performance models and the criteria specified by the user: traffic levels, analysis period, and the critical PCI value.

The present study created an expert system based on pavement performance models that integrate existing maintenance data with knowledge gained from the General Administration of Operation and Maintenance in Riyadh, Saudi Arabia. For four maintenance and rehabilitation (M&R) strategies, namely no maintenance, routine maintenance, overlay, and reconstruction for low and heavy traffic, eight regression models were initially created. Then, to assist pavement maintenance engineers in determining the most successful and efficient M&R strategies as well as the appropriate chance for application, a realistic expert system was developed.

It is envisioned that implementing the developed expert system would allow an improved and more reliable tool using machine learning techniques.

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Conflicts of Interest: The authors declare no conflict of interest.

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