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Alternatives to PCI and MicroPAVER based maintenance solutions for airport pavements

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ALTERNATIVES TO PCI AND MICROPAVER BASED MAINTENANCE SOLUTIONS FOR AIRPORT PAVEMENTS

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THESIS

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DEDICATION

To my parents

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ABSTRACT

Airport pavements need to be maintained for adequate health condition by implementing cost effective maintenance solutions. Traditionally, maintenance and repair techniques have been developed based on the minimum acceptable Pavement Condition Index (PCI). However, there are pavements which show high PCI but have low Structural Condition Index (SCI); though these pavements are good in terms of functional condition, their structural condition is not good. This may lead to pavement reconstruction after a few years of service life, instead of minor repair. Therefore, there is a need to combine a study of functional and structural conditions.

Moreover, the Life Cycle Cost Analysis (LCCA) determines the best option based on the minimum life cycle cost assuming all alternatives have equal functional benefit. By only performing LCCA, one cannot draw a conclusion about the functional benefit achieved by an alternative. A pavement may reach the end of its life cycle and then require an extensive reconstruction or major repair work which is difficult to include in LCCA.

This study focuses on PCI based and PCI-SCI based pavement evaluation of a selected 19 general aviation airports in New Mexico. Deterministic and probabilistic LCCA and Benefit Cost Ratio (BCR) of major maintenance treatments have been performed based on PCI with or without considering SCI and hence significance of SCI in LCCA of airport pavements has been studied. A new System Dynamic (SD) Model has been developed which predicts PCI as a function of time after various maintenance treatments and determines the functional benefit and life cycle treatment cost of those alternatives. Both linear and nonlinear deterioration rates have been considered in determining benefit. Different BCR design charts have been developed based on the SD study, and, different management goals have been compared using a pavement management tool named MicroPAVER.

A good correlation can be drawn between PCI and SCI, but Skid Number does not show any correlation with any other indices for this study where Skid Number (SN) represents the skid resistance of the pavement surface. Developed design charts are helpful to set cutoff PCI and to select the most effective maintenance treatment to obtain maximum BCR. PCI-SCI approach gives a higher BCR than PCI approach only for Carlsbad airport; as it has its SCI value close to its PCI value. Analysis also shows that, among all of the single maintenance treatments, spray patching is the most cost effective and Hot Mix Asphalt (HMA) overlay shows the highest functional benefit. The management goal of ‘Reach PCI 80’ has shown the highest functional benefit than other strategies and different single maintenance treatments.

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INTRODUCTION

1.1 Problem Statement

New Mexico has 43 general aviation airports with different pavement condition. A visual distress survey was performed in 2006-2007 by New Mexico Department of Transportation Aviation Division to determine the condition of different branches and sections of these airfields. A Pavement Condition Index (PCI) was determined for various sections of 19 New Mexico airports using the survey data. PCI is a numerical pavement condition index which indicates the functional condition of airport pavement and can be determined using visual distress data. However, PCI data are not enough to represent the overall condition of the airfields. The structural condition of the pavement is also important in decision making for any airport project.

In selecting the best alternative, various methods have been used by various researchers. These methods depend upon certain rules and criteria assigned by the researchers based on past experience (Hicks et al. 2000). The problem with these experience based methods is that, these methods are not enough efficient to deal with multiple pavement distress types and are not suitable for network evaluation. There is a great need to develop appropriate decision strategies which will consider condition indices consisting of PCI, Structural Condition Index (SCI) and Skid Number (SN). SCI indicates the structural condition of the airfield obtained from the visual distress survey data like PCI. SN represents the skid of the pavement surface obtained from using the locked wheel trailer. In a traditional Pavement Management System (PMS), researchers have not given adequate attention to SCI in the decision making process. Maintenance based on both SCI and PCI is performed and compared with only PCI based evaluation in this study. This study aims to identify the most appropriate maintenance approach and pavement evaluation based on current PCI, SCI and SN values of airport pavements. Benefit cost analysis and life cycle cost analysis are also performed considering both PCI and SCI condition indices with the help of a System Dynamic (SD) tool. Furthermore, the effects of rehabilitation types and time on Life Cycle Cost (LCC) of a pavement are not analyzed properly in the previous studies. Although many researchers have implemented preventive maintenance strategies, there are still very few studies on determining the optimum time of application of such treatment (Hajj et al. 2010).

MicroPAVER is a renowned pavement management tool and, has traditionally been used to design a 20 year maintenance plan for pavements of different conditions. In MicroPAVER, the user can determine a budget required to maintain a specific condition level. MicroPAVER usually applies four different maintenance categories named; localized preventive, localized safety, global preventive and major maintenance work. As a section of airport pavement reaches the critical PCI value, MicroPAVER applies major maintenance work which includes any recycling, resurfacing or reconstruction where the resulting pavement achieves a PCI of 100. It is observed that if a section has a PCI well above the critical value, MicroPAVER applies minor maintenance work such as localized preventive, localized safety work and global preventive work which does not improve the average PCI significantly for the entire airport. If a pavement is maintained too frequently, funding can be spent unnecessarily (Hicks et al. 2000). However, if various global and local treatments would have taken place at a certain interval depending on a treatment’s expected life, instead of frequent minor treatments or major treatments at critical PCI, it is possible to save maintenance cost. Most pavement maintenance management systems tend to be either non-analytical or statistical correlation models. Pavement maintenance is part of complex system that has significant feedbacks, making it a suitable field for system dynamic study (Linard 2000). To avoid frequent minor rehabilitation in MicroPAVER, a system dynamic module is developed which applies different maintenance work only in the current year and the year when the section weighed area PCI reaches the current PCI again, which depends on the expected life of the treatments. The deterministic Life Cycle Cost Analysis (LCCA) approach fails to address simultaneous variations in multiple inputs and it fails to convey the degree of uncertainty associated with life cycle cost estimation (Walls and Smith 1998). Therefore, deterministic as well as probabilistic LCCA have been done for this study.

1.2 Hypothesis

Traditionally, pavement visual distress survey data are used to determine only the PCI and maintenance work is also usually performed based on these PCI values. SCI can also be developed using distress data. Decision makers should consider SCI when selecting maintenance alternatives and optimal timing for their applications, because structural condition is also important like operational condition of the pavement. Several parameter based pavement evaluations need to be performed for airport pavements such as PCI, SCI and SN. A central database can be created with visual distress survey data, PCI data and SCI data in MicroPAVER.

It can be hypothesized from this study that, there is a significant difference in Benefit Cost Ratio (BCR) of maintenance alternatives if we consider only PCI with if we consider PCI with SCI in applying a treatment. Comparison of PCI and PCI-SCI approach should be done in this study. A 20 year life cycle cost analysis and benefit cost analysis should be performed considering both the traditional PCI approach and PCI-SCI approach. Different design charts have been developed based on the benefit cost analyses, which are capable of determining BCR for different initial PCI, PCI rise and cutoff PCI. The effects of initial PCI, PCI rise and cutoff PCI on BCR can be explained using those charts. Developed design charts help selecting cutoff PCI and type of maintenance for a given airport pavements.

MicroPAVER is a pavement management tool capable of determining suitable maintenance work and budget required to maintain pavements. The MicroPAVER approach to restore pavement at different PCI are shown in Figure 1.1 where different maintenance strategies are followed for different PCI ranges by MicroPAVER. The available pavement management software MicroPAVER has some drawbacks in applying maintenance treatments. MicroPAVER applies different maintenance treatments each year on different sections depending upon their condition to maintain PCI up to a certain PCI level, which may or may not cost more. It is not known whether yearly maintenance is cost effective or not. There may be an airport pavement for which a delayed maintenance may be better than routine yearly maintenance. A pavement management system can be modeled as function of time to find the most cost effective solution.

The second hypothesis is that, different single maintenance treatments have more BCR than different multiple treatments of MicroPAVER. Using a system dynamic tool named Powersim different modules such as a PCI module, LCC module have to develop to analyze different maintenance treatments in the evaluated 19 New Mexico airports. The PCI module is capable of determining the resulting average PCI due to different treatments. In the PCI module, different maintenance treatments should be applied only in the base year and in the year when the pavement again attains the PCI of the current year. PCI rise and expected life of any treatment can be given as an input in this module. It helps to determine the average life cycle PCI due to application of various alternatives. The LCC module helps to determine deterministic life cycle cost of different alternatives. Probabilistic life cycle cost analysis has been performed using Federal Highway Administration (FHWA) software named RealCost. Benefit cost analysis of different single maintenance techniques with MicroPAVER's management strategies have been studied to determine the most optimum pavement maintenance treatments. With the Benefit Cost Ratio (BCR), the most effective type of a maintenance treatment can be determined.

1.3 Objectives

The objectives under the first hypothesis are:

- To evaluate 19 New Mexico general aviation airports and to develop a central pavement distress database in MicroPAVER considering PCI, SCI and SN.
- To develop BCR design charts for different initial PCI, PCI rise and cutoff PCI using a SD tool and to compare BCR for PCI and PCI-SCI approach.

The objectives under the second hypothesis are:

- To determine the functional benefit of different maintenance alternatives using SD module and to perform deterministic and probabilistic LCCA of different treatments using a FHWA LCC tool named RealCost.
- To compare different single maintenance treatments applied in different intervals with different management goals of MicroPAVER which considers multiple treatments each year of analysis period.

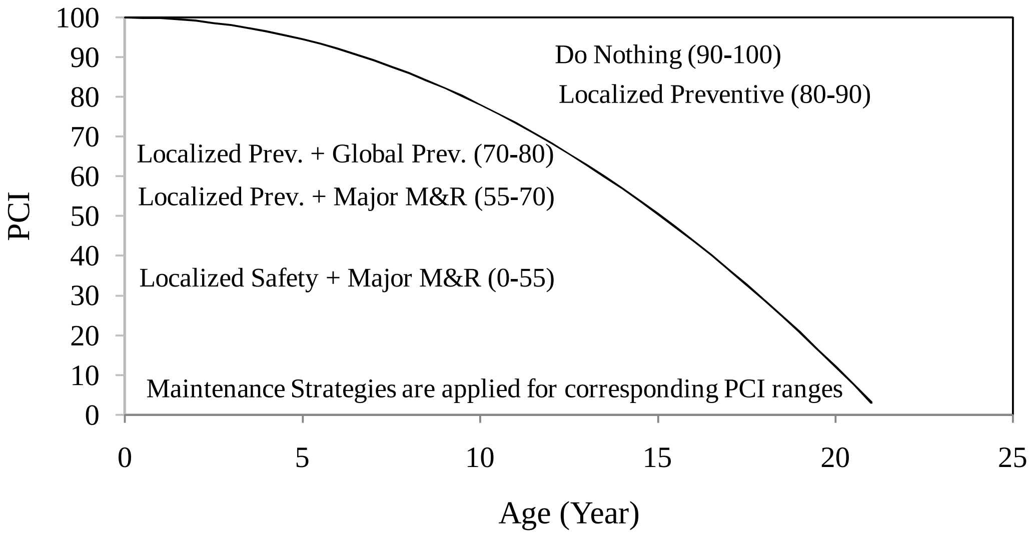


Figure 1.1: Typical pavement deterioration curve and pavement maintenance strategy

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

An engineering management system (EMS) is a system that composed of engineering tools for performing condition evaluation and condition prediction; and developing work plans to minimize spending. To improve the efficiency of decision making, provide feedback on the consequences of decisions, facilitate the coordination of activities within the agency, and ensure the consistency of decisions made at different management levels within the same organization are various functions of PMS (Hass et al. 1994).

MicroPAVER is the world's leading PMS developed by United States Corps of Engineers Research Laboratories (USACERL) for the benefit of the infrastructure community. The pavement management research and development of the MicroPAVER have been in progress since early 1970's. MicroPAVER development is supported by agencies like US Air Force, US Army, US Navy, Federal Aviation Administration and the Federal Highway Administration (Shahin et al. 2002). In general, the process of PMS consists of four main components: network inventory, pavement condition evaluation, performance prediction models and planning method (MicroPAVER 6.0). Life cycle cost analysis helps to make a pavement management decision which is also used widely for the past few decades. In order to decide if the PMS can be achieved the final objective; a decision analysis process is used. Pavement management system has significant feedbacks for system dynamic study.

2.2 Pavement Management System

PMS are able to determine cost effective solutions and develop budget scenarios. PMS are only a tool and should not be used in place of engineering judgment. It should used to help the engineer in making decisions on pavement condition and project decision making (Papaleo 1998). The function of PMS is to improve the efficiency of decision making, provide feedback on the consequences of decisions, expand the scope, facilitate the coordination of activities within the agency and ensure the consistency of decisions made at different management levels within the same structure (Hass et al. 1994). PMS is capable of providing various benefits for airport, highway or other agencies and it helps decision makers in taking decision at both the network and project levels dealing with selection and implementation of cost effective alternatives.

PMS works at two major levels known as Network level and Project level. Initial level at which various agency based programs such as new construction, maintenance and rehabilitation are performed in intent to least cost or greatest benefit is known as Network level. Project level is that, where more detailed consideration is given to alternative design, construction, maintenance or rehabilitation activities for a particular section or project within the overall program which is desired to provide minimum cost and maximum benefit over the analysis period. Two other major organization management levels are Administrative levels and Technical management level. In Management level, decisions are made regarding a program or project. Budgets and priorities appropriate to that program are known as Administrative level. And Technical management levels are that where decisions are made on the best design, maintenance or rehabilitation procedure for an individual project (Hass et al. 1994).

2.2 Traditional Pavement Management System

Traditionally, most airport managers have made decisions about pavement maintenance and rehabilitation based on immediate need or experience rather than long-term maintenance planning. This approach did not allow the sponsors to evaluate the cost effectiveness of alternative maintenance and repair strategies and it causes an extravagant use of funding. Every airport pavement management must decide how to allocate its available funds most efficiently. Typically, this is done using one of the following methods:

- Many airport managers use an “experience based” approach. In this approach the management applies the maintenance technique that their experience indicates is the best solution for the immediate problem. This approach usually results in the repeated application of a select few alternatives and may not lead to the selection of a preferred rehabilitation strategy that considers pavement performance and a life-cycle cost analysis.
- The “existing condition” approach is also used where the pavement network is first evaluated by visual distress survey and developing various condition indicators. Based on an analysis of these indicators, maintenance and repair alternatives are selected. This method does not consider life-cycle cost comparisons of various alternatives because decisions are based solely on the current condition of the pavement. This approach selects the maintenance and repair procedures that relate to the current deterioration of the pavement, but decision may not be the most cost-effective method based on life cycle analysis.

Because of success of these methods these are practices widespread all over the country. However, with limited money to spend on maintenance and rehabilitation and new technologies providing more options for repair, these established procedures do not show good results for many projects. This is because; decisions made today will have an effect on the pavements' condition in future years. The immediate and future consequences of management decisions should be studied thoroughly.

2.3 New Decision Making Process

The selection of the best action can be determined based on the predicted effects of each action taken. For example, by placing a thin overlay on all pavements, there will be an immediate improvement to all the pavements, but due to rapid deterioration of the overlays, there may be a need for further rehabilitation in a short period of time.

In addition to other pavements needing work, if some of the overlaid pavements need rehabilitation action again next year, the overall condition of the pavement network will eventually degraded. However, if a few selected pavements receive the full thickness overlay, they will not need rehabilitation for many years. During subsequent years, remaining pavements can then receive full thickness overlays, so the number of pavements needing rehabilitation will ultimately decrease. With this strategy, however, overall pavement condition will be worse in the short term because those pavements that have not been overlaid will continue to deteriorate until they are rehabilitated. In order to determine which of these actions should be taken, we must be able to predict the future consequences of the various scenarios. This warrants an understanding of the life span of a thick (e.g., 4-inch) versus thin (2-inch) overlay. Decision makers should also have a good understanding of the pavement deterioration rate, with and without maintenance, and the causes of current pavement deterioration, such as environmental conditions or pavement loading conditions. “Engineering judgment” in the decision-making process is required in predicting consequences of rehabilitation scenarios. An Airport Pavement Management System (APMS) can improve on the decision-making process, expand its scope, allow for feedback based on choices made, and ensure that consistent decisions are made throughout an organization. Innovative decision making process must include both deterministic and probabilistic life cycle cost of different alternatives.

2.5 General Structure of Pavement Management System

The objective of most PMS is to maximize the effectiveness of pavement maintenance and rehabilitation by using greatest benefits of the available fund (Ismail et al 2009). There are two main, interrelated uses of systems methodology of PMS. The first one is structuring or framing of the problem and the second one is the use of analytical tools for actually modeling and solving this problem. These are complementary and major phases of the systems are basically done at three levels. These are the systems approach, systems analysis and systems engineering. The system approach often means broad consideration of a problem. System analysis encompasses the systems approach and extends it to a more complete consideration of alternative strategies. Finally, the system engineering is a more complete exhibition of the systems method with design, implementation and performance evaluation aspects given strong attention.

The general structure of systematic pavement management are comprises of following components. Inputs must be established which includes a number of different variables plus objectives. Models must be created through which the need for analysis of alternatives was identified. Behavior such as cracking and other distresses are identified and predicted by pavement model. Accumulated distress reduces pavement serviceability and serviceability history defines pavement performance. Skid resistance and other safety responses are also important in PMS. Life cycle economic analysis is a vital part of the pavement management process. Economic and other decision criteria must be explicitly defined and considered in the analysis. Selecting the optimal alternatives is an important step in decision making and last but the most critical component is the implementation.

2.5.1 Airport Pavement Inventory

MicroPAVER inventory management is based on a hierarchical structure composed of networks, branches and sections. This hierarchical structure of MicroPAVER inventory management allows users easily organize their inventory while providing numerous fields and levels for storing pavement data. Some of the other features included in inventory are User-defined Fields (to meet user’s management requirement), Virtual Inventory (for virtual copy of the inventory and easy presentation), Surface Change (automatically updates pavement surface based on work history information), editing capability of Historical Inventory and so on (MicroPAVER 6.0). Additionally, new branch uses and pavement surface types may also be defined. Users are also able to manage their data more efficiently through an improved user interface.

A network is a group of pavements that are managed together- typically as a budget line item. For example, state aviation agencies manage multiple general aviation (GA) airports. Consequently, each GA airport is defined as a separate network within the state's pavement management database. Commercial and military airports often break airside and landside pavements into separate networks. The network is divided into branches. A branch is an area of pavement that shares a common use. For example, a specific runway may be defined as a branch. A section is defined as a pavement area within a branch that shares similar structural characteristics and loading conditions. Equally as important, however, is that a section is considered a management unit- meaning that condition analysis and work planning is performed at the section level and then rolled up to the branch and network levels (Shahin et al. 2002). Several factors are considered when dividing branches into sections; they are pavement structure, traffic, construction history and pavement condition (Ismail et al. 2009).

2.5.2 Airport Pavement Inspection

Pavement inspection is performed to assess the current condition of pavement. The AASHTO pavement design guide uses the concept of present serviceability index (PSI) as the performance variables upon which the design is based (AASHTO 1993). The concept of serviceability was developed at the AASHTO road test. The PSI is determined by measurements of roughness and distress. The PSI ranges in value from zero to five. The guide is concerned with functional and structural performance. Functional performance is a measure of how well the pavement is serving the user and structural performance relates to the physical condition of the pavement (Grogan 2000).

ASTM Standard Practices D 5340; ''Standard Test Method for Airport Pavement Condition Index Surveys'' and D 6433; ''Standard Test Method for Roads and Parking

Lots Pavement Condition Index Surveys’’ are frequently used for performing airside and landside pavement condition inspections, respectively. Both standard practices yield the Pavement Condition Index (PCI), which is a number ranging between 0 (worst condition) to 100 (best condition) (Show Table 2.1). The PCI is based on a visual distress survey which takes into account various distress types, distress severity levels and distress quantities (Shahin et al. 2002). MicroPAVER provides users the ability to customize the PCI condition rating categories and also allows the users an interface for recording the results of an online distress user guide. In addition to the PCI, MicroPAVER allows managers to use and create other condition indices, including those based on PCI distresses. For example, users can track the quality of pavement markings, through either a numeric or textural index. PCI surveys should be carried out every 2-3 years at maximum depending on pavement use.

2.5.3 Pavement Condition Evaluation

The major purpose of performance related pavement evaluation is to determine the current condition of the pavement structure. Four key measures can be used to define the condition of pavement which are: Roughness (which is related to serviceability or ride comfort), Surface distress (various cracking, their severity and quantity), Deflection (as result to structural adequacy), Surface friction or Skid resistance (as related to safety). The engineering evaluation of pavement requires a well documented set of practices and procedures, plus good training. A tool is needed to summarize the individual measures into a statistic for identifying the overall quantity or condition (Hass et al. 1994).

The Federal Aviation Administration (FAA) has developed and refines nondestructive testing (NDT) technologies to assess airport pavement condition. The National Association of State Aviation Officials (NASAO) and the FAA agreed to partner to develop a system for sharing information to optimize available airport pavement funds.

The benefit of a web-based pavement evaluation and management program were subsequently determined and are discussed as follows: a method to manage system-wide dissemination and analysis of FAA-sponsored pavement projects, a tool to tie volumes of existing airport pavement data together for project comparison, and as a means to join existing FAA airport pavement design and evaluation computer programs together for ease of operation. PAVEAIR, in its initial launch, will have the equivalent functionality of MicroPAVER version 5.3 and be designed to operate in Microsoft Internet Explorer web browser version 6.0 and above on the client side (Larkin and Hayhoe 2009). The automated system has the ability to assess the condition of the pavement and use the resulting data to create and populate a PAVER database (Cline et al. 2000).

2.5.4 Airport Pavement Condition Analysis

Condition analysis of airport pavement can give us the information about where we are now, where we can be and where we will be. The condition analysis feature in MicroPAVER allows user to view the condition of entire network or any section of the project. It can give reports of past conditions based on prior interpolated values between previous inspections. It can give reports of projected conditions based on prediction models. In MicroPAVER, conditions can be viewed on GIS maps in addition to tables and graphs (See Figure 2.1).

2.5.5 Condition Prediction Modeling

An important aspect of a pavement management system is the ability to predict future PCI of pavement sections based on the data contained in the database. Condition prediction can be used to identify pavements requiring maintenance or rehabilitation. Once pavements requiring future work have been identified, a budget for the current year and for several years in the future can be developed by using the agencies prioritization scheme, maintenance policy, and maintenance and rehabilitation costs.

MicroPAVER has the ability to predict future PCI values of pavement sections. When predicting future PCI values, it computes a PCI deterioration rate for each pavement section, which is the reduction in PCI points per year for that section. The program assumes a PCI of 100 at the construction date, and as the PCI is known for the inspection date, the reduction in PCI that occurred between the construction date and inspection date is computed by Paver. Then, based on the time difference between these two dates, the deterioration rate of the pavement in PCI points per year is computed for each pavement section. This deterioration rate is then used to predict future PCI values. When predicting a future PCI value, it is assumed that no maintenance activities will be performed on the pavement. The pavement condition historical data are used to build a model that can accurately predict the future performance of a group of pavements with similar attributes such as similar traffic, weather and factors affecting pavement performance. The state of Washington (Hass 1994) has developed a set of regression equations, based on long term pavement performance database, of the form:

$$PCR = C - mA^{P} \qquad \text{(Eq. 2.1)}$$

where

PCR = pavement condition rating, scale of 0 to 100

C = 100

m = slope coefficient

A = age of pavement, years

P = constant which controls the shape of the curve

Figure 2.2 provides an example listing of the standard or default performance curves, for western Washington, using Eq. 2.1 for different pavement designs or types. In MicroPAVER, if only one year data is given as input, PCI deteriorates linearly and the rate depends solely on current condition of the pavement. It follows the equation below:

$$r = 4.79 - \frac{cc}{20.88} \qquad \text{(Eq. 2.2)}$$

where r is the pavement deterioration rate and cc is the current condition or current PCI.

2.5.6 Airport Pavement Work Plan and Project Planning

The MicroPAVER Work Planer is a tool for planning, scheduling, budgeting and analyzing alternative pavement maintenance and repair activities (MicroPAVER 6.0). It is a new tool in MicroPAVER and added in version 6.0 which allows the user to develop project base on user specified required work and MicroPAVER recommended work. This tool greatly helps the user in planning projects and in completing the projects, automatically updates the work history data. MicroPAVER is capable of generating various reports ranging from section conditions reports to PCI re-inspection reports. It now also provides flexible reporting tools which enable users to generate reports that include only the data which users want to see. In addition to the flexible reporting tool, there are standard GIS reports available. Various maintenance cost per condition are shown in Figure 2.3.

2.5.7 Pavement Life Cycle Cost Analysis

Life-cycle cost for rehabilitation strategy selection requires consideration of some issues that are not adequately addressed by the typical guidelines that exist for life-cycle cost analysis for new pavement design selection. Among the issues that require special consideration when rehabilitation strategies are being compared are selection of an appropriate analysis period, differences in vehicle operating costs due to differences in predicted serviceability trends, and differences in work zone user delay costs due to differences in lane closure times and lengths during initial and follow up rehabilitation.

This study also provides in-depth discussion of other key issues in life-cycle cost analysis for rehabilitation strategy selection, including selection of an appropriate discount rate, characterization of residual or salvage value, estimation of other components of user costs, the different economic measures by which alternatives may be compared, weighing agency costs and user costs, and the relative sensitivity of life-cycle cost analysis for rehabilitation strategy selection to the various factors involved (ARA).

2.6 Pavement Condition Index Method

The Pavement Condition Index (PCI) method was developed by the Construction Engineering Research Laboratory of the U.S. Army Corps of Engineers. This method can be used on both asphalt surfaced and Portland Cement Concrete (PCC) pavements. This method has been adopted by Federal Aviation Administration to determine pavement condition (Advisory Circular No. 150/5380-6, Guidelines and Procedures for Maintenance of Airport Pavements). PCI became an ASTM standard in 1999. The following method is followed in the PCI method to obtain the PCI value of the pavement.

2.6.1 Divide Pavement Section into Sample Units

For asphalt concrete pavements, a sample unit consists of 5000 $\pm$ 2000 square feet of pavement. The area of the sample units to be used is determined based on the geometry of the pavement section. For a PCC pavement, a sample unit consists of 20 $\pm$ 8 slabs. The number of slabs to be included in a sample unit is determined based on the geometry of the pavement section of PCC pavements.

After determining the size of sample units, the pavement section is divided into sample units. After that, the number of sample units for inspected area is determined. After determining the number of sample units to be inspected, the spacing interval of the sample units to be inspected is to be determined. The spacing interval; i of the sample units is calculated by the following formula and rounded to the lowest whole number:

$$i = \frac{N}{n} \qquad \text{(Eq. 2.3)}$$

where N = total number of sample units in the section,

n = Numbers of sample units to be inspected

The first sample unit to be inspected is selected randomly from sample units 1 through i. The sample units within the section that are successive increments of the interval i after the first random sample unit should also be inspected. If there are sample units within the section that are not representative of the section, such sample units are inspected in addition to the sample units that are selected at random and known as additional sample unit. Such are not typical of the section, such as sample units that is very poor or good.

2.6.2 Identify and Record Pavement Distresses

The type, severity and quantity of pavement distress within each sample unit is determined by visual distress survey of the pavement and recorded on data sheets. The procedures described in ASTM Standard D 5340 are used to determine the distress types, identify severity levels, and to measure the quantity of distress. Sixteen types of distresses are identified on asphalt surfaced pavements, while fifteen types of distresses are identified on PCC pavements. The types of distresses identified on asphalt surfaced pavements and PCC pavements are presented in Table 2.2.

2.6.3 Compute PCI of Sample Units

Next step is to compute the Pavement Condition Index (PCI) of a sample unit according to ASTM standard D 5340. This procedure has been implemented in MicroPAVER to compute the PCI value of each sample unit when the distress data is entered into its database. The steps that are used to compute the PCI of a sample unit is described below:

(a) Determine Distress Quantities: For AC pavements, the total quantity of each distress type at each severity level is sum up. For PCC pavements, the total numbers of slabs that have a particular distress type for a specific severity level are added up.

(b) Determine Distress Density: For AC pavements, to obtain the percent density of each distress type and severity, the total quantity of each distress type at each severity level is divided by the total area of the sample unit and multiplied by 100. To do the same thing for PCC pavements, the total number of slabs for each distress type at each severity level is divided by the number of slabs that are contained within the sample unit and multiplied by 100.

(c) Determine Deduct Value: The deduct value for each distress type and each severity level is determined by using the deduct value curve for each particular distress type. These deduct value curves are shown in ASTM Standard D 5340. Figure 2.4 shows a deduct value curve for linear cracking in asphalt surfaced pavements.

(d) Determine Correct Deduct Value: If only one or no deduct value is greater than five, the sum of the deduct values is used to obtain the total deduct value for the sample. If not so, a value called the corrected deduct value for the sample is computed using the deduct values obtained for the different distress types. This method is used because there is an interacting effect between different distress types, and if the deduct values were not corrected an unreasonable deduct value could be arrived for the sample. The deduct values obtained for each distress type and each severity levels are combined using the procedure described in ASTM standard D 5340 to obtain the corrected deduct value for the sample.

(e) Obtain PCI of Sample Unit: Next step is to subtract the deduct value or corrected deduct value if applicable from 100 to obtain the PCI of the sample unit.

2.6.4 Compute PCI of Section

If all surveyed sample units that were surveyed were selected randomly, or if all sample units within the section were surveyed, the PCI of the section is the average of the PCI values that were obtained for the samples within the section. If additional sample units were surveyed within the section, then a weighted averaging method is used to compute the PCI of the section. The details of this method are given in ASTM standard D 5340.

2.7 Structural Condition Index Determination

Structural Condition Index (SCI) can be determined using pavement distress survey data where in calculating deduct values only the distresses responsible for structural degradation is considered.

In 2004 Garg has performed a pavement evaluation of 30 airports from 10 states and has divided all pavement distresses into five classes: i) Cracking; which includes longitudinal and transverse cracks, alligator or fatigue cracking, block cracking, slippage cracking and reflection cracking, ii) Disintegration; which includes raveling and weathering, iii) Distortion; which includes rutting, corrugation, shoving, depression and swelling, iv) Loss of skid resistance; which includes bleeding, polished aggregate and fuel spillage and v) Other distresses; which includes jet blast and patching (Garg et al. 2004). The cumulative deduct values due to distresses in a group are defined as the reduction of PCI which has been discussed earlier. Garg used following formula to determine SCI from PCI:

$$SCI = 100 - (100 - PCI) \times \frac{DSCI\ (\%)}{100} \qquad \text{(Eq. 2.4)}$$

where DSCI (%) is deduct SCI and is equal to the sum of the deduct values due to load related distresses such as alligator cracking and rutting for flexible pavements.

The minimum required value of SCI is 80 where critical PCI value is 55-70. Critical PCI is that value of PCI below which both the rate of pavement deterioration and the rehabilitation cost is much higher than relatively better condition of pavement (Shahin 2002). According to the study of Garg, runways have shown higher SCI than taxiway and aprons because of the slow speed of the aircraft on taxiways and aprons and longer load durations which are the contributing factors as both of them are related to fatigue cracking and rutting.

2.8 Skid Data Collection and Analysis

According to Green (2009), the major reason for collecting skid resistance data is to prevent or reduce accidents. The data are used to identify pavement sections with low or rapidly deteriorating levels of skid resistance. Skid resistance is defined as the force that resists the sliding of tires on a pavement when the tires are prevented from rotating vehicle control or the aircraft landing safety is highly dependent on pavement characteristics. Skid resistance is considered as a pavement property but other condition such as tire pressure, tire tread, the presence of water, temperature, load and vehicle speed also affect it. When pavements become dry, the friction between the tires and the pavement is usually high.

In general, skid resistance deteriorates with increasing traffic until it reaches a level of equilibrium. The study reported that, the deterioration of skid resistance stabilize after 2 years or after many applications of traffic. Friction measurement usually conducted along wheel path. On runways, the measurements are conducted along the entire length of the runway, 10 ft off the centerline. The coefficient of friction is referred to as friction factor and is defined as the ratio between the friction force in the plane of the interface and the force normal to the plane. Several methods for measuring the friction factor of a pavement are used all over the world such as Locked-wheel Mode, Slip Mode and Yaw ode. In Locked-Wheel Mode, the test wheel is locked and water is applied in front of it and the results are reported as Skid Number (SN) (Shahin 2002):

$$SN = 100 \times ff \qquad \text{(Eq. 2.5)}$$

where SN is the skid number and ff is the friction factor. Maintenance warrants for different skid number for runways are described at a FAA Advisory Circular (AC 150/5320- 12C).

2.9 System Dynamic Modeling in PMS

Two types of computer based pavement management system (PMS) has been used widespread for the past few decades (Linard 2000). Previous linear programming optimization for PMSs are related to development of a cost effectiveness based integer programming on a year by year basis for preserving pavement with constraint budget limitation and management goals (Yoo and Diaz 2008). Effect of treatment timing is studied in very few previous studies (Morian et al. 2006 and Peshkin et al. 2004).

Non analytical database PMS or statistical correlation modeling both have their own drawbacks such as they have little predictive capabilities and assumes small size problems not considering multi-year budgeting and frequency of maintenance life are not included. However, real world such as PMS is non linear in nature and is a complex system having many variables like pavement condition, user response, load, environment, degradation, maintenance, constrained budget and so on. System dynamics is a simulation modeling process capable of capturing the structure and behavior of any complex system. Delay time or many variables effect can be easily captured in the system dynamic model which is time consuming and difficult to achieve with the help of Monte Carlo simulation or regression modeling. Pavement condition with or without rehabilitation over an analysis period and budget scenario at different condition of a pavement which are also in a linkage with many other variables make it suitable for system dynamic study.

2.9.1 Components of the Modeling

System dynamics is a methodology and mathematical modeling technique to understanding the behavior of complex systems over time which helps managers improve their understanding of managing processes. It is currently being used by the public and private sector for policy analysis. It requires feedback loops and time delays that affect the behavior of a complex system. It is different from other approaches in studying complex systems and in application of feedback loops and stock and flows. It deals with system theory as a method for understanding the dynamic behavior of complex systems. The basis of the method is that the structure of any system such as circular, interlocking, or time-delayed are often just as important in determining its behavior as the individual components themselves.

The founder of systems dynamics, Jay Forrester has suggested that a model should have the following characteristics (Reno et al. 2011):

- Able to describe any statement of cause-effect relationships.
- Mathematically simple.
- Closely synonymous in nomenclature to economic and social terminology.
- Without exceeding the practical limits of digital computers extendable to large numbers of variables.
- Able to handle continuous interactions so that any artificial discontinuities introduced by solution-time intervals will not affect the results. Also should be able to generate discontinuous changes in decisions when these are needed.

System dynamics (SD) models represent a structure of reservoirs or levels interconnected by controlled flows. SD models include three basic features (Tidwell 2011):

(a) Reservoirs or levels that accumulate (Water, Fund, Condition Index, Roughness)

(b) Flows into and out of the reservoir (Deterioration per year, Dollar per fiscal year)

(c) Constants and other variables that influence flows (Initial condition, Life extension)

Pavement maintenance is part of a complex system comprising the road pavement, the environment, diverse users, the maintenance authority and Government. In order to decide if a certain maintenance work can achieve the final objective we need a decision analysis process. Figure 2.5 (a) indicates level, flow and constants for a pavement maintenance module and Figure 2.5 (b) indicates time graph of PCI.

2.9.3 Steps in Modeling

System dynamics modeling has four major steps: i) Conceptualization (Reference Mode and Dynamic Hypothesis), ii) Formulation, iii) Testing and iv) Implementation (Friedman

2003). The first step of system dynamic modeling is conceptualization which has two parts: reference mood and dynamic hypothesis. Conceptualization deals with the development and identification of a problem. Reference mood is often called as problem articulation which means to develop the problem statement properly. It is not possible to model the entire system; a specific problem must be addressed. The key variables, system boundary and the time horizon should be defined. Reference mood is a graphical representation of the problem that exists over time. After developing reference mood the second part of conceptualization is to establish dynamic hypothesis. Dynamic hypothesis develop a working theory of how the problem arose and how variables are dynamically linked. Causal loop diagrams capture hypothesis about causes of system dynamics and communicate the hypothesis. They are consisting of variables connected by arrows denoting the causal influence among variables. Causal loop diagram represents a distillation of feedback structures that was derived by conceptualizing the parts of the system and simulating their interactions.

The second step of system dynamic modeling is formulation which is the process of formulating equations into model structure. It is also called quantifying conceptual model; which is the next step after developing a conceptual model described in last paragraph. It is the translation of the model from an informal concept into a quantitative representation in which the causal loop diagram is put into a formulated equation. Specification of decision rules, estimation of parameters and initial conditions, tests for consistency with problem purpose and boundary; are the key components of model formulation.

The next step of the modeling process is testing and confidence building. After conceptualization and formulation the model should be tested whether it represents the problem behavior adequately or not. Robustness under extreme condition, sensitivity to the variables uncertainty and calibration with the historical system behavior is the key part of model testing. Implementation is the last step of the SDM which can be referred as Policy design and evaluation. Once the model is formulated it needs to be used for analysis and policy development.

Table 2.1: Standard PCI Rating Scale

PCI	Default Color	Comments
85-100	Dark Green	Excellent
70-85	Light Green	Very Good
55-70	Yellow	Good
40-55	Light Red	Fair
25-40	Medium Red	Poor
10-25	Dark Red	Very Poor
0-10	Dark Grey	Failed

Table 2.2: Distress types for airfield pavements

Distress Types on Asphalt Surfaced Pavements	Distress Types on PCC Pavements
Alligator Cracking	Blow Up
Bleeding	Corner Break
Block Cracking	Longitudinal, Transverse, Diagonal Cracks
Corrugation	Durability (D) Cracking
Depression	Joint Seal Damage
Jet Blast Erosion	Patching Small
Joint Reflection Cracking	Patching Large and Utility Cuts
Longitudinal and Transverse Cracking	Popouts
Oil Spillage	Pumping
Patching and Utility Cut Patching	Scaling, Map Cracking and Crazing
Polished Aggregate	Settlement or Faulting
Raveling and Weathering	Shattered Slab/Intersecting Cracks
Rutting	Shrinkage Cracks
Shoving	Joint Spalling
Slippage Cracking	Corner Spalling
Swell	

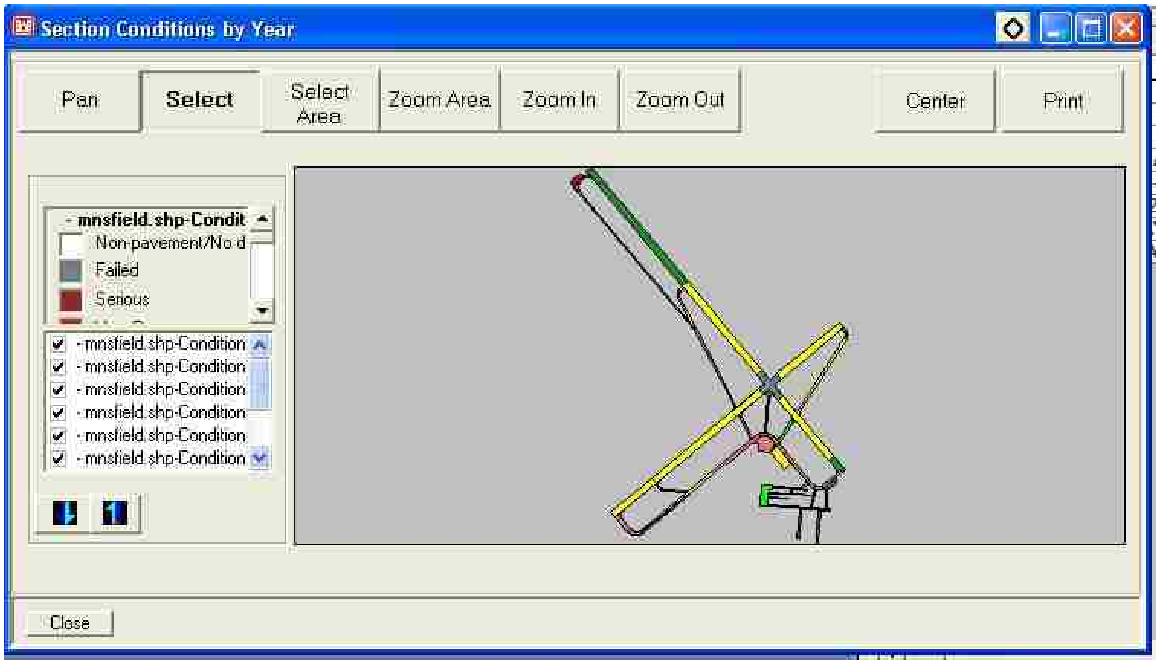


Figure 2.1: Condition Analysis outputs are displayed in GIS

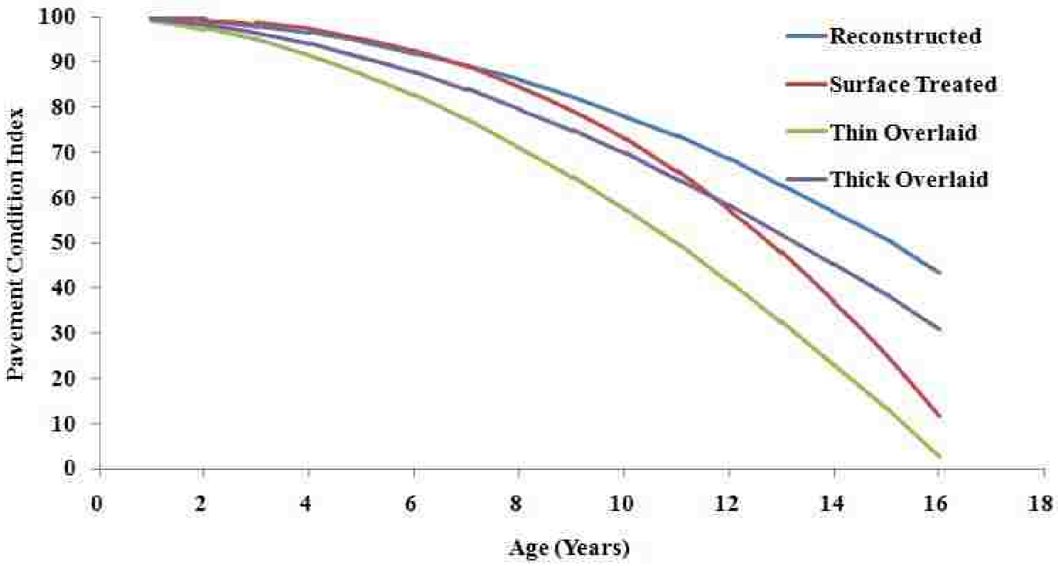


Figure 2.2: Standard performance curve in Washington State's PMS

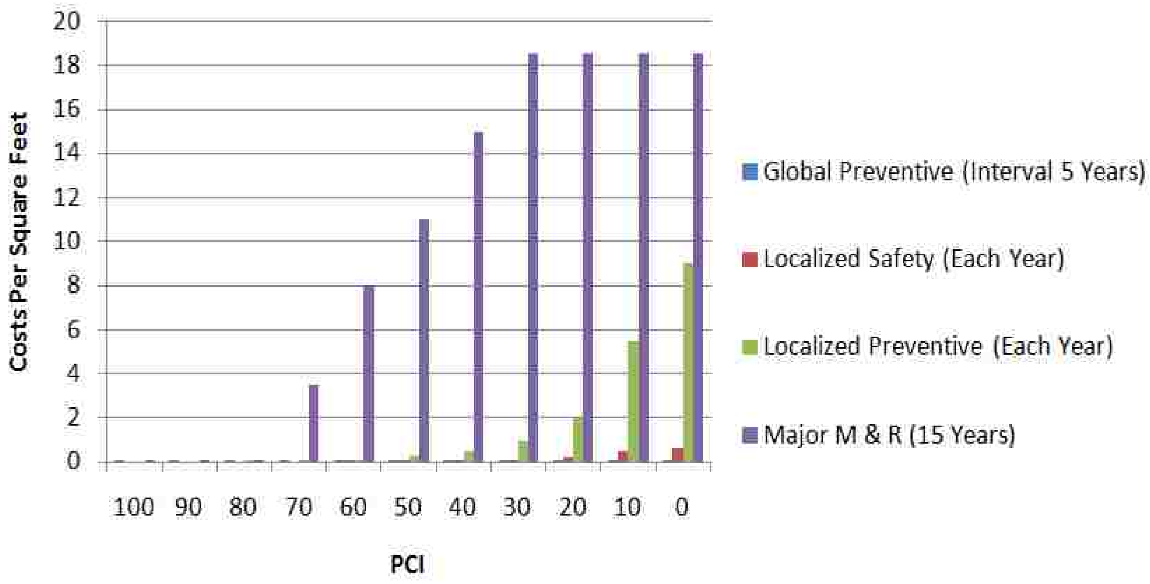


Figure 2.3: Cost per condition

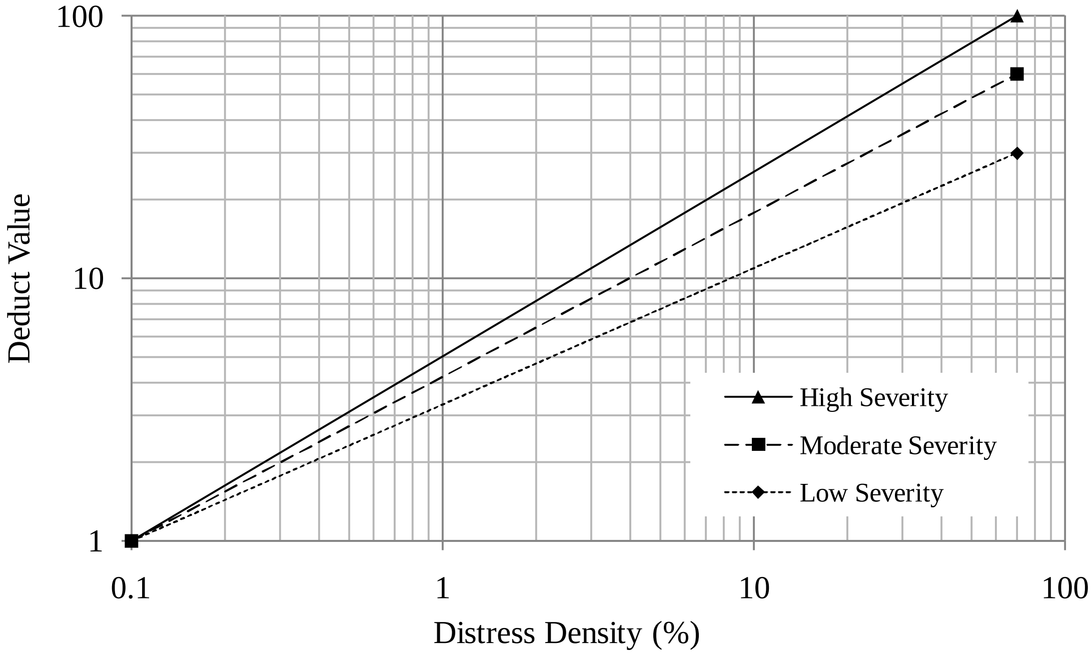
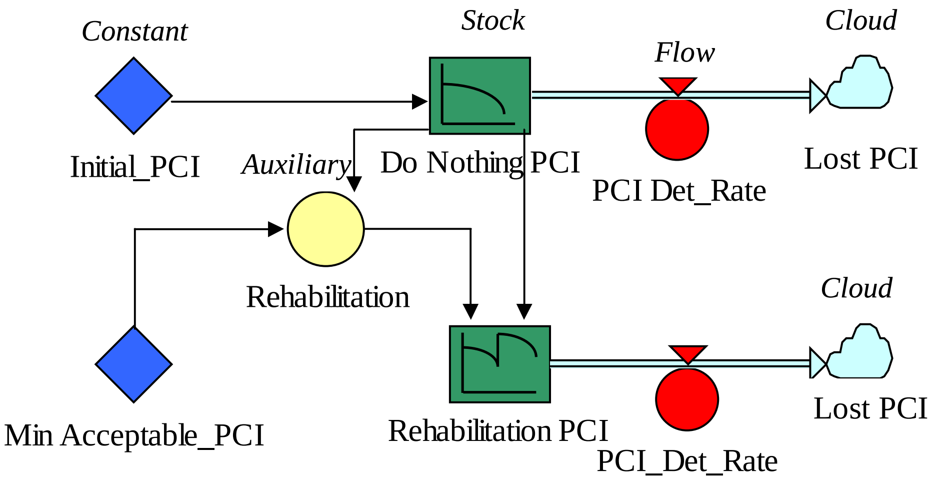
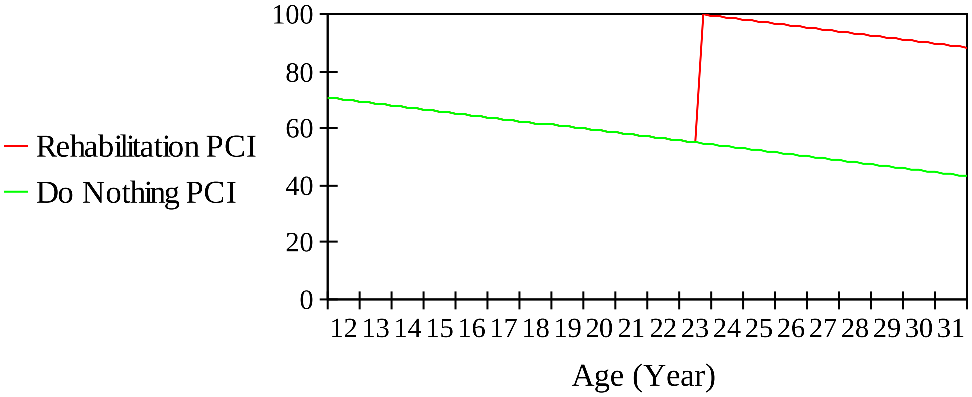


Figure 2.4: Deduct value curve for linear cracking on asphalt surfaced pavements



(a)



(b)

Figure 2.5: Notation of PCI Module and Time Graph of PCI

CHAPTER 3

PCI AND NON-PCI BASED PAVERMENT EVALUATION

3.1 Introduction

Pavements of nineteen New Mexico general aviation airports have been evaluated in this current study. The name of these airports are: (1) Artesia Municipal, (2) Carlsbad Cavern City, (3) Forts Sumner Municipal, (4) Grants Milan Municipal, (5) Lea County Hobbs, (6) Lea County Jal, (7) Lordsburg Municipal, (8) Questa Municipal, (9) Santa Rosa Municipal, (10) Belen Alexander, (11) Clayton Municipal, (12) Deming Municipal, (13) Double Eagle II, (14) Las Cruces International, (15) Moriarty Municipal, (16) Raton Municipal, (17) Roswell International, (18) Sierra Blanca Regional and (19) Grants County. These airport pavements are first evaluated using 2006-2007 survey data and, then predicted for 2012. The locations of these nineteen airports are shown in Figure 3.1.

In this chapter pavement condition index, structural condition index and skid resistance based pavement evaluation have been represented for these airport pavements. PCI and SCI have been determined with the visual distress survey data using MicroPAVER. Distress data collection was done in accordance with ASTM 5340-03 and skid resistance was carried out according to ASTM E 274-06. After the evaluation, a comprehensive study has been performed considering all these three indices.

3.2 Objectives of the Chapter

This chapter has the following two major objectives:

- Develop a MicroPAVER database containing distress data and condition data.

- Separate and combined pavement evaluation considering PCI, SCI and SN.

3.3 MicroPAVER PMS Methodology

To ensure optimum return in the investment, a systematic approach to pavement management is needed. Over the past thirty years, the following approach has evolved for as part of the development of the PAVER pavement management system. The steps of the MicroPAVER PMS methodology are described below (Shahin 1990).

3.3.1 Inventory Definition

The pavement network is divided into branches and sections. A network is a logical grouping of pavements for M&R managements. The pavement manager is the one to decide which facility types will be identified as separate networks. For this current study, every different airport is known as different network and has their unique network ID. A branch is an easily recognizable with a common use such as runway, taxiway, apron or helipad. Grants is a network consists of six different branches named Apron, Runway 13-31, Taxiway A, Taxiway B, Taxiway C and Taxiway D (Table 3.1). Each branch is broken into separate sections based on construction, condition and traffic. A branch does not necessarily have consistent characteristics throughout the entire area. Hence it is divided into smaller components as sections for managerial purposes. It is the smallest management unit to apply a maintenance treatment.

A section must also be of same surface type. Each branch consists of at least one section, but may consist of more if pavement characteristics vary throughout the branch. Runway 13-31 of Grants airport has two sections named R 13-31-1 and R 13-31-2. Current study includes 19 different network having 232 total numbers of branches and 413 total numbers of sections. Those 19 airports have total pavement area of approximately 55 million square feet (Table 3.2).

3.3.2 Pavement Inspection

Pavement inspection consists of visual distress survey at a minimum of every 1 to 5 years, Skid resistance measurement, and Nondestructive Deflection Testing (NDT) which are normally performed every 5-10 years. Current study has been performed using the visual distress survey data of 19 airports conducted in 2006-2007. Distress data collection was done according to ASTM 5340-03 for the 16 distresses and three severity levels: low, medium and high. Theses distress data were given in MicroPAVER as inputs to determine the PCI and SCI value for each pavement sections.

3.3.3 Condition Assessment

The inspection results are reduced to condition indicators that can be used for pavement management purpose. Pavement Condition Index (PCI) is widely used distress index and has a score from 0 to 100 that measures functional condition or the surface operational condition of the pavement. According to PCI, pavements can be classified into seven category as follows: Failed (0-10), Serious (10-25), Very Poor (25-40), Poor (40-55), Fair (55-70), Satisfactory (70-85) and Good (85-100). The skid resistance data is reduced to a friction index for the runways.

In calculating PCI, MicroPAVER considers all 16 distresses found in the relevant section and in determining SCI it consider the distresses responsible for structural degradation of the pavement such as alligator cracking, depression, longitudinal and transverse cracking, patching, rutting, and slippage cracking for asphalt airfields and corner break, linear crack, large patch, pumping, faulting, shattered slab for concrete airfields. The area weighted average PCI, SCI and runway average SN for 19 networks in the year of inspection are shown in Table 3.3.

3.3.4 Condition Prediction

Different prediction models work for different locations and conditions for which it is developed and the models are used to predict the future condition of the pavement sections assuming that the traffic will continue to be the same as in the past. To draw a straight line condition curve, at least two years' distress data is needed. As this study has only one year's distress data, a MicroPAVER based condition prediction curve is used which only depends on the current PCI discussed in the literature chapter.

3.3.5 Condition Analysis

Condition analysis allows the decision maker to compare past, present and future conditions assuming no major M&R is performed. It provides the manager with the ability to assess the consequence of the past budget scenarios. From the survey data, surveyed year PCI and SCI for 19 airports are developed using that strategy and are shown in Table 3.4. For skid resistance, tests are performed only on runways.

3.3.6 Work Planning

The work planning tool in MicroPAVER provides the ability to determine budget consequences for a specified fund available or alternatively, fund required to meet specified management objectives. Typical management objectives include maintaining current network condition, reaching a certain condition in the next x years, or eliminating all backlogs in x years. For this study, a 20 year work plan has performed in Critical PCI method to maintain the PCI 80 ± 3 for the whole pavement area which is consists of 19 airports. Detailed MicroPAVER M&R results will be discussed on Chapter 5.

3.4 Pavement Evaluation

Three indices PCI, SCI and SN are determined for inspection year, current year and the future year for 413 sections of all networks from the visual distress survey data performed in 2006-2007. The results obtained by MicroPAVER are described in the following section.

3.4.1 Distress Classification by Cause

Study of a specific distress type, severity and quantity provides valuable information to determine the cause of pavement deterioration, which helps to select an appropriate maintenance type. In MicroPAVER, distresses have been classified into three groups based on cause: load associated, climate associated and caused by other factors. In classifying distresses by cause, the total deduct values attributable to load, climate and other causes are determined separately and then the percentage of deducts attributable to associated cause is computed. The percentage of deduct values attributed to each cause is the key to determine the primary cause of pavement deterioration.

Table 3.4 shows the percentages of climate, load and other related distresses for various networks of current study. For asphalt pavement, alligator cracking and rutting and for concrete pavement, corner break, linear cracking and shattered slab are known as traffic load related distresses. These distresses are mainly responsible for increasing deduct values in calculating SCI. Climate related distresses are block cracking, joint reflection cracking, longitudinal and transverse cracking and raveling for asphalt airfield and blowup, durability cracking and linear cracking for concrete airfield. All other distresses are classified as caused by other factors, such as: oil spillage, patching, pop outs.

3.4.2 Pavement Condition Index

Pavement condition index represents the functional condition of the pavement. PCI of runway, taxiway, apron and helipad for the current study are shown in Table 3.5. Current study has only one helipad in Roswell airport having PCI of 84. Runways, taxiways and aprons have almost same weighted average PCI over 60 and standard deviation over 20. Taxiway has over 50% sections if numbers of section are considered and runways have almost 50% area if pavement area is considered.

PCI of different surface type are shown in Table 3.6 where 84% area is of asphalt concrete having almost same PCI of PCC pavements. PCI in inspection year of different airport networks are shown in Figure 3.2(a). Sierra Blanca has the maximum weighted average PCI of 82 and Artesia has the minimum weighted average PCI of 48. Figure 3.2(b) represents current and inspection year PCI of different airports.

Numbers of section having different condition are shown in Figure 3.3(a). From this figure it can be said that almost a three-fourth section had their condition fair or better in inspection year and one-fourth was of poor or worse condition. Figure 3.3(b) represents percent area of different condition in inspection year. 25% of total pavement area is in satisfactory condition and 29% is of fair condition. Condition analysis is performed for 20 years analysis period in MicroPAVER and numbers of section obtained of various conditions are shown in Table 3.7. Pavement deterioration curves obtained from

MicroPAVER analysis are shown in Figure 3.4(a) for all networks and in Figure 3.4(b) for Grants Milan Municipal airport. A digital plan view is drawn in AutoCAD to show inspection year pavement condition and current year pavement condition for different sections of Grants in Figure 3.5 and Figure 3.6 respectively. Digital plan views of other airports are shown in Appendix I.

3.4.3 Structural Condition Index

Only load associated distresses are considered to calculate Structural Condition Index. Following formula is used to derive SCI from PCI (Garg et al. 2004).

$$SCI = 100 - (100 - PCI) \times \frac{DSCI\ (\%)}{100} \qquad \text{(Eq. 3.1)}$$

where DSCI (%) is the deduct SCI and is equal to sum of the deduct value due to load related distresses such as alligator crack and rutting for asphalt pavement and pumping and spalling for concrete pavement.

A higher value of SCI is desired as lower SCI indicates that the pavement is structurally week and, the minimum required value is 80. Figure 3.7(a) represents inspection year SCI of various branch use considering all networks. Runway shows the maximum SCI of 90 and apron has the minimum of 84. Structural condition of pavements having different surface is shown in figure 3.7(b). Asphalt surfaced pavements have weighted average SCI of 89 and Portland cement concrete surfaced pavement have its value of 86.

Figure 3.8(a) shows SCI of different years in inspection year and in the current year. Raton and Santa Rosa have the perfect SCI of 100. Artesia had SCI of 84 in 2007 but is now going close to 80; so immediate measure is necessary for this airport. Carlsbad shows really bad structural condition having SCI below 60. Figure 3.8(b) shows current SCI and PCI of all 19 airports in the same graph where only Carlsbad shows both PCI and SCI below 60. Lordsburg and Grants County both show higher value of SCI but PCI below 50. No specific scale has been developed to classify condition according to SCI in the previous literature but 80 are used widely as the minimum threshold value. PCI is frequently used to manage pavement worldwide but SCI is always in the shadow of ignorance for decision making.

3.4.4 Skid Resistance

Dynatest vehicle and trailer are used to perform skid resistance test in the current study according to ASTM E 274-06. A standard tire of inflation pressure 24 psi is used. Vehicle speed is maintained 40 mph and the water is applied in front of test tire at a rate of 40±10 gallon/min. in. of the wetted width. With the pressure on the switch board water is applied and brake is applied to lock the test tire. Automatic reading is taken in 1-3 second interval. Friction force, speed, temperature, effective load are automatically recorded. Mean value of the interval is used to calculate the skid number using following equation.

$$SN = 100\mu = 100\frac{F}{W} \qquad \text{(Eq. 3.2)}$$

where μ = the coefficient of friction, F = the tractive force applied to the tire and W = dynamic vehicle load on tire.

Skid resistance tests are performed on 5 feet, 20 feet and 30 feet from the centerline on either direction of the runway. Table 3.8 shows the skid data obtained from a Dynatest test in Runway 13-31 of Grants from 5 feet distance from centerline. It shows the skid number below considerable limit. SN decreases with traffic and after few years in attains an equilibrium value. 50 is considered as the minimum acceptable SN for Dynatest skid test with speed 40 mph and 60 is known as the trigger value to perform maintenance planning. Skid resistance test was performed almost every runways and few taxiways for the 19 airports. Figure 3.9(a) shows the skid number for the 37 runways where the test was performed. Belen, Lordsburg and Moriarty all have one runway each having very bad skid condition, which is below 35. 12 other runways of different airports also show skid resistance below 50. Figure 3.9(b) shows SCI, PCI and SN together for runways.

3.5 Relation between Different Indices

Traditionally maintenance strategies for airport pavements are selected using the critical PCI procedure. Although, this PCI approach considers some distresses that indirectly relate to structural degradation, no well-defined relationship between structural and functional performance has been developed yet. For this current study, variation of PCI with SCI for all 413 sections and 37 runway branches are shown in Figure 3.10(a) and Figure 3.10(b) respectively.

Figure 3.10(a) shows coefficient of determination of 55 after linear regression analysis which is greater than 50, as a result indicates large correlation between SCI and PCI for all sections. Figure 3.10(b) shows regression coefficient of 37 which means medium (0.30-0.40) correlation between SCI and PCI for runway branches. SCI value can be greater than or equal to PCI as SCI only consider load related distresses in calculating deduct value. If a specific section shows PCI of 55, it is not possible to guess the SCI value without the knowledge of distress information of that particular section. For that section, SCI can be any value from 55 to 100. The more we deal with the lower PCI value, the more the possibility of variation of SCI we have. Figure 3.10 only can help to develop a scene that PCI and SCI are linearly correlated. Skid resistance and PCI or SCI are determined using entirely two different principals. PCI and SCI as well as SN decreases with time but SN does not depend on the type, quantity or severity of the distress value like PCI or SCI. Therefore, Figure 3.11(a) and Figure 3.11(b) have shown very little correlation between SN with PCI and SN with SCI respectively. If correlation coefficient falls in the range of 0.10 to 0.20 it can be interpreted as small correlation but for both these cases it is below 0.002. It means there is almost no correlation between SN and SCI or SN and PCI.

3.6 Pavement Prioritization

A normalizes PCI-SCI and PCI-SN coordinate system was developed to visualize pavement prioritization in maintenance needs. As a critical PCI, critical SCI and critical SN; 55, 80 and 50 is used because these values trigger the repair work. Instead of plotting PCI, SCI and SN values directly in a coordinate system, those values are normalized first in following manner.

$$PCI_N = PCI - 55 \qquad \text{(Eq. 3.3)}$$

$$SCI_N = PCI - 85 \qquad \text{(Eq. 3.4)}$$

$$SN_N = SN - 50 \qquad \text{(Eq. 3.5)}$$

where PCI_N, SCI_N, SN_N are normalized PCI, normalized SCI and normalized SN.

Figure 3.12(a) shows variation of normalized SCI value with normalized PCI and Figure 3.12(b) shows the variation of normalized SN value with normalized PCI. Both figures are plotted on a graph at which $PCI_N\ and\ SCI_N$ or $PCI_N\ and\ SN_N$ intersect at zero.

Normalized SCI and SN are plotted with normalized PCI to classify different pavements into different coordinates and to relate other indices with PCI. As a result, for both figures, branches having index values locating only second and third coordinate are maintained as they have PCI values below threshold point. The first coordinate have both indices above critical value, hence, it is okay not to repair this section first. However, forth coordinate in both figures is always in the shadow of ignorance for decision makers as they only consider PCI, not SCI or SN. This study shows that, we have two such runway branches in Figure 3.12(a) named RW 14L-32R and RW 3-21 and both are in Carlsbad airport and we have thirteen such runway branches in Figure 3.12(b) which should not be ignored, although they have satisfactory PCI values. In applying maintenance treatment to the runway pavement sections the prioritization should be coordinate III > coordinate II > coordinate IV > coordinate I.

3.7 Conclusion of the Chapter

Following conclusion can be made based on analysis of this chapter:

- Among 19 airports, Artesia has the lowest value of weighted average PCI and Carlsbad has the lowest value of weighted average SCI.
- Belen, Grants, Lordsburg and Moriarty have shown very bad runway skid resistance; hence special measure may be required in these runways.

- Roswell has the maximum percentage of load related distresses; hence structural measure may be needed.
- Among 413 sections, there were 15 failed sections in the inspection year and it becomes 46 now. If no maintenance is took place in next 20 years, almost half of the section will be destroyed.
- In inspection year, more than half of the total pavement area is of satisfactory and good condition considering all 19 networks.
- A good correlation can be drawn between SCI and PCI but SN does not show any correlation with any of the other index.
- Carlsbad has two runways in the forth coordinate or in the coordinate of the shadow of ignorance. Other 13 runways show PCI-SN such that PCI is satisfactory by SN is below critical value, hence special attention is needed.

Table 3.1: Pavement Condition of Grants Municipal in Inspection Year

Branch ID	Section ID	Area (SqM)	Section PCI	Branch PCI	PCI
A (Apron)	A A-1	2,148	87	85	85
	A A-2	1,516	89		
	A B	1,412	84		
	A C	397	89		
	A D	2,369	72		
	A E	1,510	98		
R 13-31 (Runway 13-31)	R 13-31-1	36,928	57	61	61
	R 13-31-2	13,043	74		
T A (Taxiway A)	T A-1	5,202	67	70	78
	T A-2	624	71		
	T A-3	624	70		
	T A-4	680	88		
T B (Taxiway B)	T B-1	8,918	92	91	
	T B-2	922	76		
	T B-3	697	93		
T C (Taxiway C)	T C-1	5,217	74	65	
	T C-2	697	9		
	T C-3	697	50		
T D (Taxiway D)	T D	465	76	76	
Total	19	84,066			69

Table 3.2: Pavement Area and Number of Sections

Network ID	Pavement Area (SqM)	Area (%)	Sections	Section (%)
Artesia	351,365	7	33	8
Belen	108,718	2	15	4
Carlsbad	457,109	9	26	6
Clayton	102,280	2	12	3
DEII	340,300	7	27	7
Deming	224,845	4	26	6
Fort Sumner	149,847	3	13	3
Grants	84,059	2	19	5
Hobbs	464,890	9	44	11
Jal	62,120	1	13	3
Las Cruces	393,404	8	25	6
Lordsburg	50,480	1	6	1
Moriarty	143,422	3	32	8
Questa	55,602	1	3	1
Raton	136,638	3	13	3
Roswell	1,389,849	27	57	14
Sierra Blanka	329,393	6	22	5
Santa Rosa	93,206	2	12	3
Grants County	162,353	3	15	4
Total	5,099,759	100	413	100

Table 3.3: Condition of Different Networks in Inspection Year

Network ID	PCI	SCI	SN
Artesia	48	84	58
Belen	66	87	34
Carlsbad	62	65	58
Clayton	76	96	65
DEII	73	92	56
Deming	68	94	51
Fort Sumner	70	96	65
Grants	69	97	39
Hobbs	63	87	58
Jal	63	87	55
Las Cruces	55	89	53
Lordsburg	58	95	25
Moriarty	66	97	32
Questa	70	97	77
Raton	80	100	51
Roswell	62	87	60
Sierra Blanca	82	99	47
Santa Rosa	74	100	40
Grants County	59	98	48

Table 3.4: Distress Classification by Cause

Network ID	Climate Related (%)	Load Related (%)	Other (%)
Artesia	79.18	18.88	1.94
Belen	79.93	10.40	9.67
Carlsbad	42.23	57.38	0.39
Clayton	87.10	11.00	1.90
DEII	53.20	8.56	38.24
Deming	73.62	13.35	13.04
Fort Sumner	69.62	20.23	10.15
Grants	66.21	22.74	11.05
Hobbs	77.93	18.20	3.87
Jal	71.31	16.15	12.54
Las Cruces	85.73	10.41	3.86
Lordsburg	94.83	4.50	0.67
Moriarty	94.45	1.34	4.21
Questa	97.33	0.00	2.67
Raton	98.38	0.00	1.62
Roswell	37.50	30.77	31.73
Sierra Blanca	88.50	7.80	3.70
Santa Rosa	91.67	0.00	8.33
Grants County	84.23	5.77	10.00

Table 3.5: Branch Use and Pavement Condition

Branch Use	Wt Avg Condition	Avg PCI	STD	Area (SqM)	Area (%)	Sectio ns	Sections (%)
Apron	61	64	24.81	1253750	24.56	104	25
Runway	66	62	22.36	2379400	46.61	73	18
Taxiway	66	68	24.52	1467914	28.75	235	57
Helipad	84	84	0.00	4185	0.08	1	0
Total	65	66	24.34	5105249	100.00	413	100

Table 3.6: Surface Type and Pavement Condition

Surface	Wt Avg Condition	Pavement Area (SqM)	Area (%)	Sections	Sections (%)
PCC	65	842999	16	35	8
AC	64	426225	84	378	92
Total	65	5105249	100	413	100

Table 3.7: Number of Sections by Conditions in next 20 Year

Year	Failed	Serious	Very Poor	Poor	Fair	Satisfactory	Good
2012	46	26	50	76	79	76	60
2013	53	25	53	75	77	76	54
2014	59	26	60	74	70	72	52
2015	64	26	74	62	70	66	51
2016	69	42	59	67	65	61	50
2017	77	40	61	64	66	55	50
2018	83	43	65	58	62	53	49
2019	86	50	60	59	61	48	49
2020	91	57	52	60	58	48	47
2021	111	53	47	55	63	40	44
2022	116	51	53	55	55	39	44
2023	124	52	48	56	52	37	44
2024	131	50	52	49	56	31	44
2025	140	53	46	51	48	36	39
2026	152	44	46	48	51	35	37
2027	164	35	50	45	49	33	37
2028	166	41	48	43	50	28	37
2029	172	41	45	51	39	28	37
2030	178	43	40	48	40	27	37
2031	185	39	43	42	44	25	35

Table 3.8: Skid Results of Runway 13-31 of Grants (% ft from centerline)

Test No	Avg SN	Min SN	Max SN	Peak	% Slip
1	44.4	30	53	91.36	10
2	45.1	38	55	84.36	19
3	39.3	29	45	85.66	10
4	38.3	35	43	93.7	4
5	38.2	31	42	97.44	13
6	37.7	31	43	107.72	7
7	38	33	44	101.23	2
8	39.8	34	47	103.23	5
9	38.2	33	42	100.24	18
10	40	31	49	107.71	27
11	38.2	32	43	90.61	21
12	42.9	34	49	81.67	9
13	43.9	35	56	102.96	18
14	36.6	29	42	101.67	13
15	34.8	29	43	99.74	8
16	39.4	34	47	106.92	10
17	42.9	29	54	100.72	34
18	38.3	29	52	104.23	4
19	48.1	38	58	105.67	10
20	65.4	55	71	102.21	11
21	57.1	52	63	102.77	7

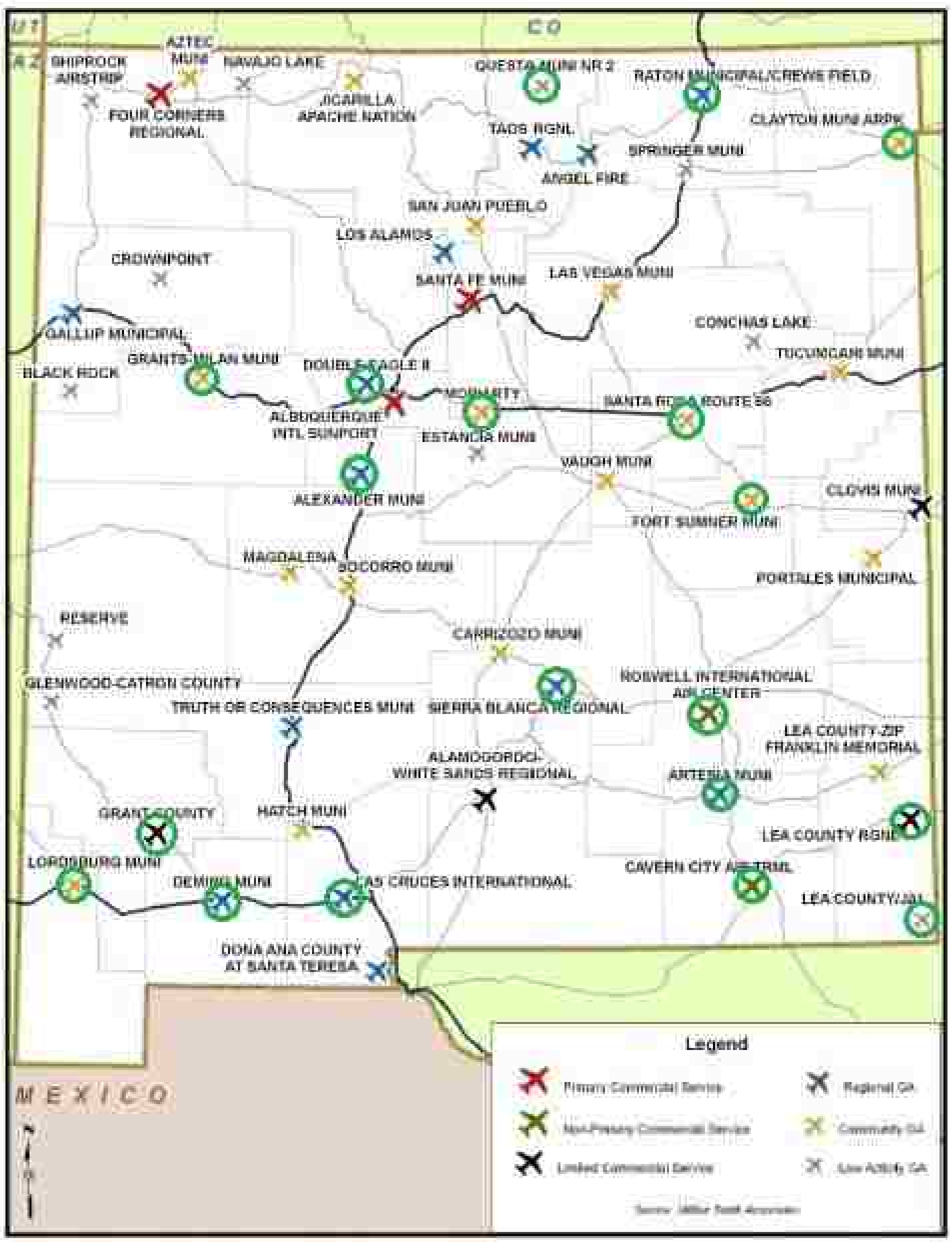
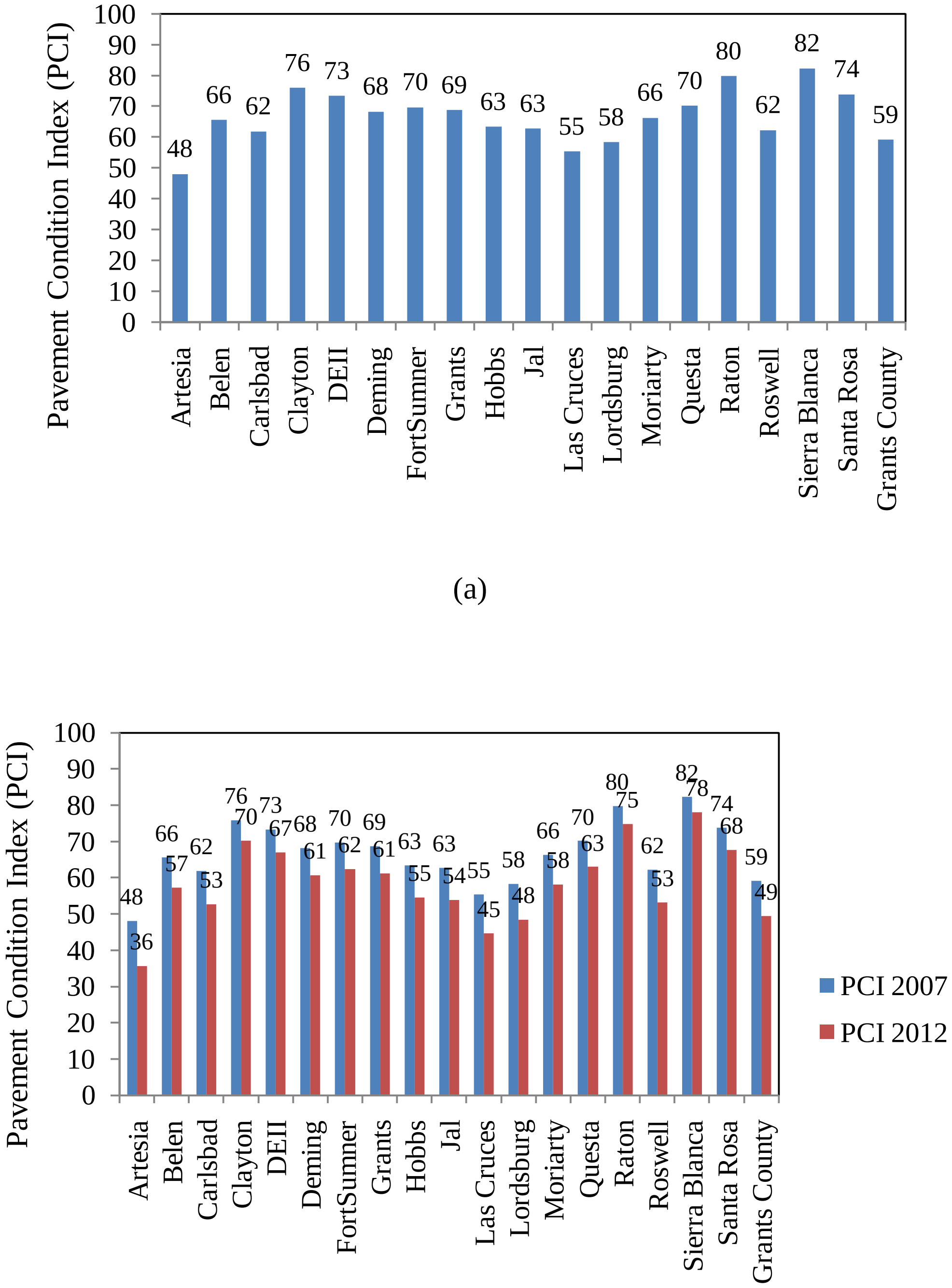


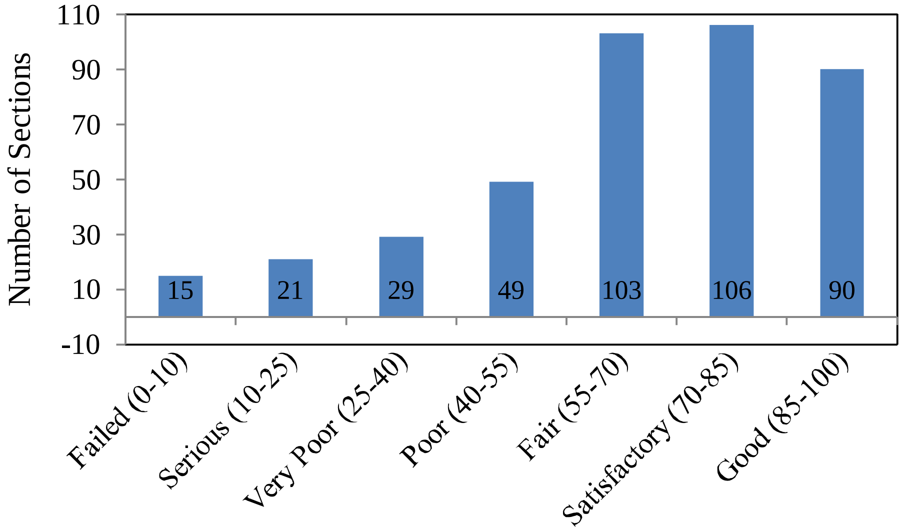
Figure 3.1: Location of New Mexico Airports



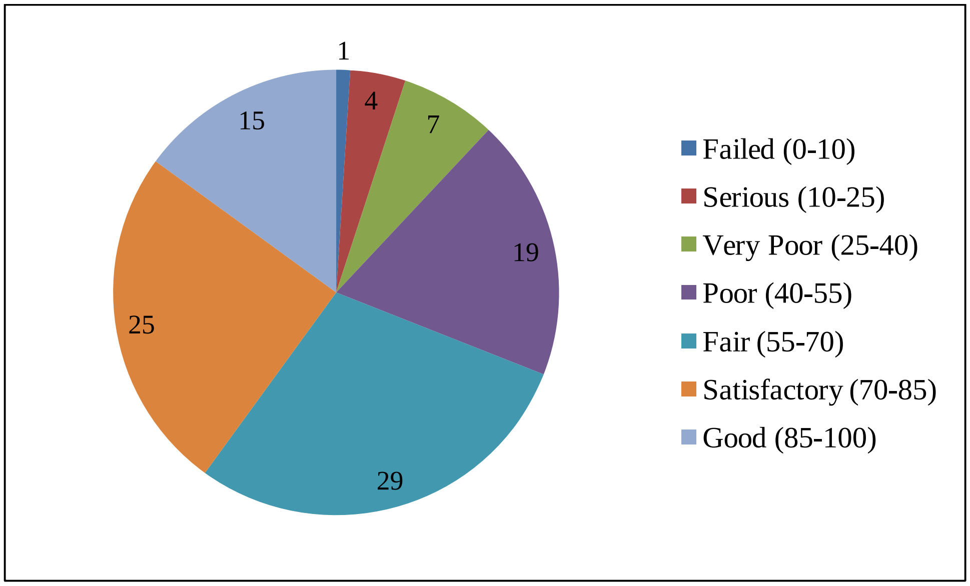
(a)

(b)

Figure 3.2: PCI at last Inspection and Current year PCI

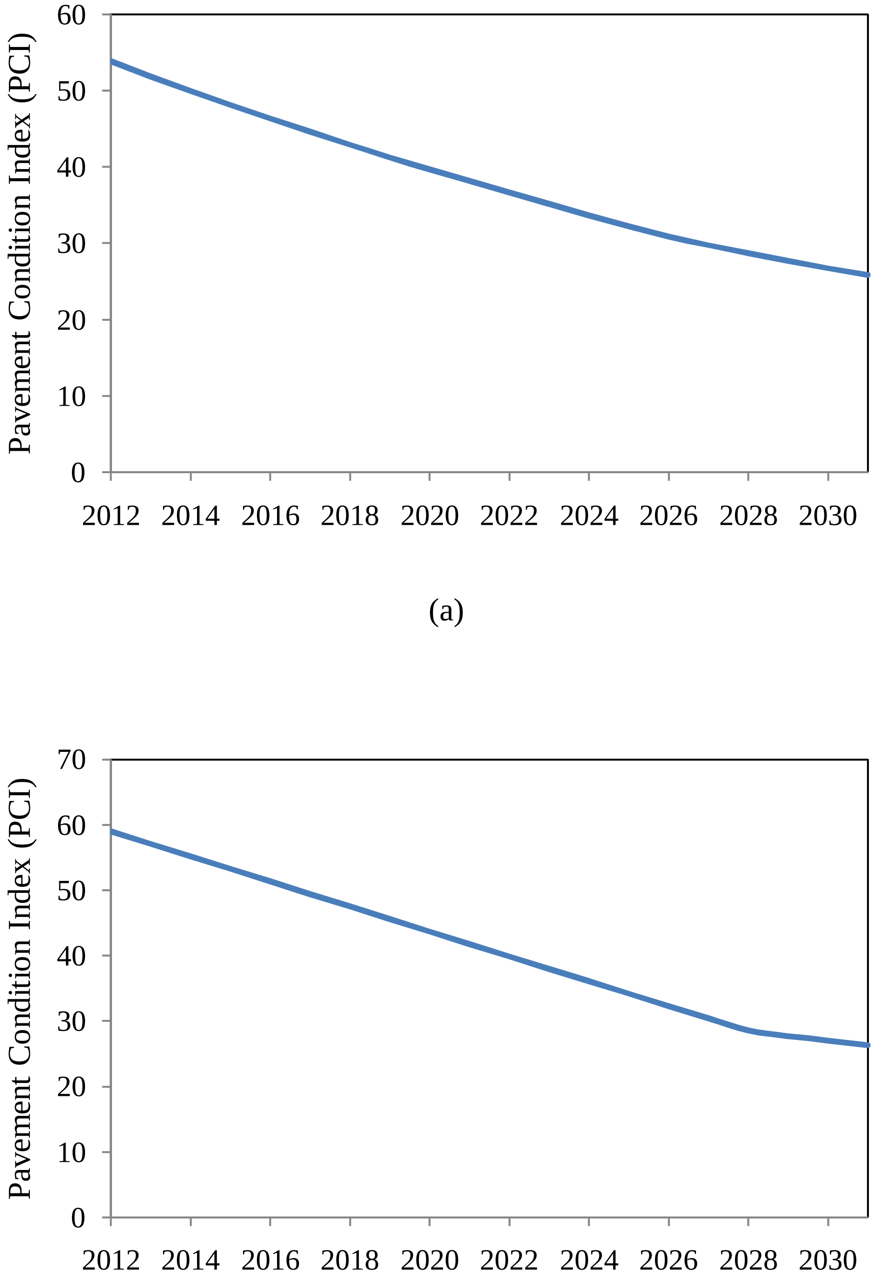


(a)



(b)

Figure 3.3: Number and Percent Area of Section having different Condition



(a)

(b)

Figure 3.4: Pavement Deterioration for all Networks and Grants

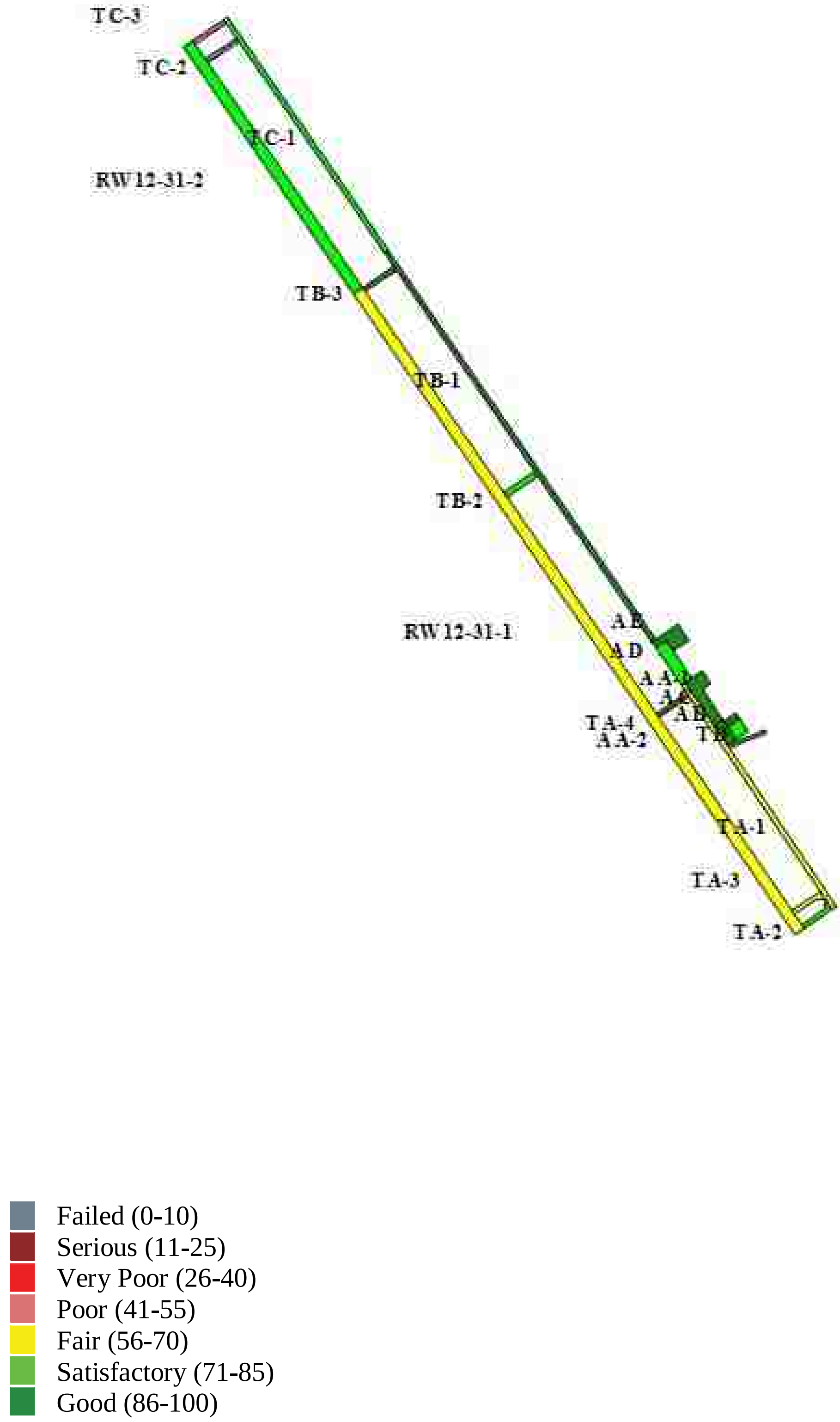


Figure 3.5: PCI digital plan for Grants Milan Municipal Airport (2007 PCI=69)

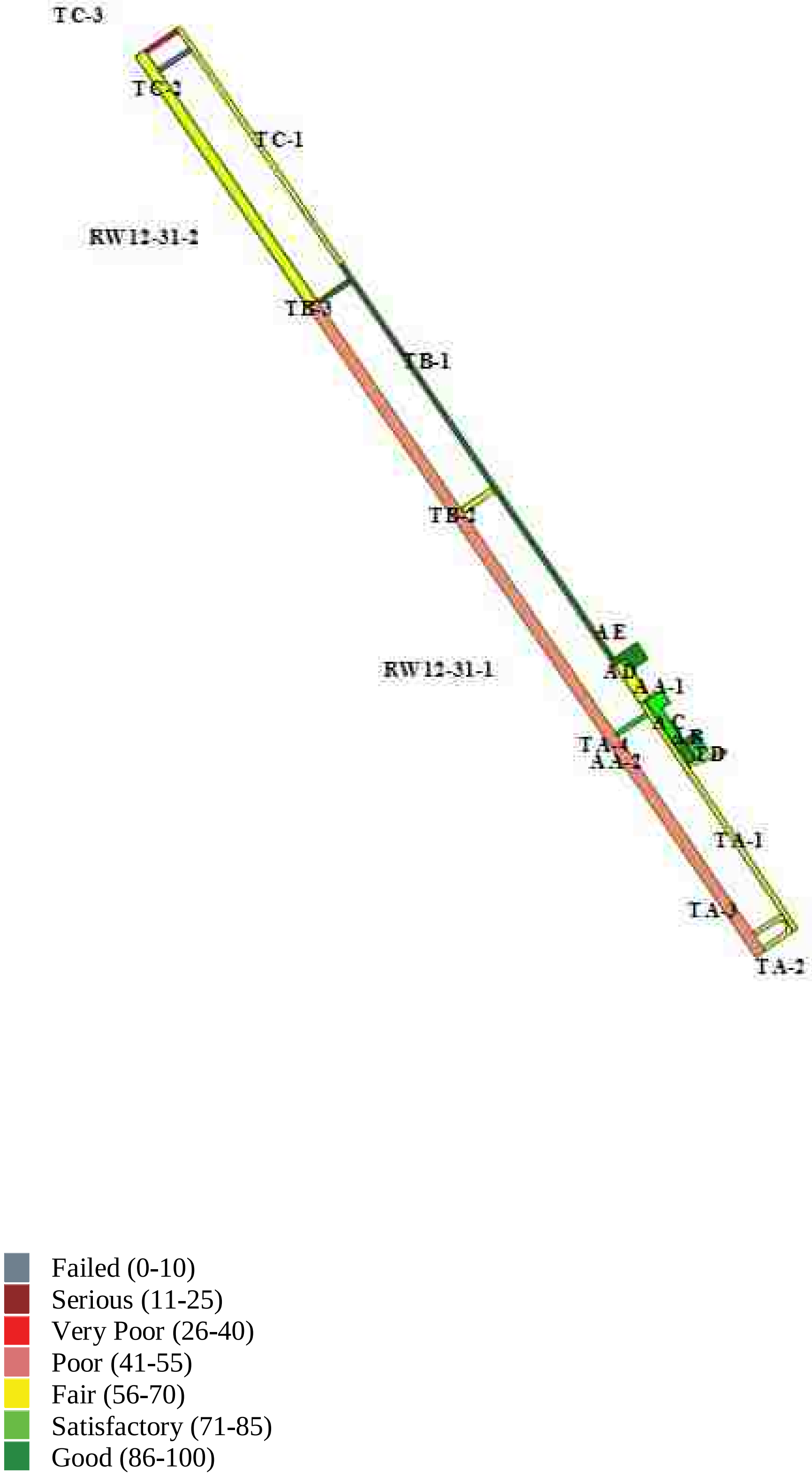
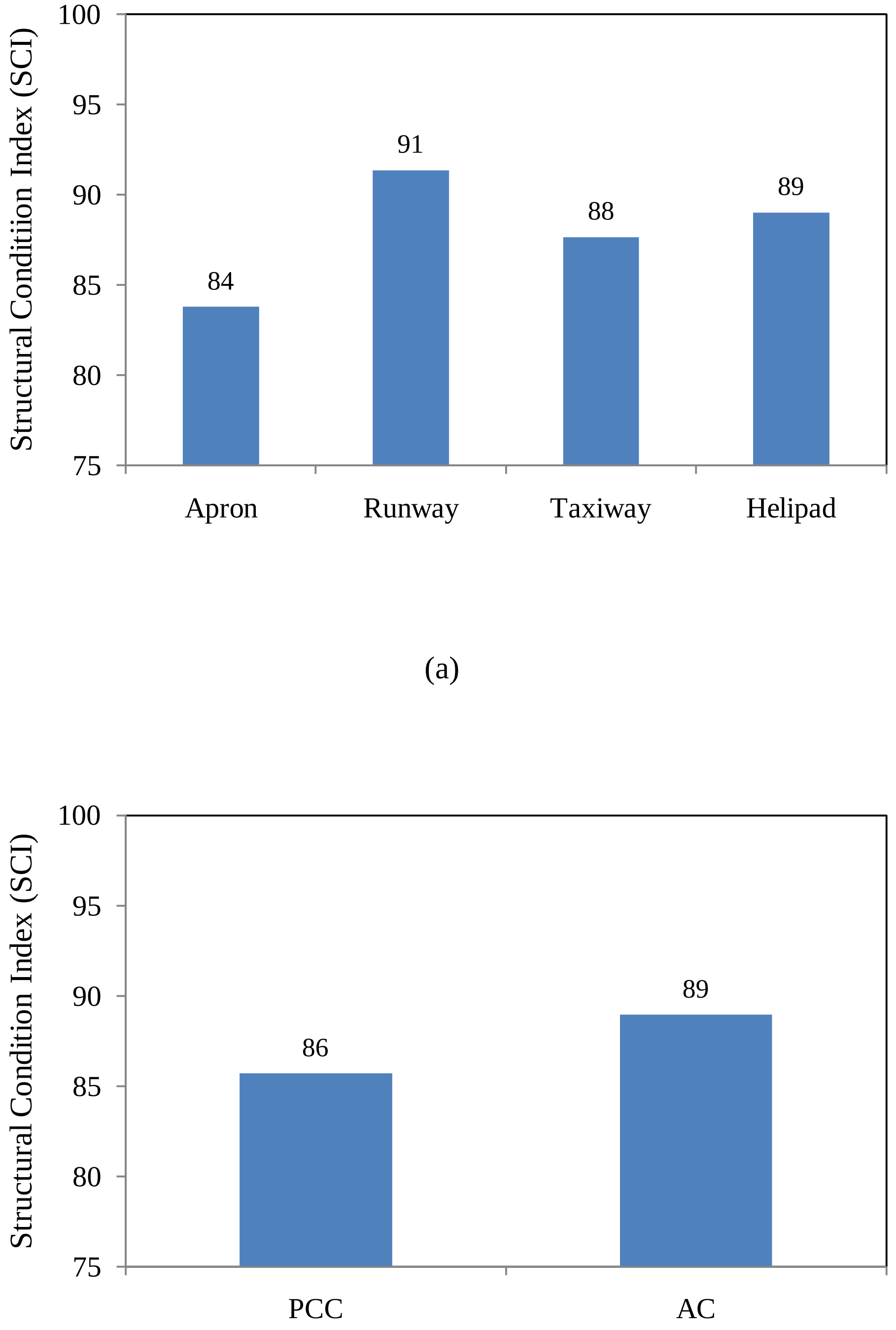


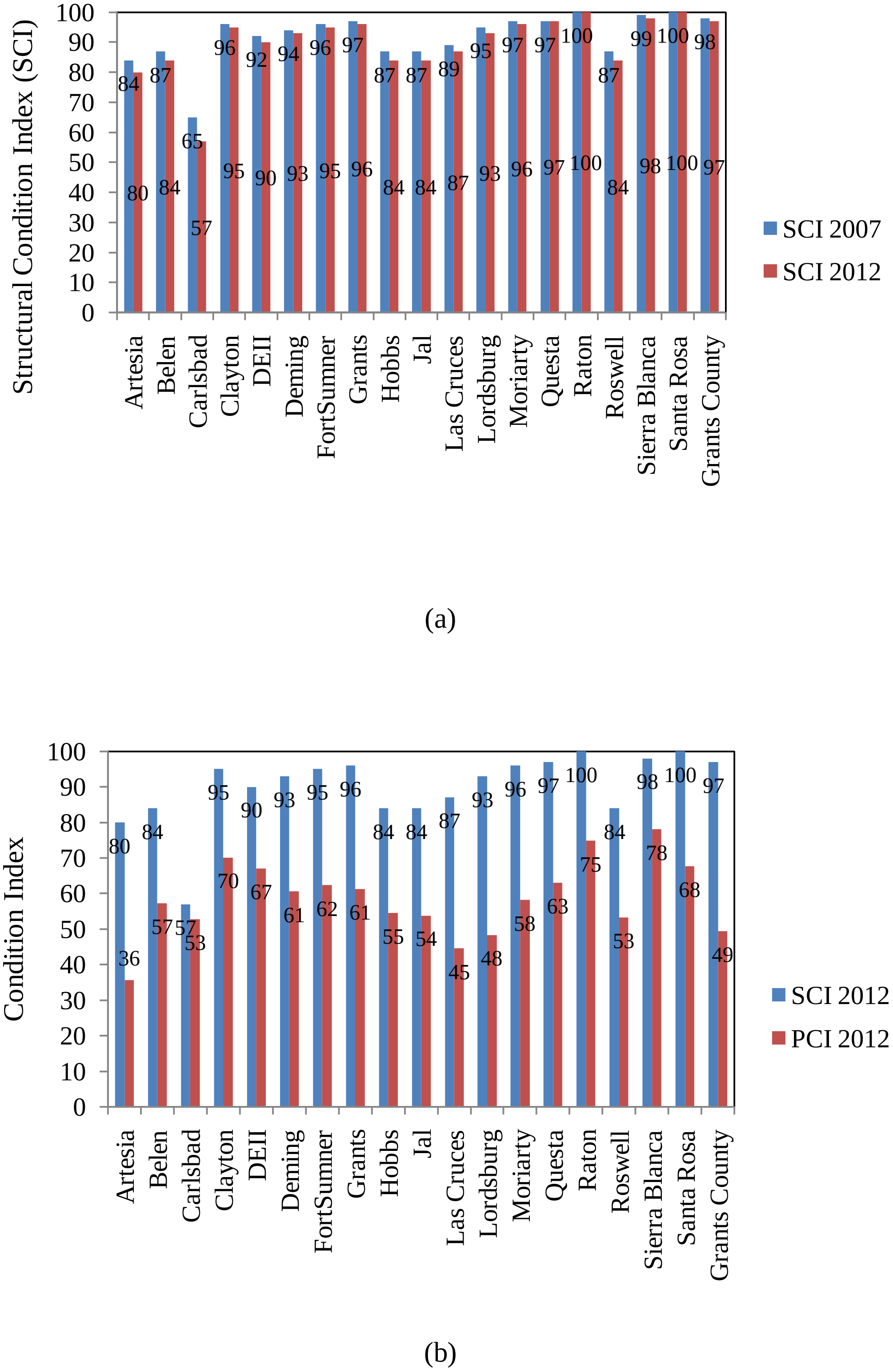
Figure 3.6: PCI digital plan for Grants Milan Municipal Airport (2012 PCI=59)



(a)

(b)

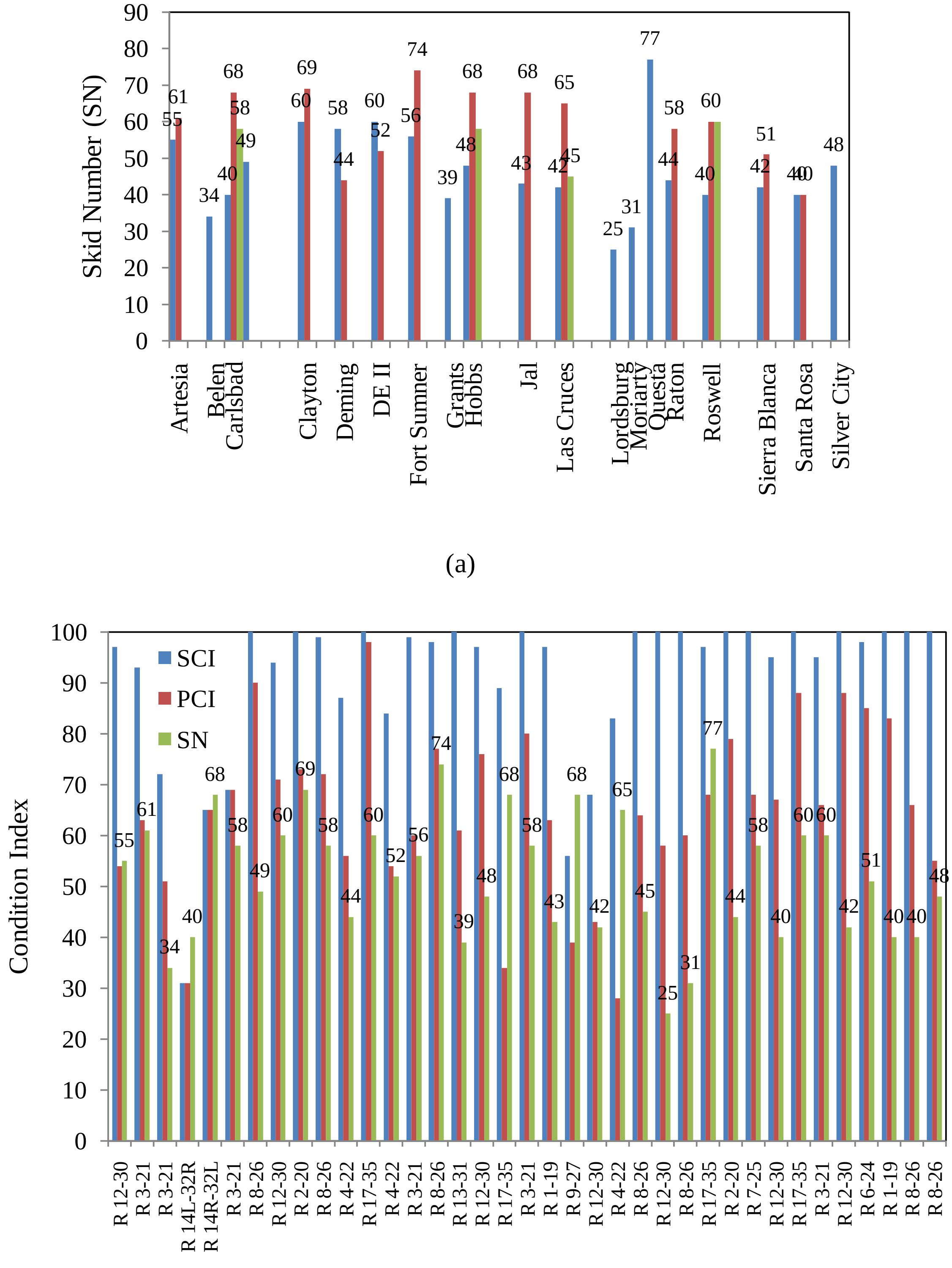
Figure 3.7: SCI of different Branch Use and Pavement Surface



(a)

(b)

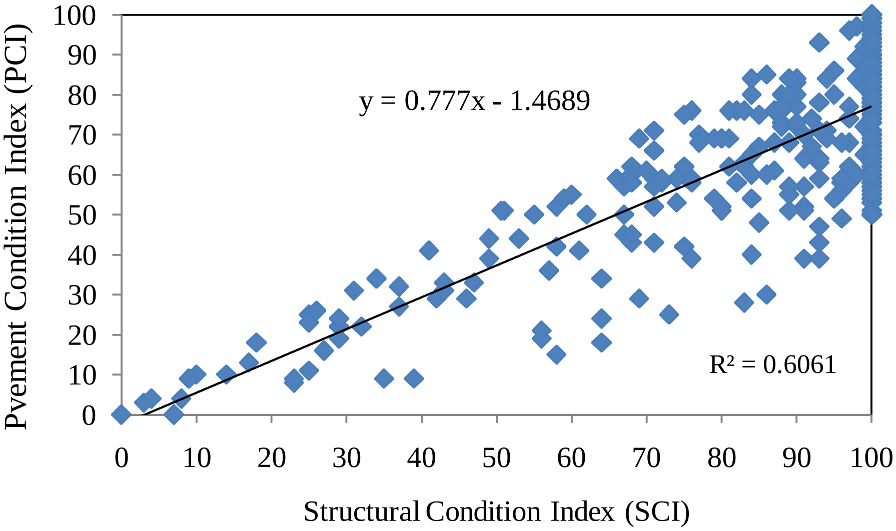
Figure 3.8: SCI and PCI of different Airports



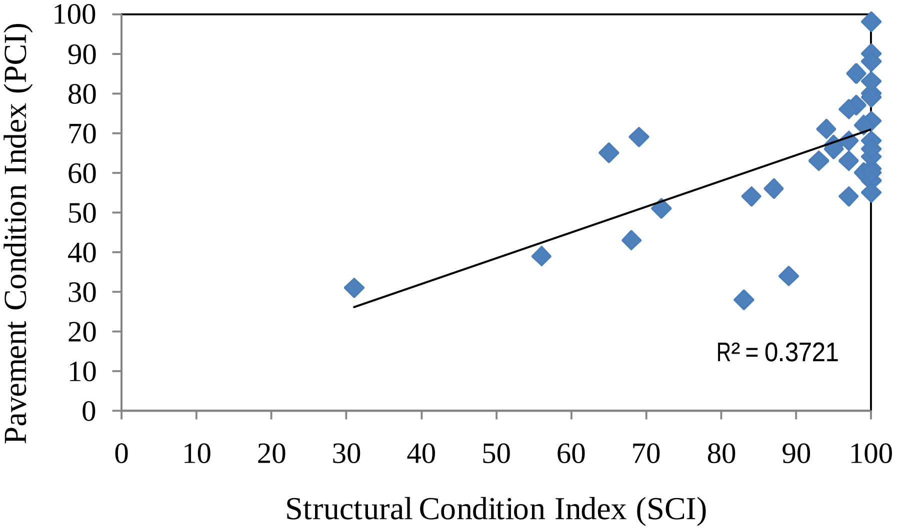
(a)

(b)

Figure 3.9: Runway Condition Indices of different airports

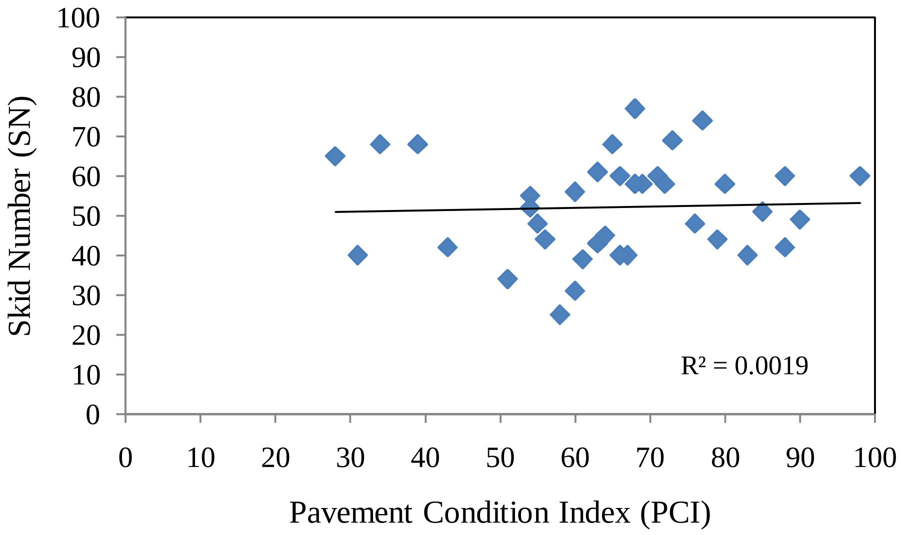


(a)

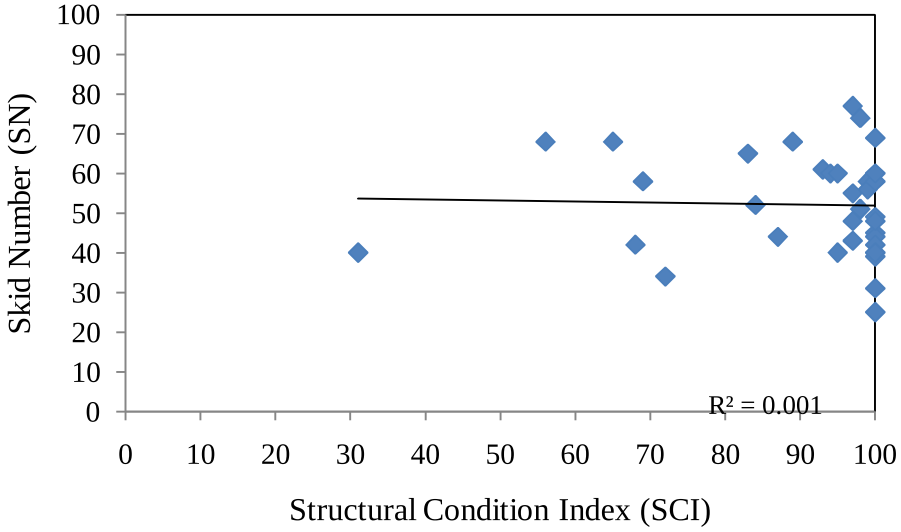


(b)

Figure 3.10: Variation of PCI with SCI for all sections and Runway Branches

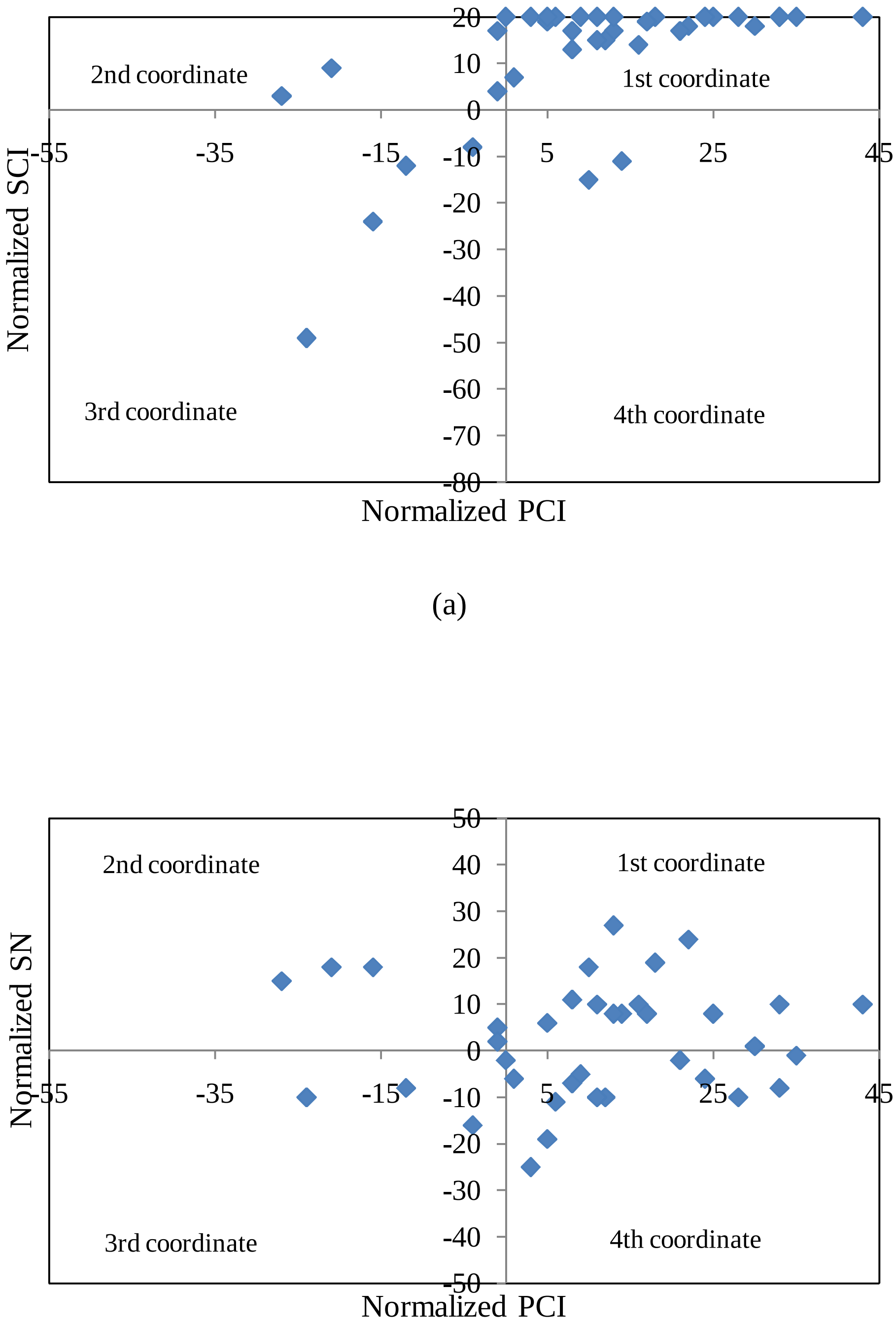


(a)



(b)

Figure 3.11: Variation of SN with PCI and SCI for Runway Branches



(a)

(b)

Figure 3.12: PCI SN Relationship and PCI SN Relationship for Runway Branches

CHAPTER 4

ALTERNATIVE TO PCI BASED MAINTENANCE SOLUTION

4.1 Introduction

In this study, maintenance solutions for 19 airport pavements in New Mexico are derived based on Pavement Condition Index (PCI) and PCI with Structural Condition Index (SCI). In a Pavement Management System (PMS), PCI indicates the functional condition and SCI indicates the structural condition of the pavement. In the PCI approach, a specific maintenance treatment is applied when the PCI value of a pavement section reaches a minimum defined value. In the PCI-SCI approach, a specific maintenance is applied when either PCI or SCI reaches a minimum assigned value. Using system dynamics modeling, modules to quantify the benefit and Life Cycle Cost (LCC) were developed and utilized to determine the relative benefit and life cycle treatment cost of a maintenance solution or treatment. The reason to include SCI in applying a maintenance treatment is that, structural pavement condition should also be in acceptable limit like functional or operational condition of the pavement.

It is shown that both the PCI and PCI-SCI approaches produce similar treatment results, but the PCI-SCI approach shows higher relative benefits and lower life cycle treatment cost for airports with low initial SCI values. It can be concluded that, if an airport pavement has a greater differences in PCI-SCI (>10), the PCI-SCI approach will not give higher benefit and thus, it is not recommended to follow this approach. Other results indicate that airports with higher initial PCI have lower functional benefit and lower LCC for maintenance solutions of different PCI improvement or PCI rises. Benefit and cost associated with both approaches are determined using two different system dynamic modules developed in Powersim and then benefit and cost are compared using developed design charts.

4.2 Objective of the Chapter

This chapter has the following major objectives:

- Develop modules using system dynamics modeling concept to determine the relative benefits and life cycle costs of maintenance treatments for a specific airport pavement section considering minimum acceptable PCI and considering both minimum acceptable PCI and SCI.
- Determine the effects of minimum acceptable PCI, PCI rise or PCI improvement, and, initial PCI on the relative benefit to cost ratio of an airport pavement.

4.3 Background

The functional condition of an airport pavement is always highlighted by decision makers in applying a maintenance treatment to a pavement section. Functional condition is important because it directly relates to the user safety and comfort. On the other hand, the structural condition is often not visible to pavement users and is not considered in maintenance decisions. However, from an engineering perspective, both the user safety and the condition of the pavement structure itself are equally important. Although, SCI based pavement evaluation is very common in pavement management practices, detailed study have not yet conducted in offering SCI based maintenance solution (Zhang el al. 2003).

Maintenance treatments are traditionally applied on a deteriorated pavement based on only the PCI. If a specific pavement shows high PCI value, it does not necessarily mean that other condition indices such as SCI is satisfactory. In fact, the structural condition may reach a minimum acceptable limit before the functional condition. It is important in the sense that, after the minimum acceptable limit both the deterioration rate and the cost of maintenance will be significantly higher. Therefore, both condition indices should be considered. The PCI method does include some distresses that are related to structural condition, but there is no well-defined relationship between structural and functional performances (Zaniewski 1991), and PCI-based pavement management systems are generally not well conceived to assess current and future structural performance (Paine 1998).

In selecting the best maintenance treatment for managing a pavement, various methods, such as decision trees and, decision matrices, are used by various researchers (Hicks 2000). These methods depend upon certain rules and criteria assigned by the researchers based on past experience. The problem associated with these experience-based methods is that, these are not accurate enough to deal with multiple pavement distress types and often consider single distress. Therefore, it is required to develop an appropriate decision technique which will consider combined condition indices like PCI and SCI (Grogan 2000). Furthermore, the effect of maintenance time on the life cycle cost of a pavement is not analyzed adequately in the previous studies. Although many researchers have implemented preventive maintenance strategies, there is still very little study on determining the optimum time of application of such treatment (Hajj et al. 2011).

Life cycle cost analysis is performed widely in PMS to select the best alternative and the optimum time of their application (Walls and Smiths 1998). In Life Cycle Cost Analysis (LCCA), a basic assumption is that all alternatives will give the same benefit. Paradoxically, the functional benefit for different alternatives is not always the same for different treatment types and different times of their application. Hence, the study of benefit to cost ratio of different maintenance treatments is more pragmatic than their simple life cycle cost analysis.

Most PMS are directed toward the development of a cost effective program on an annual basis for preserving pavements with the available budget (Yoo el al. 2008). Multi-year budgeting, and maintenance time and frequency are often not adequately considered (Keshawarz 1985). A PMS is a complex system affected by several variables such as pavement condition, PCI improvement, deterioration rate, and maintenance timing and therefore is suitable for system dynamics study (Friedman 2003). System dynamics is a mathematical modeling technique which helps the decision maker to understand the behavior of a complex system over time. It has many internal feedback loops and storages and flows which affect the behavior of its entire system. In this study, system dynamics modeling is used to estimate the functional benefit and cost associated with different PCI and SCI values in response to a range of varying parameters like minimum acceptable PCI, PCI improvements or PCI rises, and PCI deterioration rates. The PCI rise is the improvement of the PCI value after a maintenance treatment and the PCI deterioration rate is the rate at which the pavement is deteriorating. Different PCI rises indicate different type of maintenance treatment. Major maintenance treatments have higher PCI rise and higher cost to restore pavement (MicroPAVER).

4.4 Scope of the Study

Usually maintenance is done in a pavement based on only the Pavement Condition Index (PCI). In critical PCI method, maintenance is applied when it reaches critical PCI. Pavements having the same PCI may reach critical PCI in different ages depending on their deterioration rate. PCI deterioration rate is very important to predict future pavement condition. Load and environment both are related for different degradation rates. Without multiple year pavement distress data it is very difficult to predict future condition and to establish a reliable deterioration rate. In few instances, linear deterioration is assumed in pavement management for simplification of the analysis. However, non-linear deterioration rate should also be used and the results should be compared with linear degradation rates.

Relative benefit of different treatments and life cycle treatment cost are determined over design life for different minimum acceptable conditions and condition improvements. Minimum acceptable condition means minimum threshold value of PCI and, different condition improvement means the PCI rise due to maintenance treatment. However, in life cycle cost analysis, it is assumed that all alternatives will give the same benefit over the design life and this assumption is not always correct. Hence, benefit cost ratio should also be studied over the design life. Therefore, relative benefit to cost ration are determined in this study for different values of minimum acceptable PCI, PCI rise and initial PCI. BCR are determined for PCI approach in the current study for non-linear deterioration rates and various design charts are developed.

Relative benefit, life cycle cost and relative benefit to cost ratio are determined for different approaches over the design period. Benefit and cost are studied for different minimum acceptable conditions, PCI rises and plotted against different initial conditions. From BCR versus cutoff PCI, it can be said that in which condition level maintenance should be applied to the pavements of different conditions. From BCR versus initial condition results, the peak indicates the most effective airfield to start pavement maintenance. BCR curves for different PCI rise helps to determine what type of maintenance should be applied. The peak of BCR curves against initial PCI signifies the most cost effective maintenance treatment type. Peak of BCR curve indicates the most optimum treatment type and pavement type where to start maintenance. Few new outcomes are expected from this study, difference in BCR for different initial PCI helps develop an idea about which airport should be maintained in near future. BCR design charts also help determining most optimum treatment type or PCI rise, and which minimum acceptable condition to be maintained. Effect of non-linear deterioration rate on different aged pavement should be studied.

4.5 Relevant Literature

The Pavement Condition Index (PCI) for airfield pavement, roads and parking lots are published as ASTM standards, D5340 and D6433 respectively. The use of PCI is adopted as standard procedure by many agencies worldwide including Federal Aviation Administration, The U.S. Department of Defense and the American Public Work Association (Green et al. 1989). In PCI method, Maintenance is done based on critical PCI which is defined as the PCI value at which the rate of PCI loss increases with time or the cost of applying localized preventive maintenance increases significantly. PCI is a visual distress survey based pavement evaluation method and as minimum acceptable PCI 55-70 are used (Shahin 2005). The PCI method does include some distresses that are related to structural condition, but there is no well-defined relationship between structural and functional performances (Zaniewski 1991), and PCI-based pavement management systems are generally not well conceived to assess current and future structural performance (Paine 1998). However, Structural Condition Index (SCI) only considers load related distress such as alligator crack and rutting for flexible pavements and has minimum required value of 80 (Hicks et al. 2000).

Life cycle cost analysis (LCCA) is performed widely in PMS to select the best alternative and the optimum time of their application (Walls and Smith 1998). In LCCA, all alternatives are assumed to have similar benefit (Smadi 2004). However, the functional benefit for different alternatives is not always the same for different treatment types and different times of their application. Perhaps the best known method for measuring the efficiency of an activity is the benefit cost analysis (Hass et al. 1994). Hence, the study of benefit to cost ratio of different maintenance treatments is more pragmatic than their simple life cycle cost analysis. The benefit cost ratio is defined as the ratio of the benefit divided by the cost of the application of maintenance treatments. The benefit cost ratio is used to determine the relative cost-effectiveness of maintenance treatment with respect to various times of application (Morlan 2011). However, functional benefit achieved by a maintenance treatment solely depends on the life increase and frequency of the treatment over the analysis period, which is also responsible for LCCA. Different maintenance types have different pavement condition improvement and different expected life (Ningyuan 2001).

A PMS is a complex system affected by several variables such as pavement condition, PCI improvement, deterioration rate, and maintenance timing and therefore is suitable for System Dynamics (SD) study (Friedman 2003 and Linard 2000). Using SD model effect of maintenance type and timing can be studied for different pavement condition at different minimum required value. Effect of maintenance time on life cycle cost of a pavement is not analyzed adequately. Although many researchers have implemented preventive maintenance strategies, there is still very little study on determining the optimum time of application of such treatment (Hajj et al. 2011 and Peshkin et al 2004). A rational methodology is needed to evaluate pavement preservation alternatives to maximize benefits (Haider and Waqar 2011).

4.6 Data and Study Approach

A visual distress survey has been performed by the Aviation Division of the New Mexico Department of Transportation (NMDOT) to determine the conditions of different branches (runway, apron, and taxiway) of 19 airports in New Mexico. PCI and SCI were determined for various pavement sections of those airports based on the survey data. The area weighted average PCI and SCI values of those 19 airports are shown in Table 4.1.

This study focuses on the impacts of maintenance treatments on functional benefit and life cycle cost. First, a traditional approach is applied where only the PCI of the pavement is considered. Next, an alternative approach is applied where maintenance is included, where either the PCI or the SCI reaches the minimum acceptable value. Benefit analysis and life cycle cost analysis were performed using both PCI and PCI-SCI data collected by the visual distress surveys. Benefit cost results for different current PCI aids in determining the optimum time of maintenance application. No condition deterioration data was available. Therefore, only one year of data were given as input. Pavement condition was assumed to deteriorate linearly at a rate that depends solely on the initial condition of the pavement (Ningyuan 2001).

$$CI_{Current} = CI_{Initial} - 4.79(Y) - \frac{(CI_{Initial})(Y)}{20.88} \qquad \text{(Eq. 4.1)}$$

where $CI_{Current}$ is the current condition index defined by PCI or SCI, $CI_{Initial}$ is the initial condition index of the pavement and Y is the service life in years.

4.7 Preliminaries of System Dynamic Methodology

System dynamics is a general modeling technique which determines the change in a specific parameter with time, explicitly accounting for its relationship with other variables and parameters. System dynamics must contain a conceptual model or flow chart that describes the processes included in the model. The conceptual model helps to identify the variables and their interconnections. Storages and flows are the building blocks of a conceptual model. Storages are the accumulators in the system and help characterize the state of the system. Flows indicate the rate of movement of commodities in and out of the system. Values and relationships for each storage and flow are to assign in the form of constants, equations or data tables. When a system dynamics model is developed, it describes cause-effect relationships of its different variables and handles continuous interactions between its parameters.

In this study, a system dynamics module was developed to determine the relative functional benefits of different maintenance strategies known as benefit module. Pavement condition without any maintenance (which is known as do nothing condition) and after maintenance treatment were used as storage in this module. Pavement condition deterioration rate was used as outward flow in the model. The do nothing deterioration rate and the deterioration rate after maintenance were determined by using Eq. 4.2 and Eq. 4.3 respectively.

$$r = 4.79 - \frac{PCI_{Initial}}{20.88} \qquad \text{(Eq. 4.2)}$$

$$r = 4.79 - \frac{PCI_{Cutoff} + \Delta PCI}{20.88} \qquad \text{(Eq. 4.2)}$$

where $r =$ PCI Deterioration Rate, $PCI_{Initial} =$ Initial PCI, $PCI_{Cutoff} =$ Minimum Acceptable PCI where maintenance is applied, $\Delta PCI =$ PCI rise after maintenance.

Initial pavement conditions and minimum acceptable conditions were used as constants which can operate the do nothing condition changes and timing of condition improvement or maintenance treatment in the entire analysis period. Different initial condition indices were used for different airport pavements. Other system dynamic model parameters used in this module are shown in Table 4.2.

Figure 3.10(c) shows the variation of PCI with SCI for 413 pavement sections of 19 airports. Minimum acceptable SCI for a specific minimum acceptable PCI are determined using the following correlation from Figure 3.10(c):

$$PCI = 0.777SCI - 1.4689 \qquad \text{(Eq. 4.3)}$$

Benefit module established relationship of relative benefit of pavements of different conditions with different minimum acceptable conditions, condition improvements and deterioration rates. It applied a treatment whenever pavement condition reaches the minimum acceptable limit and the condition curve after maintenance is known as the maintenance condition curve. The do nothing condition curve and the maintenance condition curve were used to determine the relative functional benefit of a treatment or PCI rise. Figure 4.1 shows the procedure to determine the relative benefit using those two curves. The relative benefit is the ratio of the benefit area (B) or the area under the maintenance PCI curve over the area under the do nothing PCI curve (A) up to the terminal value of PCI. The terminal value of PCI is used as the minimum PCI or 0.

LCC module can determine the life cycle cost after taking output values from the benefit module as input; including maintenance year, corresponding PCI, and PCI rise. As unit cost of major maintenance varies depending upon PCI when the treatment was applied, the unit cost of maintenance treatment can be estimated from the benefit module. The PCI after last maintenance, maintenance deterioration rate, and last maintenance spend life also are the output of benefit module and are used as inputs in LCC module to calculate salvage Net Present Worth (NPW). Pavement area is assumed to be same for all airports which is 10000 square meter. A 4% discount rate and 20 year analysis period are assumed as those values are used widely in pavement maintenance practices. M&R Cost NPW, Salvage NPW, NPW, and Equivalent Unit Annual Cost (EUAC) are calculated for different PCI rises at different minimum acceptable PCI. EUAC is the annual cost of different maintenance applications over the entire analysis period and obtained from the total NPW of maintenance treatments. Unit cost to increase PCI to 100 depends on current PCI in following manner (Shahin 2005):

$$UC = (137.53 - 1.5814 \times PCI_{Cutoff}) \times \frac{\Delta PCI}{100 - PCI_{Cutoff}} \qquad \text{(Eq. 4.4)}$$

where UC is the Unit Costs of a maintenance treatment in dollar required to maintain per square meter of pavement area and PCI_{Cutoff} is the minimum acceptable PCI.

4.7.1 Benefit Module

The PCI method measures some distresses that indirectly related to structural degradation but there is no well-defined relationship between the structural and the functional performance of the pavement (Khanna 2007). Benefit module helps distinguish the results obtained from two different approaches. In benefit module, condition indices have been used as stock and deterioration rate has been used as flow. To determine the do nothing condition of a pavement section in the analysis period is the first step to follow in benefit module. The do nothing condition depends on two factors, the initial index value and the deterioration rate. If PCI deterioration rate of a specific pavement section is unknown, do nothing PCI deterioration rate can be determined by using Eq. 4.2. For SCI deterioration rate same equation has been used. Rehabilitation is applied when PCI reaches minimum acceptable value. Alternative approach applies rehab work when either PCI or SCI reaches minimum acceptable value.

Flow Charts of Relative Benefit: Figure 4.2(a) illustrates the flowchart to determine benefit for the first solution approach where as inputs, only do nothing PCI and minimum acceptable PCI is considered. Rehabilitation takes place when do-nothing PCI reaches minimum acceptable PCI value. After application of each repair work PCI as well as the SCI value improves and revised PCI and SCI is known as do something PCI and do something SCI respectively. Then relative benefit can be determined. The relative benefit is the ratio of the benefit area (B) or the area under the do something PCI curve over the area under the do nothing PCI curve (A) up to the terminal value of PCI which is 0.

The relative benefit can be considered as the improvement in the serviceability of the pavement and is related to the user satisfaction. Relative benefit is different from pavement performance benefit as it is the ration of improved pavement serviceability due to maintenance work and the existing pavement serviceability. Figure 4.2(b) illustrates the flowchart to determine benefit for the alternative solution approach where as inputs, do nothing PCI, do nothing SCI, minimum acceptable PCI and minimum acceptable SCI is considered. Rehabilitation takes place when either do-nothing PCI reaches minimum acceptable PCI value or do nothing SCI reaches minimum acceptable SCI value. The rehabilitation method and the benefit calculation method are the same as the previous approach.

<u>Diagrams of Benefit Module of PCI Based Approach:</u> Maintenance is applied when the do nothing PCI reaches a minimum acceptable value in the PCI based approach. Figure 4.3 shows the conceptual model of PCI based benefit module where the diamond and the circular symbols are active tools for constant and for auxiliary, respectively. The rectangular box represents active tool for storage, and the circular sign with valve indicates the flow with rate.

In this approach, Initial PCI and minimum acceptable PCI were considered as inputs. Initially, the do nothing PCI was equal to the initial PCI and it decreased with time because of deterioration rate. When the do nothing PCI reached the minimum acceptable PCI, this module applied a maintenance treatment with an assigned PCI rise. Different PCI rises were taken for this current study. After application of a maintenance treatment, the PCI value improves by the PCI rise value and revised PCI is known as maintenance PCI. Values of 10, 20, 30, and 40 are used for the PCI rise and as minimum cutoff PCI values of 10-80 were used for all 19 airports.

Diagrams of Benefit Module of PCI-SCI Based Approach: PCI-SCI based approach applies maintenance work when either PCI or SCI reaches a minimum acceptable value. Figure 4.4 shows the conceptual model of PCI-SCI based benefit module. Initial PCI, minimum acceptable PCI, Initial SCI and minimum acceptable SCI are considered as inputs. When either do nothing PCI or do nothing SCI reached the minimum acceptable value, this module applied a maintenance treatment with an assigned PCI rise and SCI rise. A particular maintenance has given same rise in PCI and SCI. Minimum acceptable SCI values were determined for corresponding minimum acceptable PCI using Eq. 4.3. Two approaches considered different parameters in applying a maintenance treatment. However, both approaches determined relative benefit using the area under the maintenance PCI curves, and do nothing PCI curves as we are concerned only about the functional benefit. Moreover, if different curves would have been chosen for these two approaches the result must have been different and the comparison could not be considered as a fair comparison.

Outputs of Benefit Module: For a typical pavement section having PCI 53 and SCI 57, and, for 10 PCI and SCI rise, the output curve of benefit module for both approaches is shown in Figure 4.5. As SCI reaches the critical value before PCI reaches its critical value, alternative approach in Fig. 4.5(b) applies first maintenance work earlier than traditional approach in Fig. 4.5(a). In this particular scenario, alternative approach has given higher do something area as well as higher relative benefit but without performing the life cycle cost analysis and considering benefit cost ratio no conclusion should be made about the effectiveness of these two approaches. PCI approach has applied maintenance treatment in the year 1 and 15, where PCI-SCI approach has applied treatments in the year 0 and 18. Therefore, the differences in these two approaches are in the treatment time. If both approaches have applied maintenance treatment in the same year of the analysis period, the benefit results would be the same. This is because, the rise and deterioration rate for both PCI and SCI are assumed to be same for both PCI and PCI-SCI approach.

4.7.2 LCC Module

LCC module is capable of performing life cycle cost due to maintenance work. Benefit module applies maintenance work when it requires, and PCI module can calculate LCC taking output values of benefit module as input. If simulation of benefit module is done, it is then provide important information like maintenance year, corresponding year PCI to LCC. As unit cost of major maintenance varies depending upon PCI when the treatment applied (depicted in Figure 2.3), it can be said that initial and maintenance cost also can be estimated from benefit module. PCI after last maintenance, maintenance deterioration rate and last maintenance spend life also is the output of benefit module and are used as inputs in LCC module to calculate salvage Net Present Worth. As cost is calculated per 1000 square meters, pavement area is fixed for all sections. 4% discount rate and 20 years as well as 40 years analysis period have been taken as in a typical PCI discount rate is used 3%-5%. Simplified LCC module for both approaches is shown in Figure 4.6 where to calculate M&R Cost NPW, Salvage NPW, NPW, and EUAC (Equivalent Unit Annual Cost) the following equations are used:

$$M\&R = IC + \sum_{k=1}^{n} MC_K \frac{1}{(1+i)^k} \tag{Eq. 4.5}$$

$$Sal = MC \times \frac{LR}{LD} \times \frac{1}{(1+i)^n} \tag{Eq. 4.6}$$

$$NPW = M\&R + Sal \tag{Eq. 4.7}$$

$$EUAC = NPW \left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] \tag{Eq.4.8}$$

where $i =$ discount rate, $k =$ year of expenditure, $n =$ analysis period, $MC_k =$ Maintenance treatment cost at year k, $IC =$ Initial Cost, $LR =$ Last maintenance remaining life, $LD =$ Last maintenance design life, $NPW =$ Net Present Worth, $M \& R =$ Maintenance and rehabilitation NPW, $Sal =$ Salvage NPW.

EUAC is particularly useful when funds are used on an annual basis, therefore is well suited to pavement maintenance treatment evaluation. Where, NPW discounts all costs to a single base year which can then be compared, EUAC discounts all alternative activities to a yearly cost which is then can be compared.

With benefit module dynamic response of PCI and SCI due to maintenance treatment can be seen and these responses can be used in calculating benefit and cost for the analysis period. As analysis period and discount rate those values are used which are used frequently by a typical airport project. Benefit results and LCC results for all sections of the current study for both approaches will be discussed in the following sections.

4.8 Benefit Cost Ratio Design Charts for PCI Approach

Relative benefit to cost ratio (BCR) is simply drawn from dividing relative benefit by EUAC. As EUAC was in 1000 dollars, it is converted into dollar value before using it to get BCR. It is also divided by analysis period to get BCR for a year. BCR signifies the relative functional benefit achieved by the airport pavement after one dollar investment in a year in a square meter of a pavement area for pavement restoration. Several BCR design charts were developed using system dynamics modules which help to determine benefit cost ratio for different initial PCI, different cutoff PCI and PCI rises.

Figure 4.7 shows the effect of cutoff PCI on relative benefit to cost ratio (BCR) for 20 years analysis period. Figure 4.7(a), 4.7(b), 4.7(c) and, 4.7(d) have shown the results for PCI rise 10, 20, 30 and, 40 respectively. Different curves on a graph indicate BCR for different initial PCI. Figure 4.7 shows that, higher rise always gives higher BCR and a specific maintenance always gives higher BCR if it is applied on more deteriorated pavements. For rise 10 and for a specific initial PCI, maximum BCR is obtained for maximum cutoff PCI. However, as PCI rise increases, it shows different slopes and for rise 40 maximum BCR is obtained for few cutoff PCI values close to 40. If several cutoff values show similar BCR like 40 showed, then most cost effective treatment should be applied. The dashed line indicates the average BCR of all pavement maintenance for the specific maintenance or rise. This line helps to take a maintenance which will give higher BCR than the average value. Figure 4.8 shows the effect of cutoff PCI on relative benefit to cost ratio (BCR) for 40 years analysis period. 40 years BCR curves have shown similar trend or shape like 20 years analysis period. However, rise 40 for initial PCI 30 has shown different results for 40 years. Maximum BCR has obtained for cutoff PCI 50 for 40 years analysis period.

Figure 4.9 shows the effect of PCI rise on BCR for 20 years analysis period. It indicates that, higher rise always gives higher BCR for a specific initial PCI and cutoff PCI. The dashed line indicates the average BCR for maintenance of different rise for a specific initial PCI. For initial PCI 80, rise 10 has given maximum BCR and, for a specific PCI rise, highest cutoff PCI usually has shown the maximum BCR. However, for rise 20 and initial PCI 60, maximum BCR has shown by cutoff PCI 60. Few more similar results were obtained by higher initial PCI, where maximum cutoff PCI does not show maximum BCR. Figure 4.8(f) indicates that, rise 40 and 30 has given same BCR at cutoff PCI 50. Maintenance treatment having less maintenance cost should be applied. Figure 4.10 shows the effect of PCI rise on BCR for 40 years analysis period. It indicates that, higher rise always gives higher BCR for a specific initial PCI and cutoff PCI. Initial PCI 80, rise 10 has given maximum BCR and, for a specific PCI rise highest cutoff PCI has shown the maximum RB to cost ratio. Figure 4.10(d) indicates that, rise 20 and 30 has given same BCR at cutoff PCI 60. Maintenance treatment having less maintenance cost should have been applied. Figure 4.10 indicates that, if analysis period increases, maximum BCR is more likely to obtain by maximum cutoff PCI.

Fig.ure 4.11 shows the effect of initial PCI for different PCI rise, for 20 years analysis period. Figure 4.11 indicates that, different rise have shown higher BCR for lower initial PCI and lower cutoff PCI. The surface plot creates an inflated surface diagonal with two horizontal axes. As PCI rise increases, the peak of the surface becomes wider and the slope of the surface becomes flatter. This figure helps to take different maintenance having similar BCR so that most cost effective maintenance can be chosen. Figure 4.12 shows the effect of initial PCI for different PCI rise, for 40 years analysis period. Figure 4.12 has shown similar surface plot result like Fig. 4.12 except few coordinates has shown different values.

4.9 Benefit Cost Ratio Design Charts for PCI-SCI Approach

PCI-SCI approach has given higher BCR for airport pavements having SCI close to its PCI. It means if a pavement section has SCI close to PCI then both PCI and SCI should be considered in maintaining pavement. After performing study for different rises it is observed that, if a pavement has SCI 10 point higher than its PCI, then PCI-SCI approach shows similar result like PCI approach, hence PCI-SCI approach is not warranted.

Table 4.3 shows difference in two approaches for initial PCI 70 and rise 20. It has shown that, pavements having SCI equal to PCI has shown higher BCR for cutoff PCI 45, 50 and 60. A pavement having 70 PCI and 80 SCI has shown higher BCR only for cutoff PCI 60. Other initial PCI and PCI rise has shown similar results where greater benefits are achieved by pavements which has PCI less than 10 points from its SCI value. Among all 19 airports only Carlsbad airport has shown different results in PCI and PCI-SCI approach. Carlsbad has PCI 53 and SCI 57 and it has shown higher BCR for different minimum acceptable PCI and SCI. For those cases where the PCI-SCI approach was different than the PCI approach, the PCI-SCI approach yielded a larger do something area as a higher relative benefit.

4.10 Conclusion of the Chapter

Following conclusion can be made based on analysis of this chapter:

- System dynamic modules allow the users to apply maintenance treatment to the pavement at any initial PCI, cutoff PCI and, PCI rise.
- Higher PCI rise has given higher BCR for any particular PCI rise. However, slopes of BCR against cutoff PCI varies depending on the corresponding rise.
- BCR design charts are capable to show the BCR for airport pavements having initial PCI 30 to 80.
- PCI-SCI based maintenance treatment has shown significant difference in BCR value comparing PCI based maintenance for only one airport having SCI close to its PCI (PCI-SCI difference ≤ 10).

Table 4.1: Current Condition Index of different Airports

Airport	Name	Pavement Area (Sq. Meter)	Average PCI	Average SCI
1	Artesia	351365	36	80
2	Belen	108718	57	84
3	Carlsbad	457109	53	57
4	Clayton	102280	70	95
5	DEII	340300	67	90
6	Deming	224845	61	93
7	Fort Sumner	149847	62	95
8	Grants	84059	61	96
9	Hobbs	464890	55	84
10	Jal	62120	54	84
11	Las Cruces	393404	45	87
12	Lordsburg	50480	48	93
13	Moriarty	143422	58	96
14	Questa	55602	63	97
15	Raton	136638	75	100
16	Roswell	1389849	53	84
17	Sierra Blanca	329393	78	98
18	Santa Rosa	93206	68	100
19	Grants County	162353	49	97

Table 4.2: Relative Benefit Comparison using Parametric Test

Initial PCI	Initial SCI	Cutoff PCI	Cutoff SCI	PCI Rise	SCI Rise
30	40	10	15	10	10
40	53	20	30	20	20
50	66	30	40	30	30
60	80	40	53	40	40
70	90	50	66		
80	100	60	80		
		70	90		
		80	100		

Table 4.3: BCR Comparison

	PCI	SCI	Cutoff PCI	Cutoff SCI	B Area	A Area	UC/ Year	RL/ DL	EU AC	BCR
PCI	70		45		49.06	1100.71	24.13/17	9/12	304	0.73
			50		119.14	1100.71	23.38/14	8/14	545	0.99
			60		296.44	1100.71	21.32/7	8/21	919	1.46
			70		583.47	1100.71	17.89/0	30/30	1002	2.65
PCI-SCI	70	100	45	60	49.06	1100.71	24.13/17	9/12	304	0.73
			50	66	119.14	1100.71	23.38/14	8/14	545	0.99
			60	79	296.44	1100.71	21.32/7	8/21	919	1.46
			70	92	583.47	1100.71	17.89/0	30/30	1002	2.65
	70	90	45	60	49.06	1100.71	24.13/17	9/12	304	0.73
			50	66	119.14	1100.71	23.38/14	8/14	545	0.99
			60	79	296.44	1100.71	21.32/7	8/21	919	1.46
			70	92	583.47	1100.71	17.89/0	30/30	1002	2.65
	70	80	45	60	49.06	1100.71	24.13/17	8/12	304	0.73
			50	66	119.14	1100.71	23.38/14	8/14	545	0.99
			60	***79***	***526.96***	***1100.71***	***18.75/1***	***6/25***	***1175***	***2.04***
			70	92	583.47	1100.71	17.89/0	30/30	1002	2.65
	70	70	***45***	***60***	***296.44***	***1100.71***	***21.32/7***	***13/20***	***942***	***1.43***
			50	***66***	***448.23***	***1100.71***	***19.50/3***	***4/21***	***1151***	***1.77***
			60	***79***	***583.47***	***1100.71***	***17.89/0***	***30/30***	***1002***	***2.65***
			70	92	583.47	1100.71	17.89/0	30/30	1002	2.65

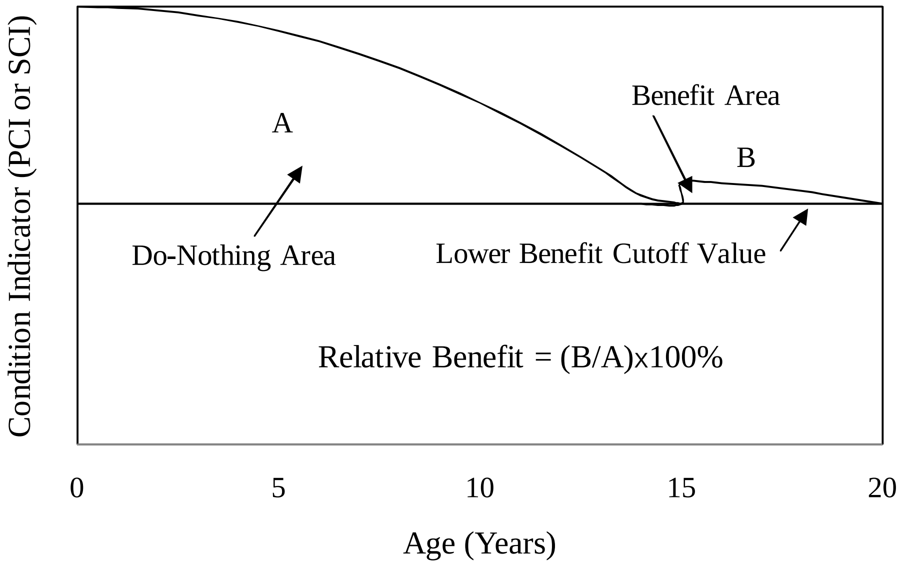
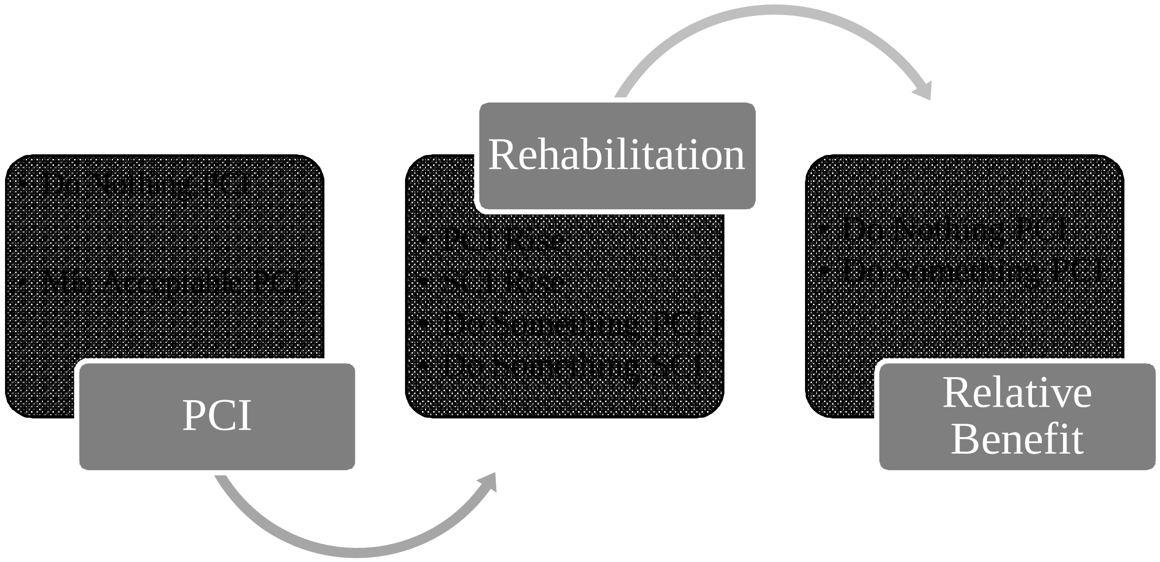
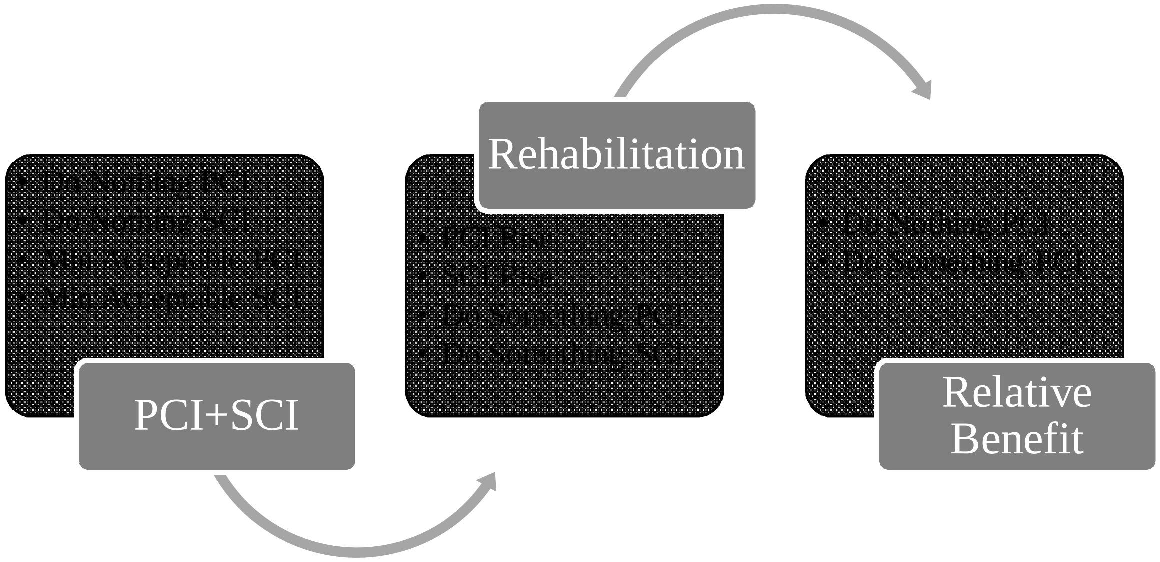


Figure 4.1: Conceptual illustration of benefit areas and do nothing areas



(a) PCI based Maintenance



(b) PCI-SCI based Maintenance

Figure 4.2: Flowchart of Relative Benefit

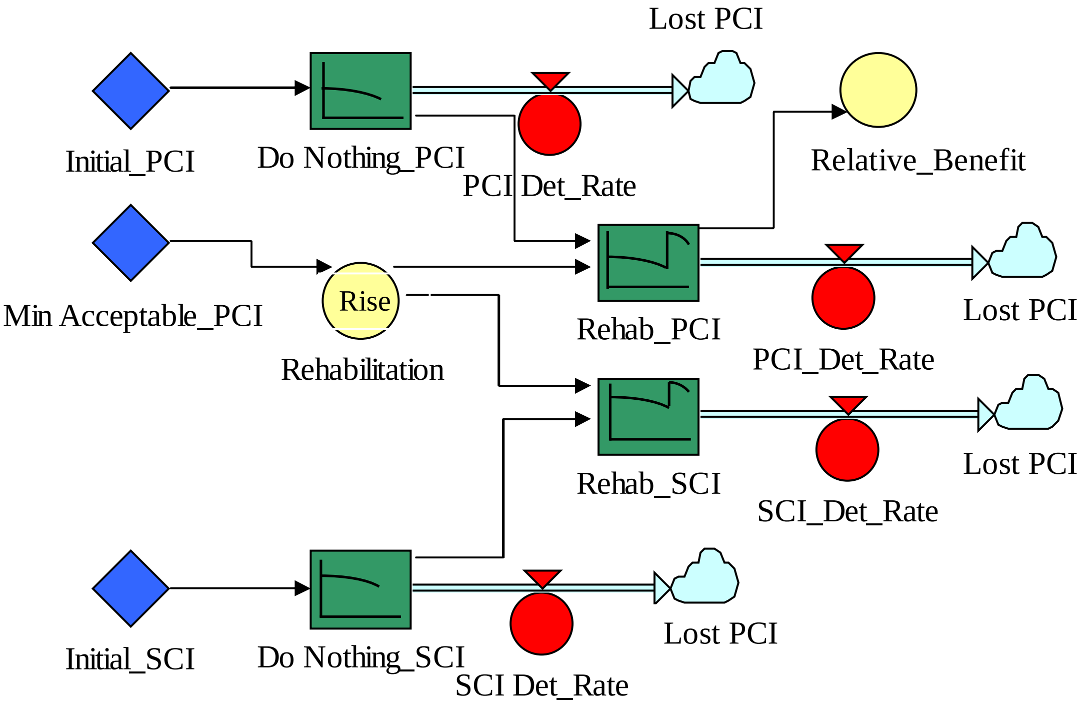


Figure 4.3 Benefit module of PCI based Maintenance and Rehabilitation

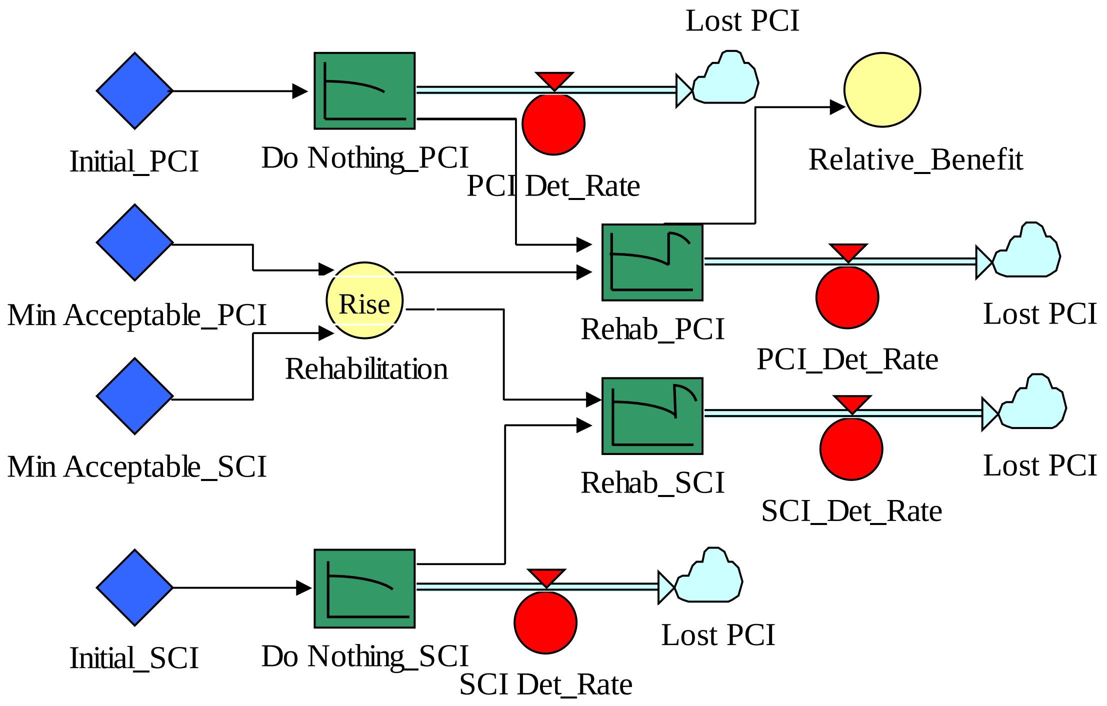
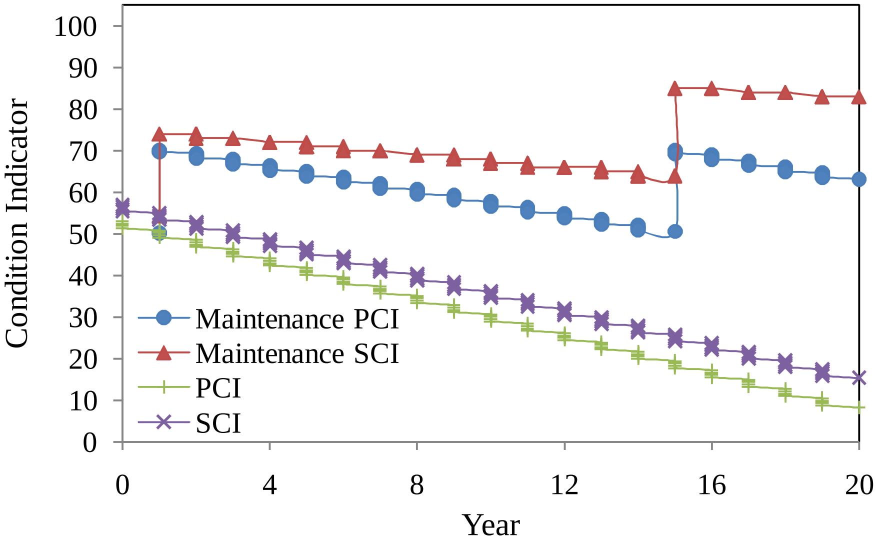
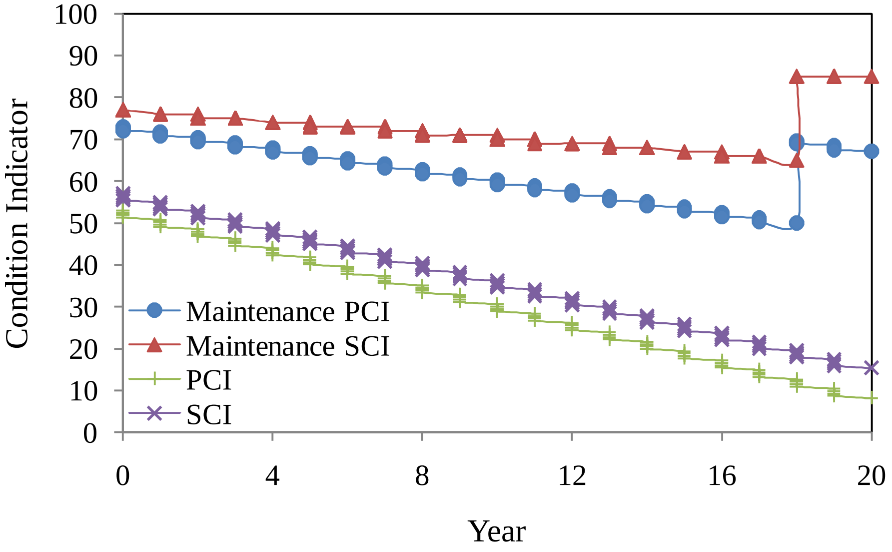


Figure 4.4: Benefit module of PCI-SCI based Maintenance and Rehabilitation



(a) Condition curve of PCI based Maintenance and Rehabilitation



(a) Condition curve of PCI-SCI based Maintenance and Rehabilitation

Figure 4.5: Pavement Condition Curve

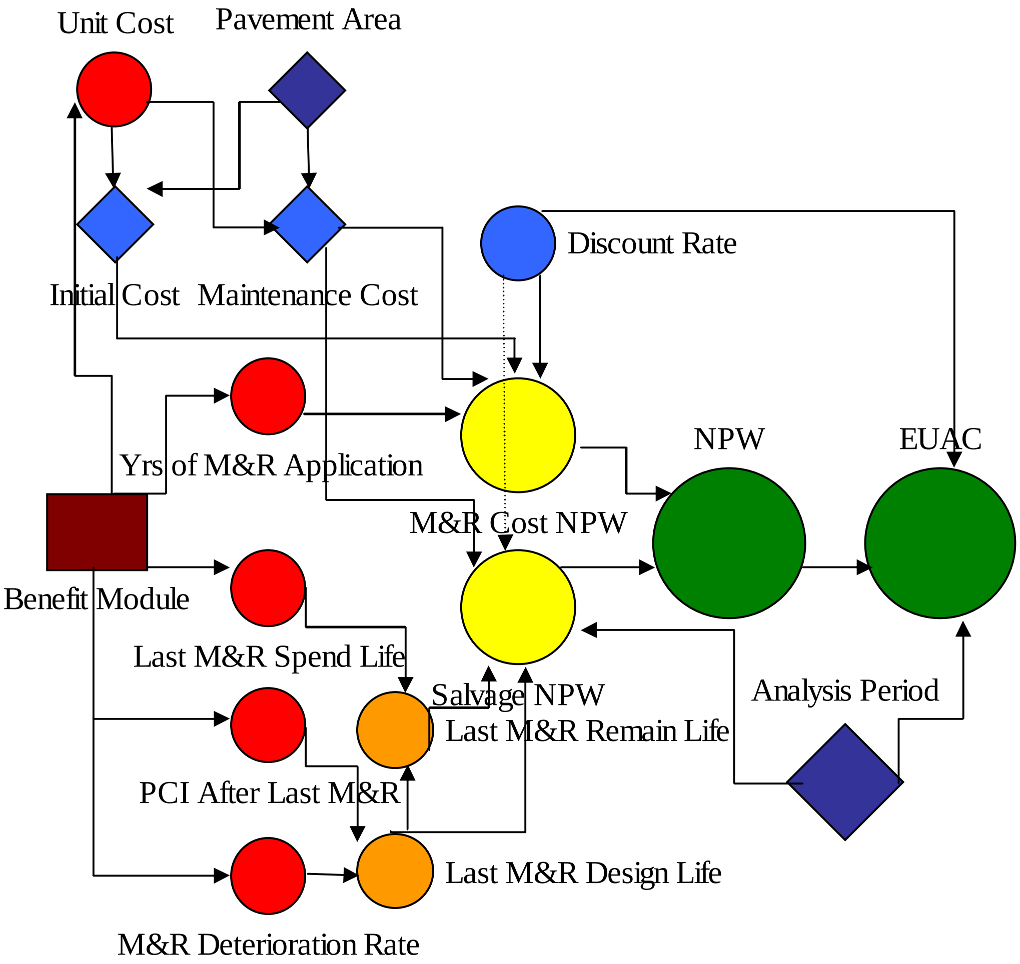
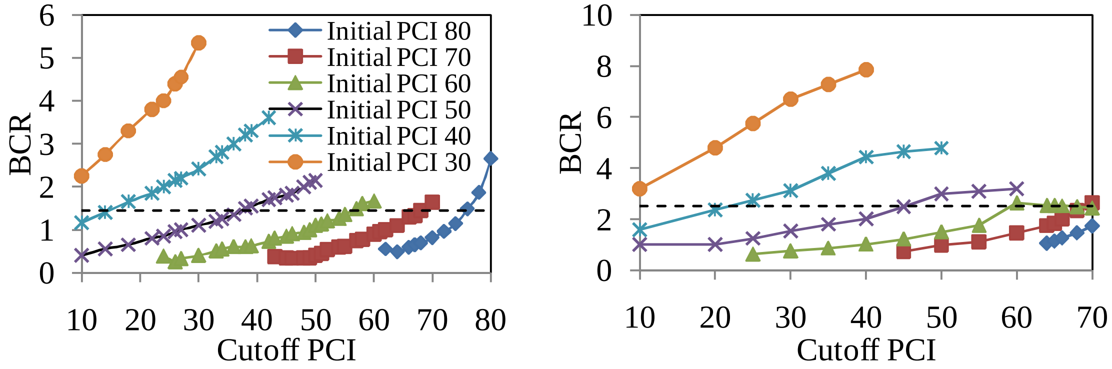
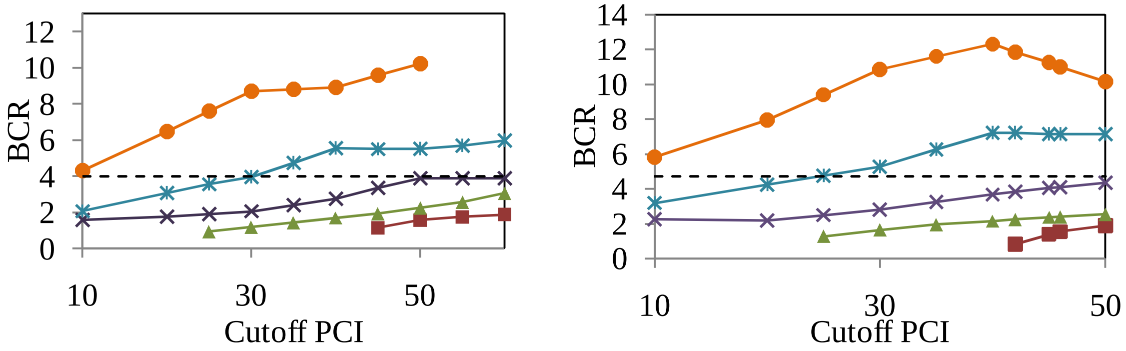


Figure 4.6: LCC Module



(a) Rise = 10

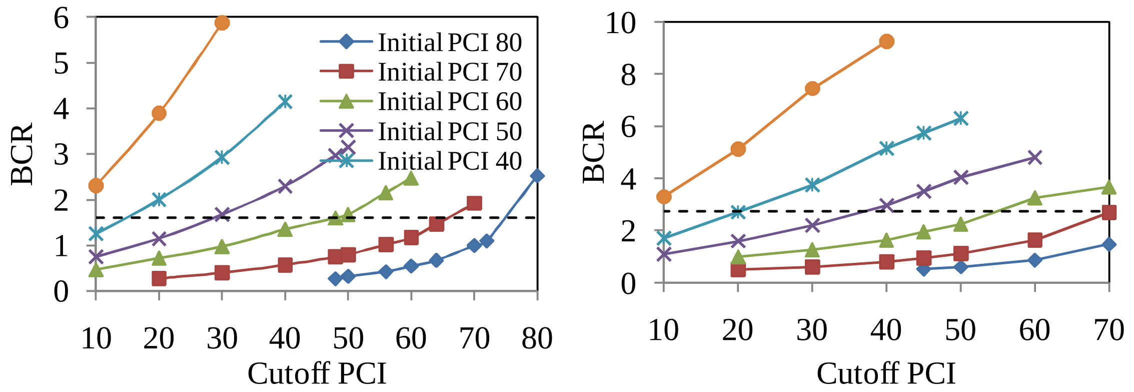
(b) Rise = 20



(c) Rise = 30

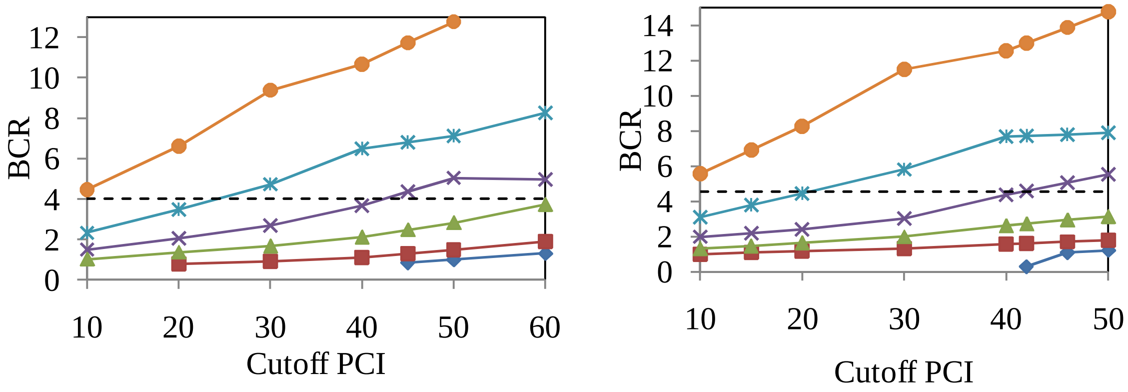
(d) Rise = 40

Figure 4.7: Effect of Cutoff PCI for 20 years Analysis Period



(a) Rise = 10

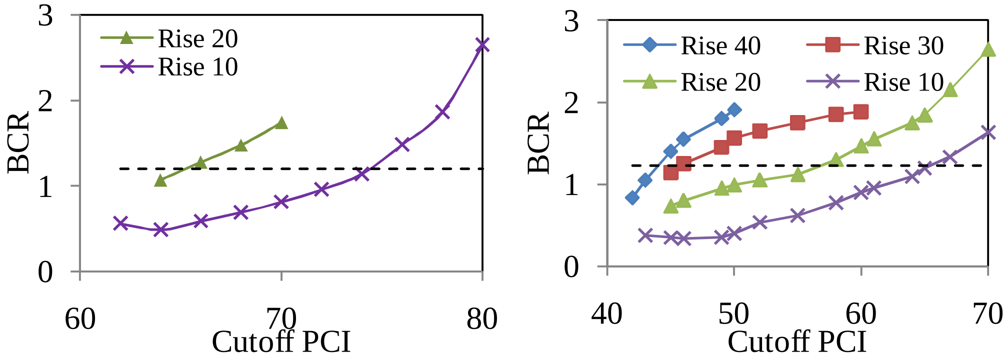
(b) Rise = 20



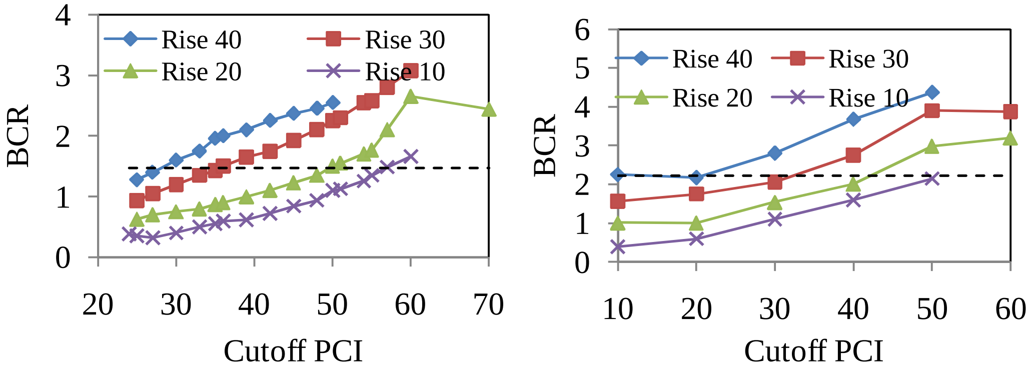
(a) Rise = 30

(d) Rise = 40

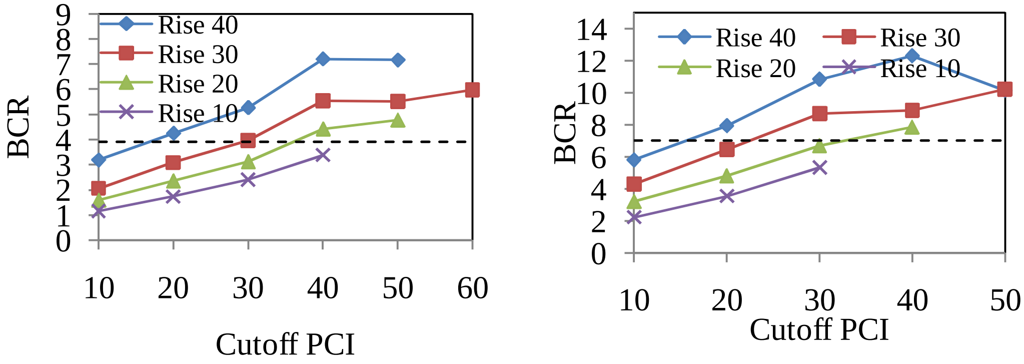
Figure 4.8: Effect of Cutoff PCI for 40 years Analysis Period



(a) Initial PCI = 80 (b) Initial PCI = 70

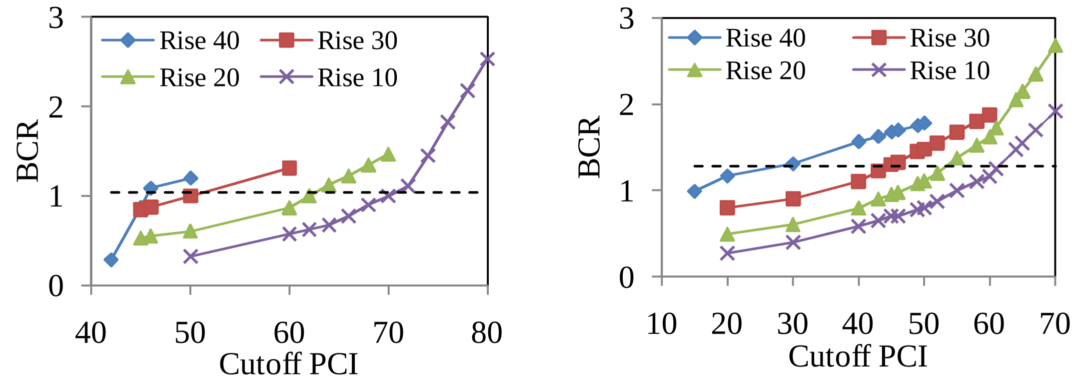


(c) Initial PCI = 60 (d) Initial PCI = 50



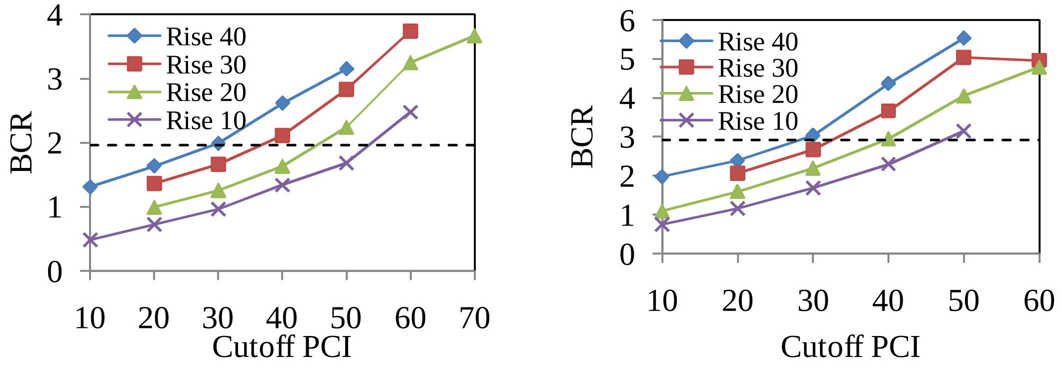
(e) Initial PCI = 40 (f) Initial PCI = 30

Figure 4.9: Effect of PCI Rise for 20 years Analysis Period



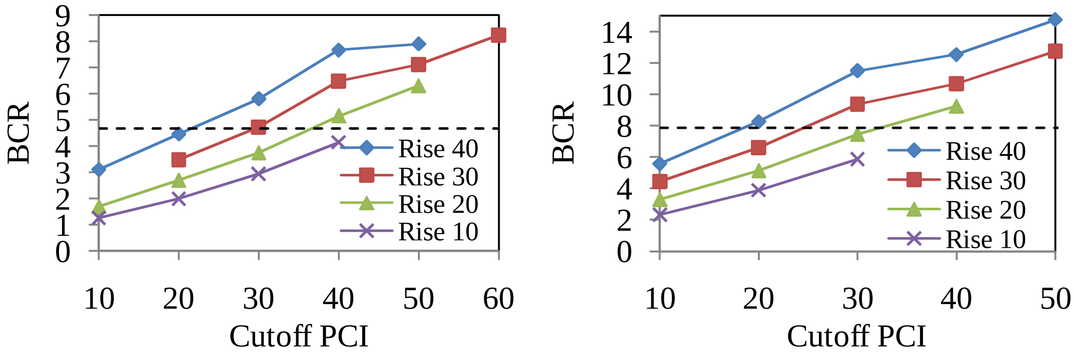
(a) Initial PCI = 80

(b) Initial PCI = 70



(c) Initial PCI = 60

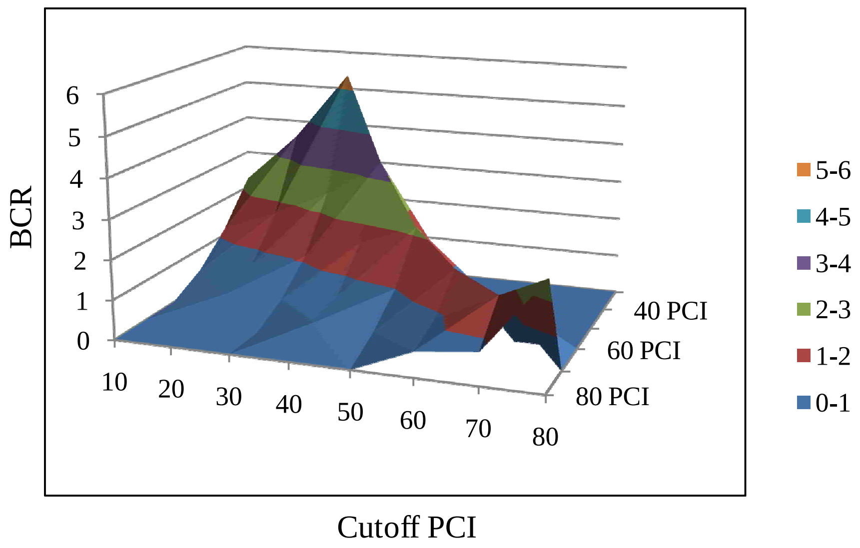
(d) Initial PCI = 50



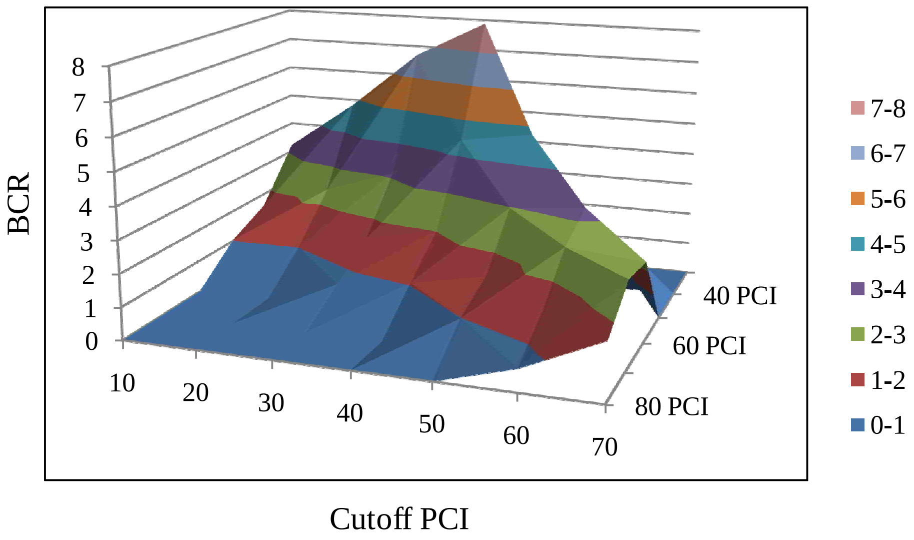
(e) Initial PCI = 40

(f) Initial PCI = 30

Figure 4.10: Effect of PCI Rise for 40 years Analysis Period

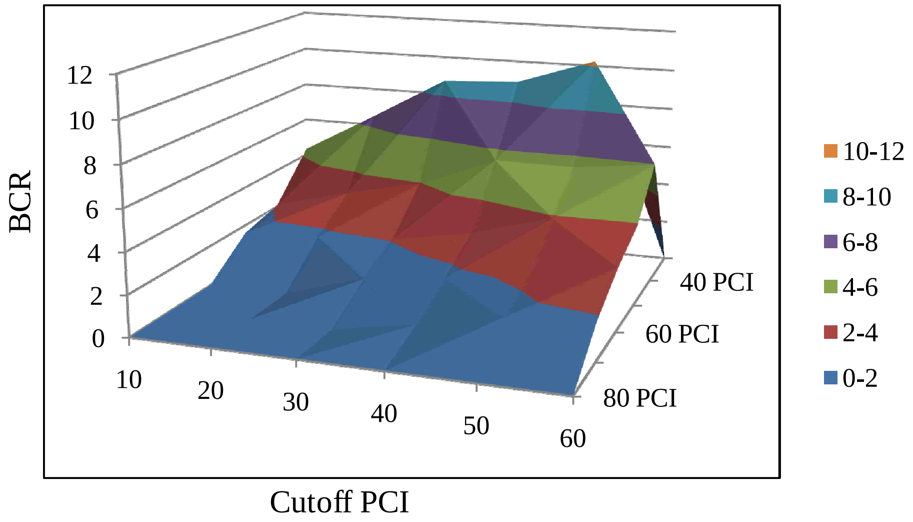


(a) Rise = 10

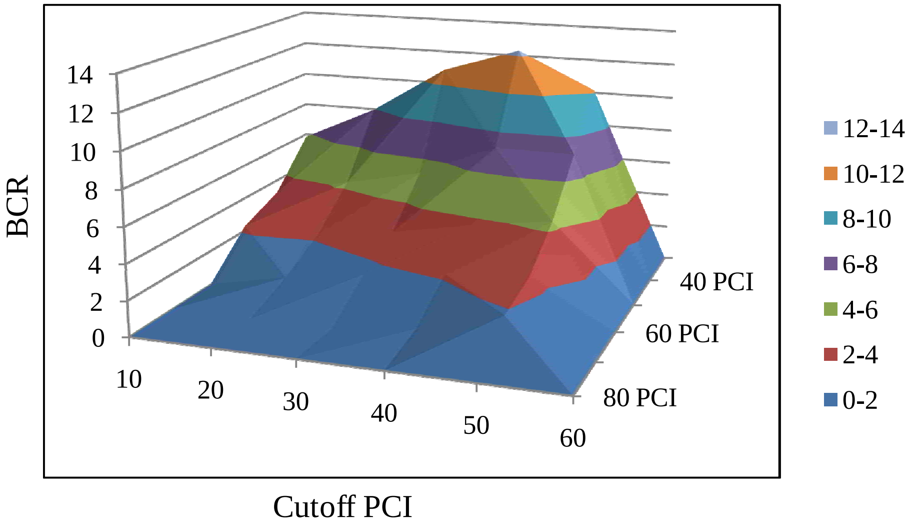


(b) Rise = 20

Figure 4.11: Effect of Initial PCI for 20 years Analysis Period

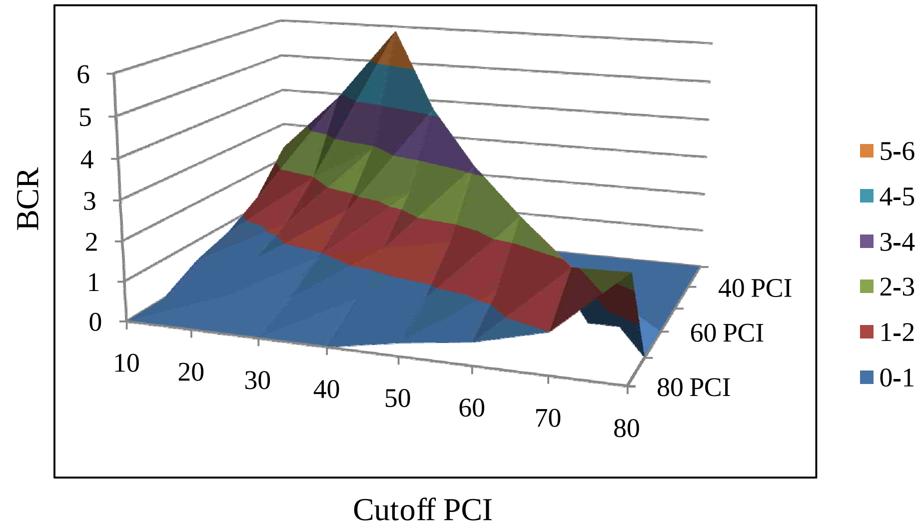


(c) Rise = 30

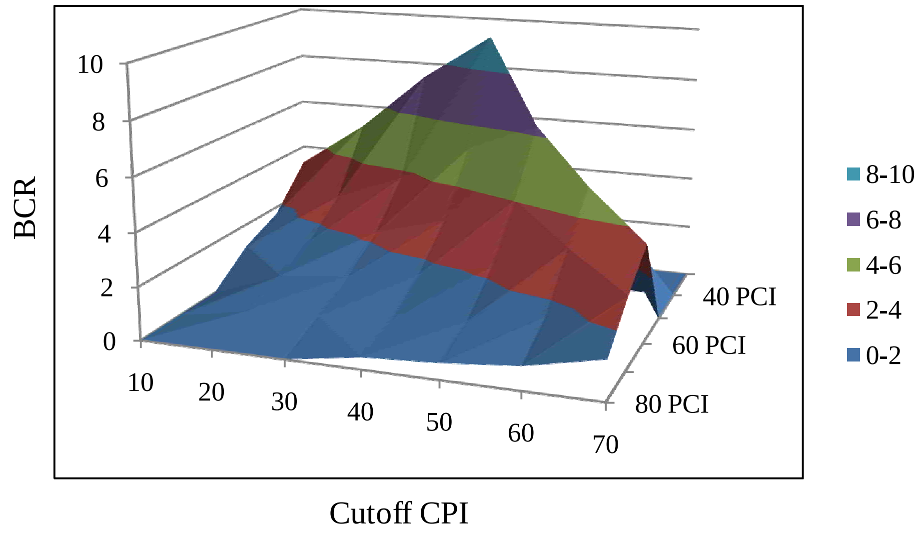


(d) Rise = 40

Figure 4.11(Continued): Effect of Initial PCI for 20 years Analysis Period

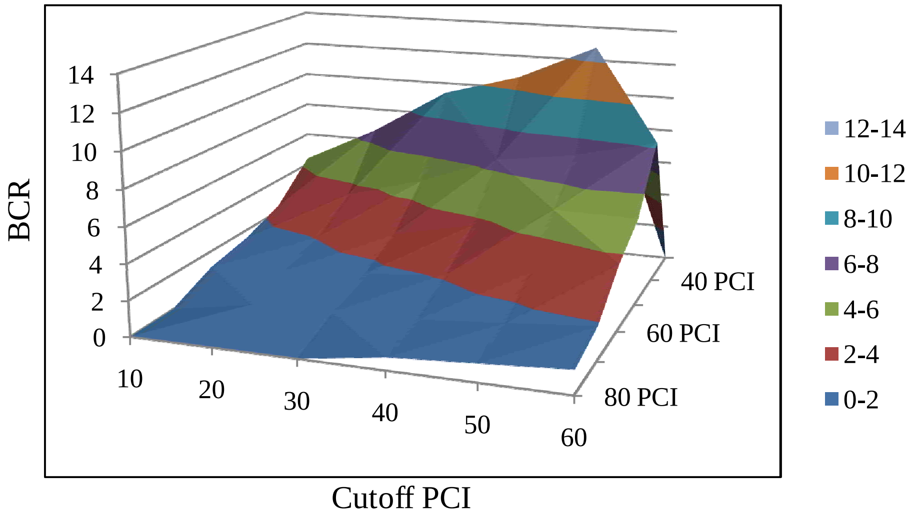


(a) Rise = 10

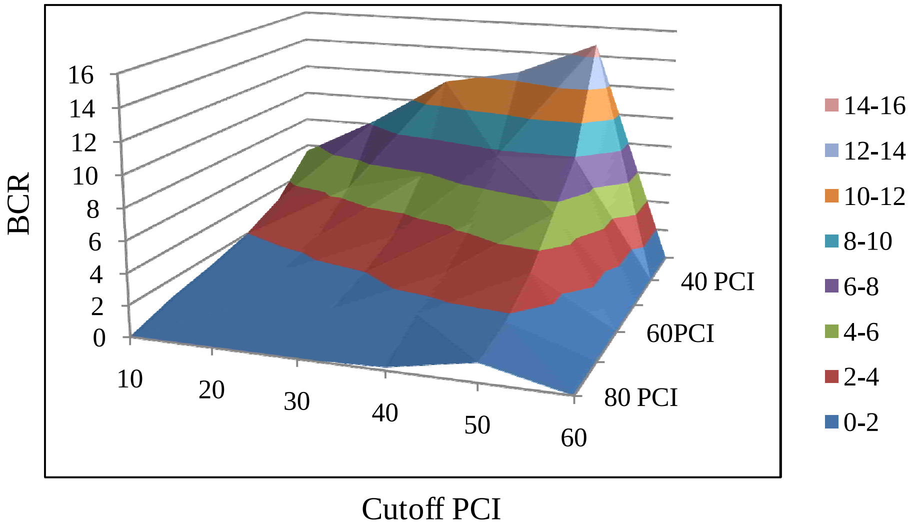


(b) Rise = 20

Figure 4.12: Effect of Initial PCI for 40 years Analysis Period



(c) Rise = 30



(d) Rise = 40

Figure 4.12 (Continued): Effect of Initial PCI for 40 years Analysis Period

CHAPTER 5

ANALYSIS OF NON LINEAR PAVEMENT DETERIORATION

5.1 Introduction

Pavements can be deteriorated both linearly or non-linearly depending on loading and environmental condition. Because of only one year PCI data, we do not have an explicit deterioration rate equation for our airport pavements. That is why different linear and non-linear deterioration equation should be used for this study from few previous literatures. In the previous chapter, pavement deterioration rate was assumed to be linear and was a function of current condition of the pavement. This chapter has introduced nonlinear pavement deterioration rate.

Non linear pavement deterioration rate is a function of the age of the pavement and an equation developed from previous study was used. This chapter will help to have better understanding of BCR and comparing linear and non linear equation used. Initial PCI, cutoff PCI and PCI rise would be taken similar to the linear chapter. PCI based maintenance treatment should be studied in this chapter.

5.2 Objective of the Chapter

This chapter has the following major objectives:

- Develop modules using system dynamics modeling concept to determine the relative benefits and life cycle costs of maintenance treatments for a specific airport pavement section considering minimum acceptable PCI where the deterioration rate will be non-linear and a function of the age of the pavement.

- Determine the effects of minimum acceptable PCI, PCI rise or PCI improvement, and, initial PCI on the Benefit Cost Ratio (BCR) of different airfields and to develop design charts.

5.3 Prediction Model

Pavement deterioration models consider the network and project levels of pavement management. Two basic types of models are deterministic and probabilistic which are further classified into primary response, structural, functional and damage for the deterministic type, and survivor curve and transition for the probabilistic type. Prediction models can be broken down into four basic types for operational purposes:

- Mechanistic: based on some primary response or behavior parameters such as stress strain and deflection.
- Mechanistic-empirical: Response parameters are related to measured structural or functional deterioration, such as distress or roughness, through regression equations.
- Regression: The dependent variable of observed structural or functional deterioration is related to one or more independent variables like subgrade strength, axle load, layer thickness, environmental factors and their interactions.
- Subjective: Experience is captured in a formalized or structured way, using transition process models.

The state of Washington has developed a set of regression equations, based on a long-term pavement performance data base, of the form:

$$PCR = C - mA^{P} \quad \text{(Eq. 5.1)}$$

where

PCR = pavement condition rating, scale of 0 to 100

C = 100

m = slope coefficient

A = age of pavement, years

P = constant which controls the shape of the curve

Table 5.1 provides an example listing of the standard or default performance curves, for Washington State’s pavement management system for different pavement types. For the nonlinear analysis equation for new or reconstructed asphalt concrete type has been used in this study. We do not have deterioration data for NM airports, hence deterioration equation from a renowned PMS having greater data points have been used in this study. As we have lower traffic condition for NM airports, we can used deterioration equation previously developed for newly or reconstructed pavements. For different PCI rise, same deterioration rate after corresponding age has been used. Different benefit module has been used which has taken nonlinear deterioration rate as input instead of the linear deterioration rate. However, benefit has been determined using the same concept. Same LCC module has been used.

5.4 Relative Benefit and Life Cycle Cost

To determine relative benefit for different initial PCI, PCI rise and cutoff PCI a newly developed module has been used. Nonlinear module has used similar variables like initial

PCI, PCI rise, cutoff PCI and deterioration rate which were also used in previous linear module. The only exception is in deterioration rate, where nonlinear module used age dependent equation used by Washington State’s PMS. Relative benefit is obtained by dividing area under the do something curves by area under the do nothing curves similar to the linear module. As initial PCI, PCI 30 to 80 has been used with cutoff PCI 80 to 10. 10 to 40 PCI rise has been used like linear analysis. To determine the life cycle cost, same LCC module has been used like linear analysis, because, nonlinear analysis only varies in PCI deterioration rate not in EUAC calculation. Figure 5.1 shows do nothing and do something PCI deterioration curves for nonlinear benefit module. This figure shows analysis output for initial PCI 60, cutoff PCI 40 and PCI rise 20. For this instance, benefit area and do nothing area was obtained as 745 and 260 respectively which gives 14.32% benefit per year. As deterioration rate, Washington State’s PMS equation has been used. Pavement PCI reaches at 40 in 2015 and a maintenance treatment of 20 PCI rise has been applied. Do something PCI again reaches cutoff PCI 40 in 2018 where second maintenance treatment has been applied. Number of treatment applied in 20 years analysis period was 6, having unit cost \$ 24.76 per square meter each. Unit cost has been calculated using Eq. 4.4. Equivalent Unit Annual Cost (EUAC) has been obtained \$ 7 per square meter pavement area. Benefit Cost Ratio (BCR) has been found 2.03 for this instance which indicates relative functional benefit achieved after one dollar investment in a year in a square meter of pavement area for pavement restoration.

5.5 Benefit Cost Ratio Design Charts

Relative benefit to cost ratio (BCR) is simply drawn from dividing relative benefit by EUAC. As EUAC was for 1000 square meter, it is converted for unit area before using it to get BCR. It is also divided by analysis period to get BCR for a year. BCR signifies the relative functional benefit achieved by the airport pavement after one dollar investment in a year in a square meter of a pavement area for pavement restoration. Several BCR design charts were developed using system dynamics modules which help to determine benefit cost ratio for different initial PCI, different cutoff PCI and PCI rises.

Figure 5.2 shows the effect of cutoff PCI on relative benefit to cost ratio (BCR) for nonlinear analysis. Figure 5.2(a), 5.2(b), 5.2(c) and, 5.2(d) have shown the results for PCI rise 10, 20, 30 and, 40 respectively. Different curves on a graph indicate BCR for different initial PCI. Figure 5.2 shows that, higher rise always gives higher BCR and a specific maintenance always gives higher BCR if it is applied on more deteriorated pavements. For rise 10 and for a specific initial PCI, maximum BCR is obtained for maximum cutoff PCI. However, as PCI rise increases, it shows different slopes and for rise 40 cutoff-PCI 40 and 50 has shown almost same BCR. If several cutoff values show similar BCR like this, then most cost effective treatment should be applied. For PCI rise 30 and 40, initial PCI 60, 70 and 80 has shown almost same BCR. The dashed line indicates the average BCR of all pavement maintenance of all data points obtained for a specific maintenance or rise. This line helps to take a maintenance which will give good results or BCR values more than the average BCR obtained for that particular rise.

Figure 5.3 shows the effect of PCI rise on BCR for nonlinear analysis. It indicates that, higher rise always gives higher BCR for a specific initial PCI and cutoff PCI. The dashed line indicates the average BCR for maintenance of different rise for a specific initial PCI. For initial PCI 80, rise 10 has given maximum BCR and, for a specific PCI rise, highest cutoff PCI always has shown the maximum BCR. In nonlinear analysis, maximum cutoff-PCI always shows maximum BCR unlike the linear analysis. Figure 5.3 indicates that for different initial PCI different PCI rise has given almost same BCR for lower cutoff PCI.

Figure 5.4 shows the effect of initial PCI for different PCI rise, for nonlinear analysis. Figure 5.4 indicates that, different rise have shown higher BCR for lower initial PCI and lower cutoff PCI. The surface plot creates an inflated surface diagonal with two horizontal axes. As PCI rise increases, the peak of the surface becomes more wide and the slope of the surface become more flat. This figure helps to take different maintenance having similar BCR so that most cost effective maintenance can be chosen.

5.6 Conclusion of the Chapter

Following conclusion can be made based on analysis of this chapter:

- Non-linear deterioration equation has given almost similar BCR like linear equation. Hence, BCR has very little effect on deterioration rate.
- BCR design charts are capable to show the BCR for airport pavements having initial PCI 30 to 80, cutoff-PCI 10 to 80 and rise 10 to 40.
- For PCI rise 30 and 40, initial PCI 60, 70 and 80 has shown almost same BCR for different cutoff PCI.

Table 5.1: Standard Performance Equations of Washington State's PMS

Type of Construction	Pavement Surfacing	Number of Units	Performance Equation
New or Reconstructed	Bituminous Surface Treatment	2	$PCR = 100 - 0.086(Age)^{2.50}$
New or Reconstructed	Asphalt Concrete	26	$PCR = 100 - 0.22(Age)^{2.00}$
New or Reconstructed	Portland Cement Concrete	19	$PCR = 100 - 0.85(Age)^{1.25}$
Resurfacing	BST over AC	5	$PCR = 100 - 8.50(Age)^{1.25}$
Resurfacing	BST over BST	6	$PCR = 100 - 3.42(Age)^{1.50}$
Resurfacing	AC Overlay under 1.2 inches	75	$PCR = 100 - 0.58(Age)^{2.00}$
Resurfacing	AC Overlay 1.2 inches to 2.4 inches	126	$PCR = 100 - 0.76(Age)^{1.75}$
Resurfacing	AC Overlay over 2.4 inches	19	$PCR = 100 - 0.54(Age)^{1.75}$

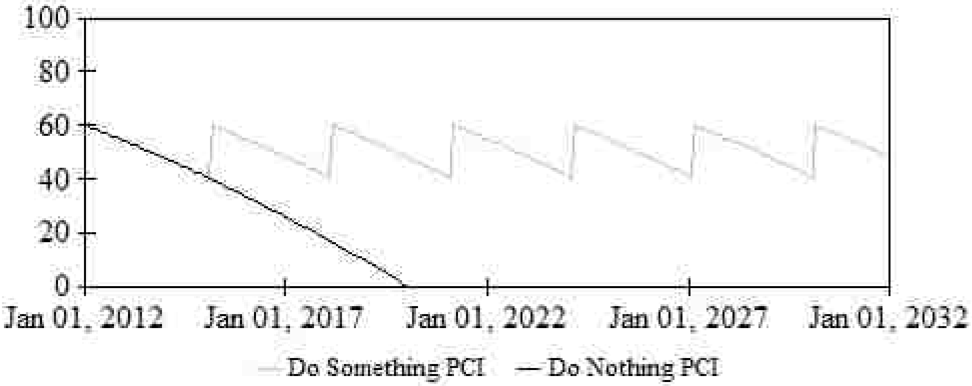
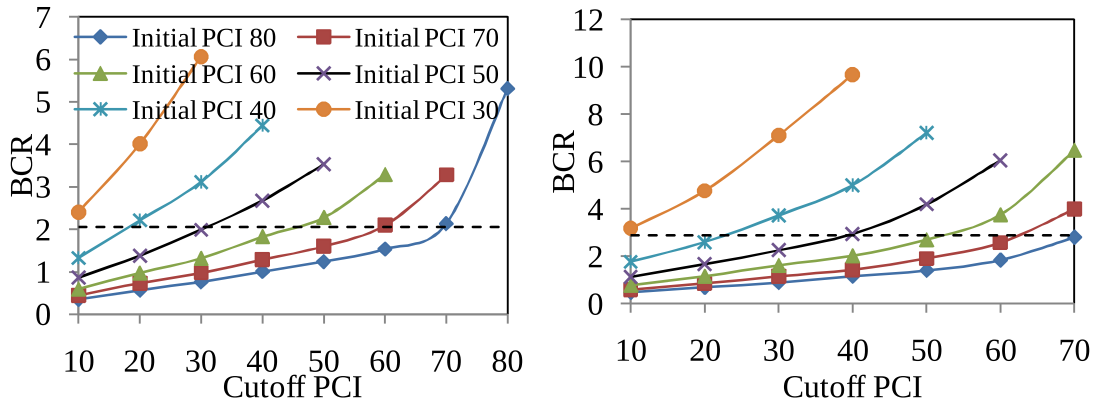
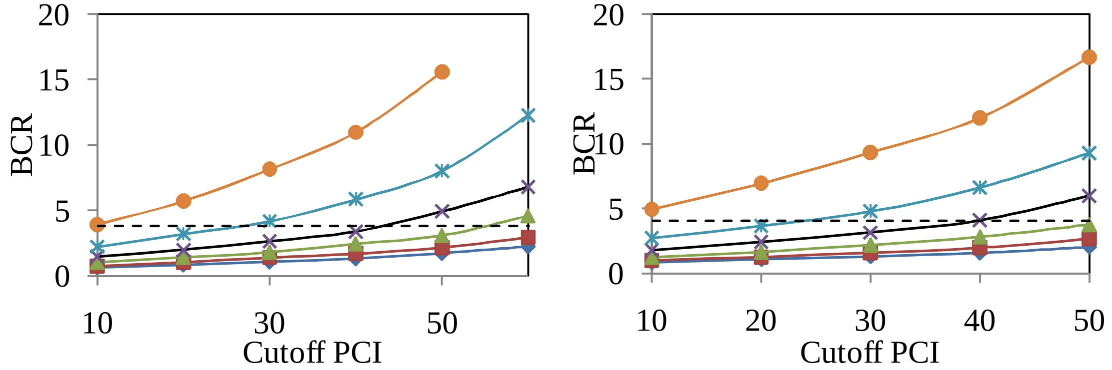


Figure 5.1: Nonlinear Do Nothing and Do Something Condition Curve



(a) Rise = 10

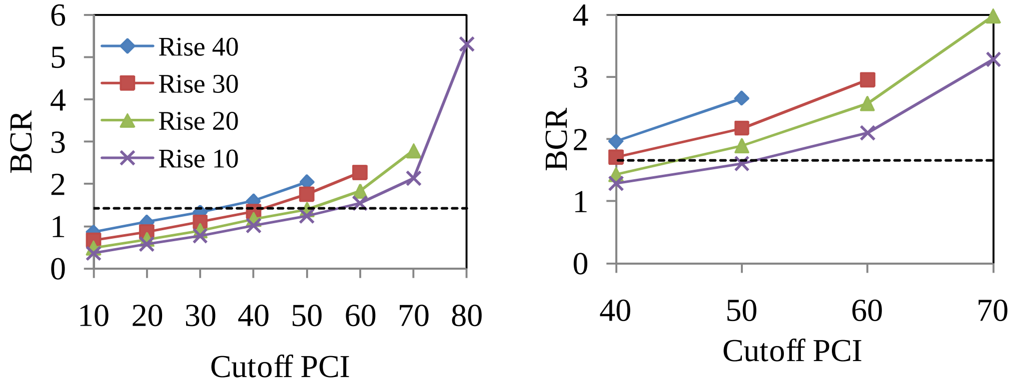
(b) Rise = 20



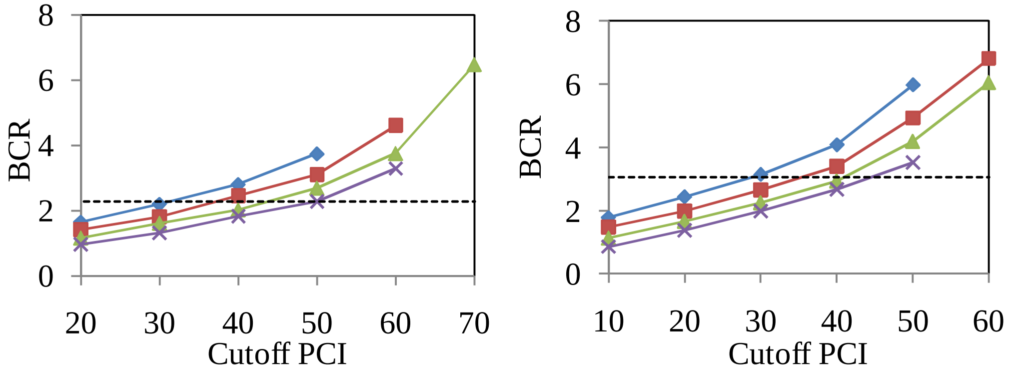
(c) Rise = 30

(d) Rise = 40

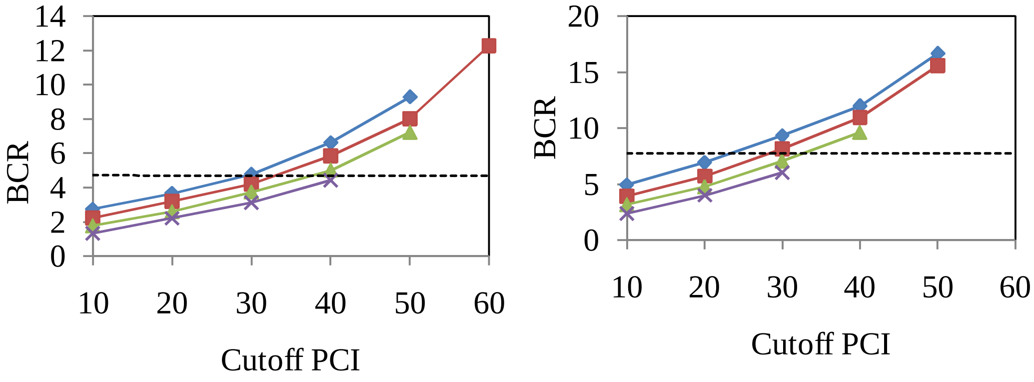
Figure 5.2: Effect of Cutoff PCI



(a) Initial PCI = 80 (b) Initial PCI = 70

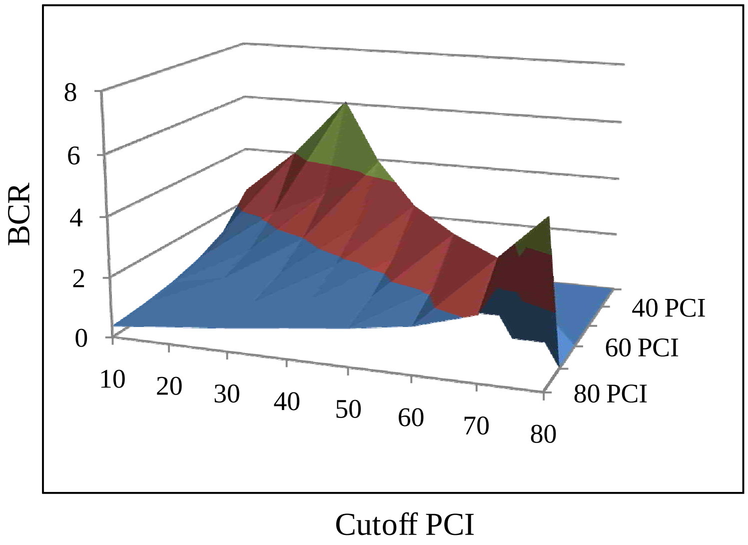


(c) Initial PCI = 60 (d) Initial PCI = 50

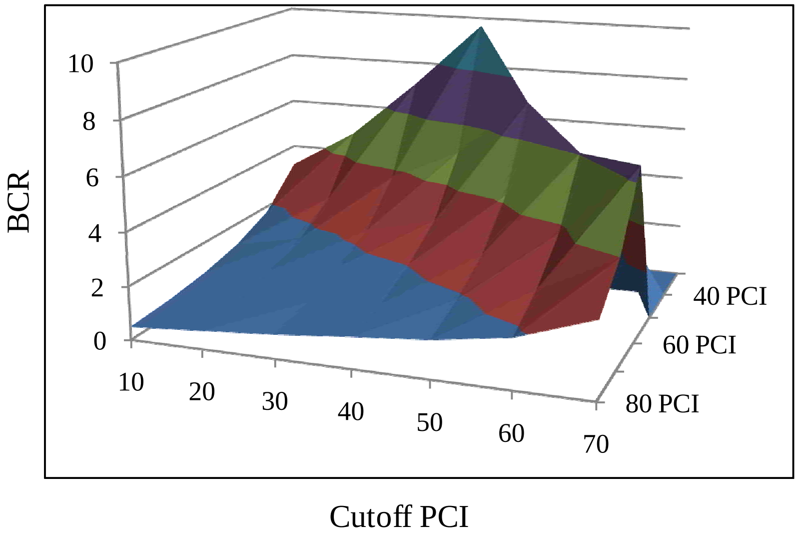


(e) Initial PCI = 40 (f) Initial PCI = 30

Figure 5.3: Effect of PCI Rise

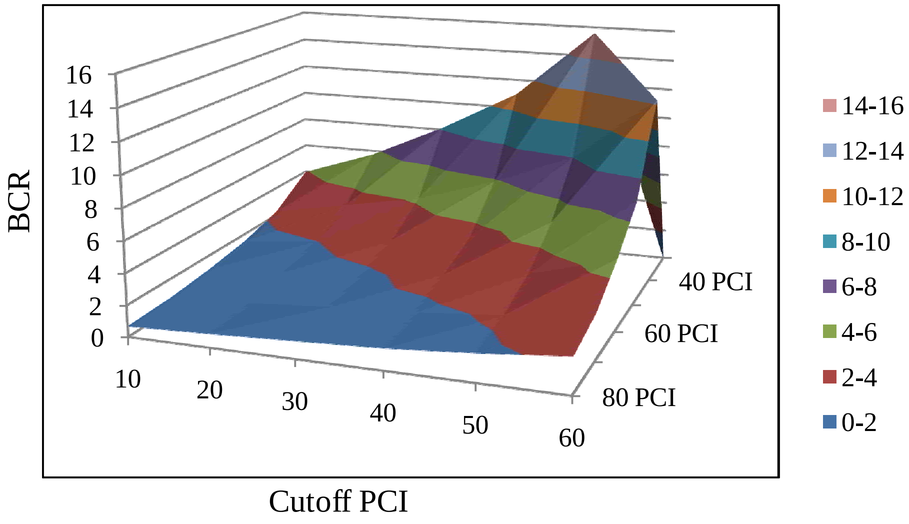


(a) Rise = 10

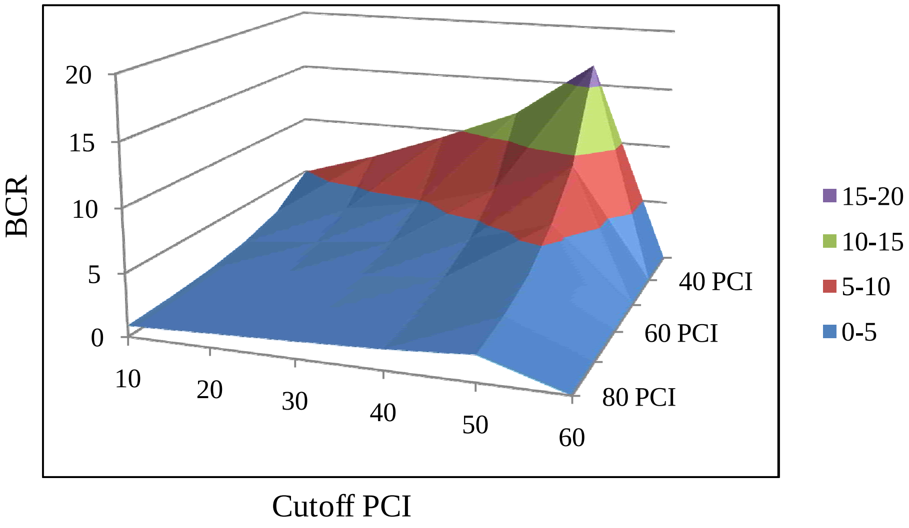


(b) Rise = 20

Figure 5.4: Effect of Initial PCI



(c) Rise = 30



(d) Rise = 40

Figure 5.4(Continued): Effect of Initial PCI

CHAPTER 6

ALTERNATIVE TO MICROPAVER BASED MAINTENANCE SOLUTION

6.1 Introduction

MicroPAVER is capable of determining budget requirements for airport pavement management projects in order to achieve different management objectives. However, to achieve those objectives, this tool applies different maintenance strategies on different sections of the airport pavement too frequently, depending on their current condition. From the BCR results it can be said that, functional benefit achieved by this tool is well above the satisfactory level. Because of the frequent maintenance, it requires a greater budget than any other alternate methods.

MicroPAVER has a limitation in applying maintenance treatment each section of the management network to achieve the highest benefit. Therefore, their strategies are satisfactory for unlimited budget. However, for budget constrain, it does not consider Benefit Cost Ratio (BCR) instead of only the benefit or cost individually. Alternative of this tool is developed using system dynamic modeling technique which is capable of applying different minor maintenance, major maintenance, minor rehabilitation and major rehabilitation on the studied pavement section and can increase pavement PCI value and service life. Probabilistic life cycle cost for both approaches has been performed using FHWA life cycle cost tool named RealCost. Benefit cost analysis has been performed for both MicroPAVER and system dynamic tool.

6.2 Objective of the Chapter

This chapter has the following major objectives:

- Using a system dynamic tool, to develop different modules capable of managing airport pavement in applying various treatments in different interval and to perform probabilistic and deterministic life cycle cost analysis.
- To compare different alternatives obtained from system dynamic model with MicroPAVER and to perform benefit cost analysis.

6.3 Motivation

The New Mexico Department of Transportation (NMDOT) Aviation Division recently collaborated with the Civil Engineering Department of University of New Mexico to perform a survey of the pavements of almost 50 General Aviation airports of New Mexico for the Federal Aviation Authority (FAA). Their goal was to identify the current condition of runways, taxiways and aprons, as well as propose the necessary preventive maintenances. Creation of a central database including Pavement Condition Index (PCI), predicted PCI, Maintenance and Rehabilitation (M&R) work plan and budget required for different sections of the airport pavement was the key requirement for the decision makers. The current pavement condition of these airports is not good. So selection of the necessary measures to boost the condition of these airport pavements is urgent along with estimating the accompanying financial requirements.

A general aviation airport covers a large range of services, both commercial and non commercial. According to the U.S. Aircraft Owners and Pilots Association, general aviation provides more than one percent of the United States' GDP, accounting for 1.3 million jobs in professional services and manufacturing. Proper allocation of funding for pavement management of those airports is a challenging task. A PCI survey for all New Mexico General Aviation Airports was conducted in 2007. A MicroPAVER database containing detailed pavement distress data and Pavement Condition Index (PCI) data was developed. The goal of various pavement maintenance works is to increase the PCI and to reduce the rate of PCI degradation. At the initial age, PCI degradation rate is relatively low but after certain age it goes faster. It is better to apply rehabilitation before a critical PCI (55 to 70) because after that the rehabilitation cost would be 4-5 times higher. To maintain better functional condition in an airport pavement, Pavement Condition Index should be at least on acceptable limit. To ensure the required PCI, maintenance work should be performed on the airfields periodically. The main purpose of the current study is to compare the functional benefit of different treatments in selected New Mexico airports due to various maintenance works.

6.4 MicroPAVER Maintenance and Rehabilitation Methodology

MicroPAVER Maintenance and Rehabilitation (M&R) are grouped into four categories: localized safety or stop-gap maintenance, localized preventive, global preventive and major M&R. Localized safety M&R is defined as the localized distress repair work need to keep the airport pavement operational in a safe condition. Localized preventive works such as crack sealing and patching are the distress repair activities performed in the pavement aiming to slow down the deterioration rate. Localized distress maintenance policy for good pavement condition is referred as localized preventive policy and for bad pavement condition is known as localized safety policy.

The localized safety policy is a stop-gap treatment until major maintenance can be performed. This policy is limited to repairing those distresses that can be a safety hazard or affected the functional condition too much. Global preventive M&R is also known as surface treatment and is defined as the maintenance work applied to entire pavement sections to increase the section PCI and to slow down the deterioration rate. Major M&R is also applied into the entire pavement section but is capable of restore the PCI near 100 and it improves the existing structural and functional condition of pavement. Major M&R is more expensive; it includes reconstruction and structural overlays.

MicroPAVER applies those four M&R depending on pavement current PCI and management objectives described which is already described in the literature. For multi-year pavement management this tool applies critical PCI method. Critical PCI is that value of PCI after which both the deterioration rate and the maintenance cost increases significantly. It is developed by studying results from the dynamic programming network optimization analysis and by performing many life cycle cost analysis on many previous projects. In the critical PCI method, MicroPAVER is more concern about the pavements which have PCI near critical limit (55-70). The first factor in budget prioritization is the M&R category in following manner: localized safety> localized preventive> global preventive> major above critical PCI> major below critical PCI. The reason behind giving higher priority to major M&R above critical than major M&R below critical is to minimize the cost before the deterioration rate increases. Within each M&R category, a priority factor is assigned based on the combination of pavement use and functional classification such as: runways> taxiways> aprons> helipads. Budget requirements are determined for different management objectives in critical PCI method are described in previous study (Shahin 2002):

- Eliminate backlog of major M&R in a specified period of time.
- Maintain current-weighted PCI over a specified period of time.
- Reach desired are-weighted PCI in a specified period of time.

Select Backlog Elimination as the objective in budget analysis in MicroPAVER will report what M&R is required to achieve an overall weighted average PCI above critical within specified period. In this current study most of the airports have PCI below critical limit, and analysis is done only for maintaining current PCI and to reach PCI near 80 or above. Backlog elimination objective is eliminated from this current study as the other two objectives give resulting PCI below and above its value and benefit cost ratio for backlog elimination is in between other two objectives. As this current study will focus on benefit and cost for different methods for MicroPAVER and system dynamic tool, only extreme good and extreme bad methods are taken from MicroPAVER. MicroPAVER calculates budget requirements for any of the above objectives by performing budget consequences with a built-in iteration procedure having following steps:

- Step 1: Run a budget consequence scenario plan with unlimited budget and to set the highest annual budget during the analysis period (which is usually the first year budget as 1 year as specified period to achieve goal) as the maximum budget and zero as the minimum budget.

- Step 2: If an unlimited budget cannot achieve the goal it stops the analysis. It usually happens when desired PCI at the end of the analysis period is higher than what possible. Specifying a network average PCI greater than 80 is always difficult to achieve. If the goal is achieved it continues to the Step 3.
- Step 3: It sets the average of maximum and minimum budget as current budget. If goal achieved it sets current budget as maximum or if not achieved current budget as minimum budget.
- Step 4: It repeats Step 3 until the end condition tolerance or allowed number of iteration is achieved.

6.5 System Dynamics Maintenance and Rehabilitation Methodology

Two types of computer based pavement management systems (PMS) have been widely used for the past few decades. Non analytical database PMS or statistical correlation modeling both have their own drawbacks, as they have little predictive capabilities and assume the past condition will continue into the future. But real world such as PMS is non-linear in nature and is a complex system having many variables like pavement condition, user response, load, environment, degradation, maintenance, constrained budget and so on. System dynamics is a simulation modeling process capable of capturing the structure and behavior of any complex system. Delay time or many variables effect can be easily captured in the system dynamic model which cannot be achieved with the help of Monte Carlo simulation or regression modeling. Pavement condition with or without rehabilitation over an analysis period and budget scenario at different condition of a pavement which are also in a linkage with many other variables make it suitable for system dynamic study.

The available pavement management software MicroPAVER has some drawbacks in applying maintenance treatment in appropriate time. A new system dynamic model need to be developed to reinforce PCI based evaluation and application of maintenance strategies.

Using a system dynamic tool named Powersim, different models such as Benefit module; LCC module has been developed to analyze different maintenance treatments in the evaluated 19 New Mexico airports. Benefit module is capable of determining the resulting average PCI and Functional Benefit with or without different treatments for analysis period of 20 years. It helps to compare the resulting PCI obtained from MicroPAVER. The problem with MicroPAVER is that, it applies different maintenance works each year on different sections depending upon their condition to maintain a certain PCI or reach a specific PCI, which eventually gives lower benefit or higher costs. LCC module helps to determine deterministic life cycle cost of different alternatives. Probabilistic life cycle cost analysis has been performed using RealCost. The most cost effective maintenance treatment type and the optimum time of their application can be determined using those modules.

The problem addressed in this study is selecting the optimum pavement maintenance strategy. This selection has been made based on maximum Benefit to Cost ratio. Functional benefits have been estimated using PCI increase due to a maintenance treatment which is the key component of this study. Data regarding the PCI rise and unit cost has been used form previous study (Ningyuan et al) where cost has been converted to the current dollar value comparing consumer price index (CPI). Average expected life of different maintenance strategy is chosen based on survey data of different agency obtained from previous study (Geoffroy 1996). Standard deviation of cost is estimated from cost range of common airport pavement maintenance practices.

A system dynamic model has been developed using Powersim to estimate the average PCI and functional benefit after do nothing or applying a treatment over the analysis period of 20 years. The do nothing PCI trend and the predicted rate of deterioration are determined using MicroPAVER. If we apply different types of M&R in every year of the design life to fulfill the objective to reach area weighted PCI 80 or to maintain current PCI; life cycle costs are determined from critical PCI budget analysis method in MicroPAVER.

Results of these two approaches of MicroPAVER are compared with that of the four alternatives developed in system dynamic modules. In system dynamic modules, four different maintenance treatments are applied in the current year and in the year when PCI reaches the current year PCI value. Relative benefit of a treatment is the percent area improvement under the do something curves over the do nothing curves. As lower benefit cutoff value the zero PCI is chosen because we did not apply a treatment based on a minimum acceptable PCI rather we apply treatment to maintain PCI at least equal to current year PCI. In determining relative benefit for both MicroPAVER and System Dynamic Tools the same procedure has been applied to maintain consistency in results. LCC module is the same as the previous chapter but the only exception is that salvage cost is ignored as MicroPAVER does not consider salvage cost and LCC is calculated for the whole pavement section rather than a unit area. Simplified benefit module and the causal loop diagram are shown in Figure 6.1.

6.6 Project Alternatives

The following alternatives are considered for the current study:

- Spray Patching (Routine Maintenance),
- Route & Seal Cracks (Major Maintenance),
- Slurry Seal or Surface Treatment (Minor Rehabilitation) and
- Hot Mix Overlay (Major Rehabilitation).

Spray patching is a maintenance treatment that includes the application of a bituminous compound covered with a layer of aggregate. Spray patching can be classified as a routine maintenance treatment. It can be done manually or by specialized mechanical equipment that sprays an emulsion, applies the cover aggregate, and provides the initial compaction; all in a single pass. If spray patching is applied on the full width of a facility, then it can be considered as a surface treatment. It is used to lower the pavement deterioration rate and to repair localized distresses such as raveling and block cracking. It also provides improved surface friction. Machine patching is typically used to repair large pavement area. Route and seal cracks can be referred as a major maintenance.

Crack sealing is a maintenance technique which seals cracks with rubberized bituminous material. It includes routing of the crack, cleaning the routed surface and applying sealant at the top of the crack. Crack filling is similar to crack sealing, but without the routing. Crack filling is easily damaged by snow plows than and hence is not cost-effective. The primary purpose of route and seal crack is to prevent water from entering the pavement structure. It can also prevent spalling and raveling of unsealed cracks.

The Slurry seal itself is a surface treatment and known as a minor rehabilitation. It is an unheated mixture of asphalt emulsion, graded fine aggregate, mineral filler, water, and other additives, mixed and uniformly spread over the pavement surface as slurry. Slurry seal is maintained with the objective of creating a bitumen-rich mortar. Slurry seals are used to amend surface distresses such as raveling and coarse aggregate loss, seal slight cracking. It improves pavement friction and slow surface oxidation.

Hot mix overlay of AC pavement is considered as a major rehabilitation and consists of placing a layer of hot mix over the existing AC surface. Conventional AC overlays are usually constructed with a minimum thickness of $1\frac{1}{2}$ inch. Overlays less than $1\frac{1}{2}$ inch thick are called thin overlay. It is used to restore pavement serviceability by improving ride quality and providing a new waterproof surface that covers cracking, rutting and other pavement defects. Unit cost, service life and PCI rise of different alternatives are shown in Table 6.1. Resulting improved PCI due to various alternatives at Artesia Municipal is shown in Figure 6.2.

6.7 Benefit Cost Analysis

Usually in life cycle cost analysis for airport pavements, the functional benefit achieved from different alternatives are assumed to be the same. But different alternatives can give different benefit results. Therefore, benefit cost ratio of different maintenance work needs to be analyzed to draw the conclusion in decision-making. In this study, benefit and cost of four alternatives are compared using a developed system dynamic model with that obtained from a pavement management tool named MicroPAVER. Table 6.2 shows the pavement area, Pavement Condition Index and deterioration rate for the 19 Mexico Airports of the current study. For these airports, functional benefit obtained from four different maintenance works and two different approaches of MicroPAVER are studied using the average PCI achieved in the analysis period by those techniques using system dynamic model. MicroPAVER gives the life cycle cost of both approaches and deterministic and probabilistic life cycle cost analysis for four alternatives are performed using FHWA LCCA software RealCost.

6.7.1 Benefit Results

Life cycle average PCI due to different types of maintenance are shown in Table 5.3. do nothing PCI indicate the average PCI of the pavement if no maintenance is applied in the analysis period. In the system dynamic model, four alternatives of different pavement improvement capabilities and different expected life are applied on different airports in the current year and the year when PCI reaches the current condition again. Their corresponding life cycle PCI is show on the table.

MicroPAVER applies two different approaches where each approach is consisting of localized safety, localized preventive, global preventive and major M&R work. It has applied different treatment depending on maintenance goal. First approach is to reach PCI of 80 within second year of the analysis period shows higher value of life cycle PCI. In the system dynamic model, specific alternative is applied in the entire airport but MicroPAVER applies different maintenance work in different sections depending on their priority, critical PCI, section priority, and maintenance objective. For some airports, such as Raton, the goal cannot be reached and the achieved PCI was 65 because major maintenance is responsible for large PCI improvement and no major work is applied in some large sections as it is not warranted in that particular section.

Reach PCI 80 approach is the best among all alternatives as it has shown good life cycle condition but to achieve this value frequent maintenance has been applied which eventually costs more. “Maintain current PCI” approach has maintained current year average PCI throughout the design life. Table 6.3 shows the weighted average PCI value because it better represents the condition of entire airfield. In maintaining current year average PCI throughout the analysis period always gives lower value of weighted average PCI for any particular year. This is because MicroPAVER always applies major work in smaller area to save the available budget. In MicroPAVER there is no maintenance technique to maintain weighted average PCI. For Questa, two different MicroPAVER approaches shows the same result as it is a very small airport having only three sections of good condition and the only one M&R took place in 2014. Table 6.4 shows the relative benefit of different approaches which is the area under the improved PCI due to any treatment curve over the do nothing curves. Two approaches of MicroPAVER have shown the highest and the lowest benefit cost rations.

6.7.2 Life Cycle Cost Results

Table 6.5 indicated the deterministic cost results of different alternatives. The first approach of MicroPAVER has shown better functional benefit as well as greater life cycle costs. Similarly, the second approach has given lowest life cycle cost and as we see previously it has also lowest functional benefit among all alternatives. The four alternatives developed in system dynamics have shown cost within the limit of two cost results obtained from both MicroPAVER approaches. The life cycle cost analysis of different alternatives of system dynamics are described in next paragraph.

LCCA is an engineering economic analysis tool useful in comparing the relative economic merits of competing construction or rehabilitation design alternatives for a single project. LCCA helps in determining the lowest cost way to accomplish the performance objectives of a project. LCCA is applicable only to decisions where benefits are considered to be equal for all alternatives. LCCA process begins with the development of alternatives to fulfill the performance objectives for a project. Initial and future activities involved in implementing each of the project design alternatives are then scheduled and costs of these activities are estimated. For this current study, only direct agency expenditures (maintenance activities) are considered but user costs that result from agency work zone operations is ignored as it is very abstruse to measure. Using an economic technique known as discounting, these costs have been converted into present dollars and then summed for each alternative.

Two computational approaches can be used in LCCA, deterministic and probabilistic. The methods differ in the way they address the variability related with the LCCA inputs. In the deterministic approach, each LCCA input variable is considered to have a discrete or fixed value. Probabilistic LCCA inputs are defined by probabilistic functions that convey both the range of likely inputs and the likelihood of their occurrence (Walls 1998). RealCost 2.5 is used for probabilistic LCCA for this study. In the current study, triangular distribution has been taken to signify the variability of discount rate as the minimum, maximum and the most likely value of discount rate is known from previous airport projects. For all alternatives 3%, 4% and 5% are chosen as minimum likely, most likely and maximum likely value of the discount rate, respectively. For maintenance cost, normal distribution has been taken. Mean value and the standard deviation of unit cost for patching, crack sealing, slurry seal and overlay are taken as shown in Table 6.1.

Undiscounted expenditure stream at Artesia airport is shown in Figure 6.3. Spray patching, route and seal crack, slurry seal and overlay has been applied in Artesia in 3, 4, 6 and 7 years interval respectively because in those years Artesia weighed average PCI reaches the current PCI value. Deterministic EUAC for different alternatives for different airports are presented in Table 6.5. 4% is used as a discount rate in this deterministic study. Discount rate is the interest rate by which future costs (in dollars) will be converted to present value. Real discount rates typically range from 3% to 5%. Salvage costs are ignored in this current study as MicroPAVER did not consider salvage cost in M&R analysis. From Figure 6.5, it can be said that spray patching is more economical than all other alternatives and HMA overlay is most expensive. But a decision should not be made without comparing benefit cost results because different alternatives have shown different functional benefits which has been discussed previously.

Probabilistic LCCA is performed using RealCost with 1,000 iterations. Figure 6.4(a) shows the risk profile of the NPV for the four alternatives in histogram form for Artesia airport, where the probability is the area under the curve. The entire range of conceivable outcomes is arrayed with the estimated probability of each outcome actually occurring. There is no presumption that any particular alternative is better. The main advantage of the histogram is that it shows the variability about the mean. The wider distribution signifies greater variability. As shown, the outcome for Alternative 2 or route and seal crack is more uncertain than other alternatives.

The cumulative risk profile for maintenance cost in Artesia airport is given in Figure 6.4(b). This figure shows the risk profiles for all alternatives in cumulative form. As shown, there is 80 percent probability that maintenance cost for Alternative 1 or spray patching will be less than $ 20,000,000. This means that for the 1,000 iterations that were processed, 80 percent of the calculated values for NPV were less than $ 20,000,000. The variability for an alternative is inversely proportional to the slope of the cumulative curve. Therefore, steeper slope means less variability and flatter slope indicates greater variability. As shown, the slope for Alternative 2 is flatter than that for Alternative 1, and route and seal crack is therefore more variable than the spray patching. It is important for the decision maker to define the level of risk the organization can tolerate in making decision based on risk analysis results. Decision makers who can tolerate little risk prefer a small spread in possible results, with most of the probability associated with desirable results. On the other hand, if decision makers are risk-takers, then they will accept a greater amount of spread, or possible variation in the outcome distribution (Walls 1998).

NPV histograms of other 18 airports are shown in Figure 6.5 and cumulative risk profiles of other airports are shown in Figure 6.6. Various alternatives are applied according to their expected life which is the observed increased in pavement life due to the application of a treatment. Previously many studies have been done assuming the remaining service life is the number of year between today and the time when a pavement section accumulated the pre-specified distress threshold (Baladi et. al. 2010). Or in few other studies survival time for each alternatives was calculated as the difference between the date of treatment application and the first time the section became poor (Eltahan et al. 1999). According to Labi and Sinha (2003), the relative timing between maintenance activity and the performance inspection is crucial to the estimation of the treatment effect. A pavement condition regression models has been developed by Hein and Rao for various alternatives (2010).

6.7.3 Benefit Cost Ratio

BCR for four different alternatives used in system dynamic model is shown in Figure 6.7. As seen in the figure, the difference between BCR of those alternatives increases with decreasing current PCI. BCR for two different approaches used in MicroPAVER is shown in Figure 6.8. As seen in the figure, the difference between BCR of two approaches also increases with decreasing current PCI. Figure 6.9 shows the mean value of different treatments of system dynamic approaches and the MicroPAVER approaches. System dynamic approaches or application of a single treatment shows higher benefit cost values than MicroPAVER approaches or critical PCI approach. From the trend line it can be said that, for MicroPAVER approaches BCR increases with decreasing current PCI. However, system dynamic approach has shown highest BCR at current PCI near 40. The difference between BCR of MicroPAVER and System Dynamic approach is higher for the intermediate PCI but those are close in relatively high and low current PCI region.

6.8 Conclusion

Following conclusion can be made based on analysis of this chapter:

- For different maintenance alternatives in system dynamic module Spray Patching is most cost effective and HMA Overlay has shown highest functional benefit.

- For different MicroPAVER critical PCI method, ‘reach PCI 80’ has shown highest benefit and highest life cycle cost. If we want to maintain current PCI MicroPAVER gives lowest benefit and lowest life cycle cost.
- If we apply only a single treatment into the airport pavement not considering critical PCI method, it has shown higher benefit cost ratio than the other.
- SD model has given higher BCR than different multiple treatments and management goals of MicroPAVER.

Table 6.1: Life Extension and Unit Cost of Different Alternatives

Project Alternatives	Expected Life (yr)	SD (yr)	PCI Rise	Unit Cost (\$/m^2)	SD (\$/m^2)
Spray Patching	3	1.5	5	6.50	2.40
Route and Seal Cracks	4	2	15	9.50	4.20
Slurry Seal	6	1.5	30	19.00	5.4
HMA Overlay	7	3	Up to 95	26.00	4.8

Table 6.2: Current PCI and Deterioration Rate of Different Airports

Airport	Area (m^2)	Current PCI	Deterioration Rate (PCI/yr)
Artesia	351,314	36	1.46
Belen	108,718	57	1.65
Carlsbad	457,109	53	1.21
Clayton	102,280	70	2.11
DEII	340,300	67	1.30
Deming	224,845	61	1.88
Fort Sumner	149,847	62	1.72
Grants	84,059	61	1.82
Hobbs	464,890	55	1.31
Jal	62,120	54	1.84
Las Cruces	393,404	45	1.98
Lordsburg	50,480	48	2.43
Moriarty	143,422	58	2.30
Questa	55,602	63	1.86
Raton	136,638	75	1.18
Roswell	1,389,849	53	1.61
Ruidoso	329,393	78	1.23
Santa Rosa	93,206	68	1.43
Silver City	162,353	49	2.32

Table 6.3: Life Cycle Average PCI of Different Maintenance

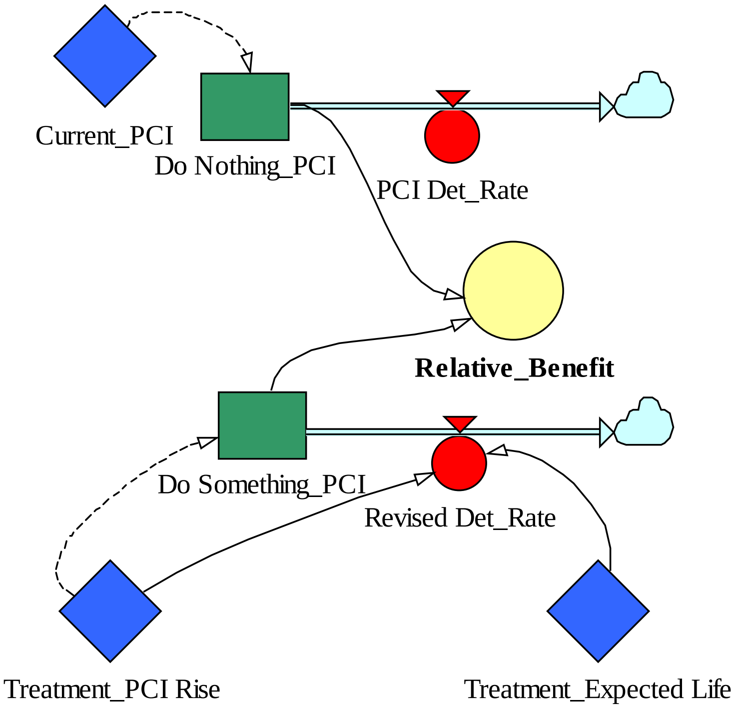
Analysis Tool	System Dynamic Model					Micro PAVER	
Airport	Do Nothing	Spray Patch	Seal Crack	Slurry Seal	HMA Overlay	Reach PCI 80	Maintain Current PCI
Artesia	21.58	38.79	43.97	52.63	67.82	84.04	30.65
Belen	40.71	59.77	64.97	73.64	77.49	82.69	45.95
Carlsbad	41.05	55.79	60.97	69.63	75.65	83.63	45.2
Clayton	49.16	72.79	77.97	83.85	83.48	70.69	54.55
DEII	52.16	69.79	74.97	82.52	82.1	90.28	55.55
Deming	42.44	63.79	68.97	77.63	79.34	83.78	46.65
Fort Sumner	44.02	64.79	69.97	78.63	79.8	77.71	45.7
Grants	43.03	63.79	68.97	77.63	79.34	83.35	44.15
Hobbs	42.06	57.79	62.97	71.63	76.57	77.35	49.45
Jal	35.83	56.79	61.97	70.63	76.11	75.69	46.6
Las Cruces	25.45	47.79	52.97	61.63	71.96	78.41	32.85
Lordsburg	20	50.79	55.97	64.63	73.35	72.18	25.05
Moriarty	35.27	60.79	65.97	74.63	77.95	78.32	45.35
Questa	44.63	65.79	70.97	79.63	80.26	70.68	70.68
Raton	60.35	77.79	82.97	86.08	85.79	65.05	63.9
Roswell	37.1	55.79	60.97	69.63	75.65	78.48	49.25
Ruidoso	65.85	80.79	85.97	87.42	87.17	68.54	67.65
Santa Rosa	53.88	70.79	75.97	82.96	82.56	70.54	56.35
Silver City	26.09	51.79	56.97	65.63	73.81	82.35	32.95

Table 6.4: Relative Benefits of Different Maintenance in Percentage

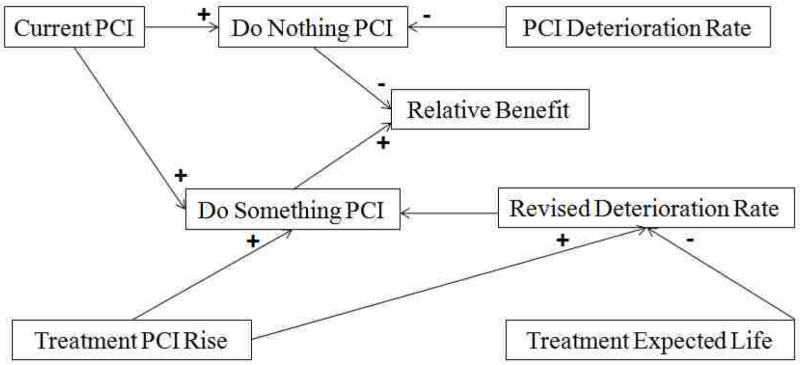
Analysis Tool	MicroPAVER		System Dynamic Model			
Airport	Reach PCI 80	Maintain Current PCI	Spray Patch	Seal Crack	Slurry Seal	HMA Overlay
Artesia	289	42	80	104	144	214
Belen	103	13	47	60	81	90
Carlsbad	104	10	36	49	70	84
Clayton	44	11	48	59	71	70
DEII	67	3	29	38	52	52
Deming	97	10	50	63	83	87
Fort Sumner	73	2	44	55	75	77
Grants	94	3	48	60	80	84
Hobbs	84	18	37	50	70	82
Jal	111	30	59	73	97	112
Las Cruces	208	29	88	108	142	183
Lordsburg	201	4	112	133	169	206
Moriarty	122	29	72	87	111	121
Questa	58	67	47	59	78	80
Raton	2	1	23	31	36	35
Roswell	112	33	50	64	88	104
Ruidoso	4	3	23	31	33	32
Santa Rosa	31	5	31	41	54	53
Silver City	216	26	99	118	152	183

Table 6.5: Deterministic EUAC of Different Maintenance in Thousand Dollar

Analysis Tool	MicroPAVER		System Dynamic Model			
Airport	Reach PCI 80	Maintain Current PCI	Spray Patch	Seal Crack	Slurry Seal	HMA Overlay
Artesia	2579	616	833	1007	1394	1540
Belen	857	114	258	311	431	477
Carlsbad	2305	429	1084	1309	1813	2004
Clayton	766	63	242	293	406	448
DEII	1659	186	807	975	1350	1492
Deming	1771	212	533	644	892	986
Fort Sumner	1183	47	355	429	594	657
Grants	566	39	199	241	333	369
Hobbs	4321	647	1102	1332	1844	2038
Jal	450	155	147	178	246	272
Las Cruces	3931	505	933	1127	1561	1725
Lordsburg	361	44	120	145	200	221
Moriarty	1210	222	340	411	569	629
Questa	211	211	132	159	221	244
Raton	24	24	324	391	542	599
Roswell	10686	3152	3285	3970	5497	6075
Ruidoso	136	107	781	944	1307	1444
Santa Rosa	282	88	221	267	370	409
Silver City	1619	242	385	465	644	712

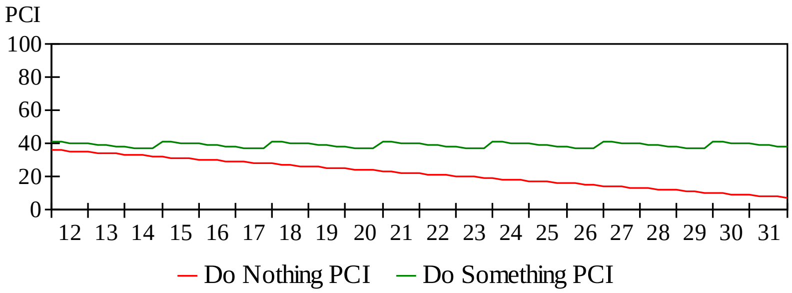


(a) Simplified Benefit Module

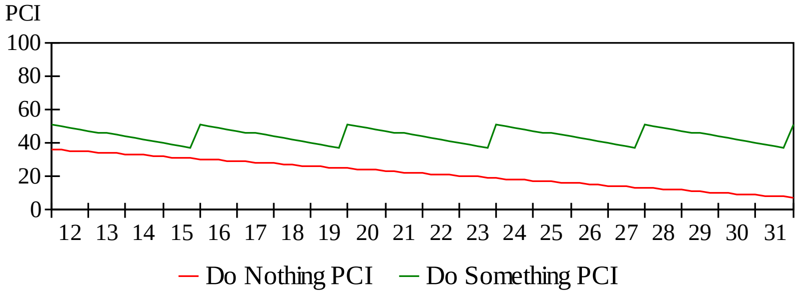


(a) Benefit Module Causal Loop Diagram

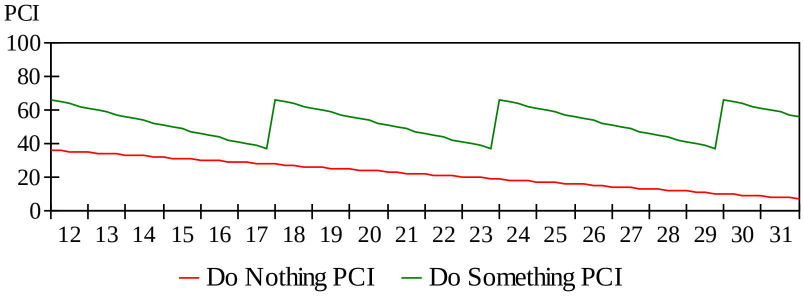
Figure 6.1: Benefit Module and Causal Loop Diagram



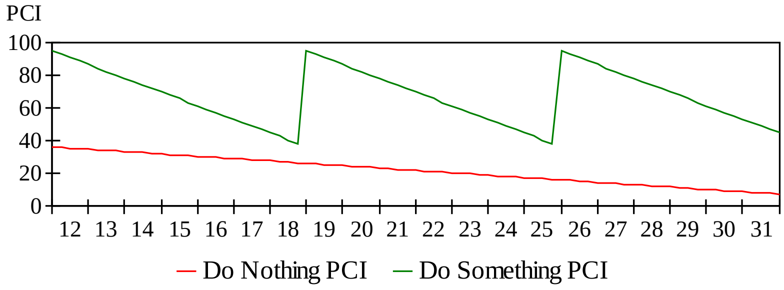
(a) Spray Patching



(b) Route and Seal Cracks



(c) Slurry Seal



(d) HMA Overlay

Figure 6.2: Improved PCI due to Maintenance Treatments at Artesia

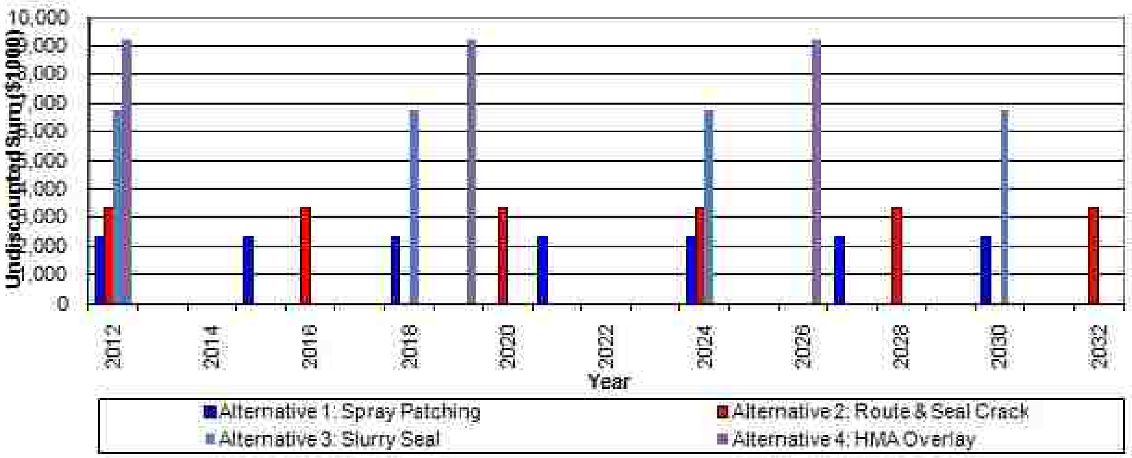
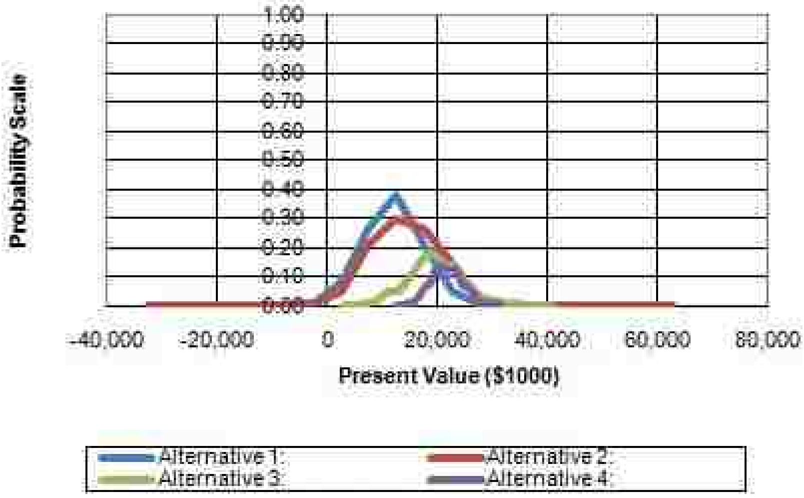
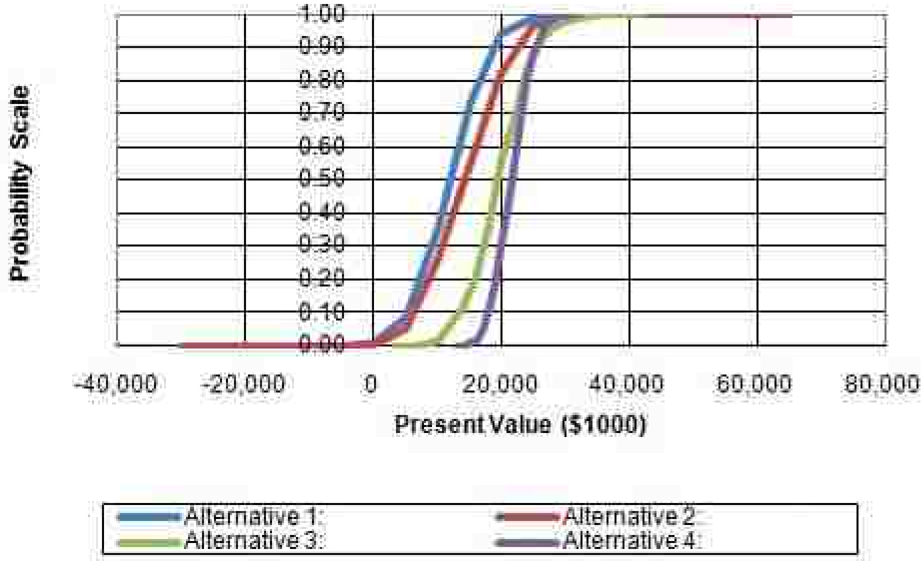


Figure 6.3: Expenditure Stream for Artesia Municipal Airport

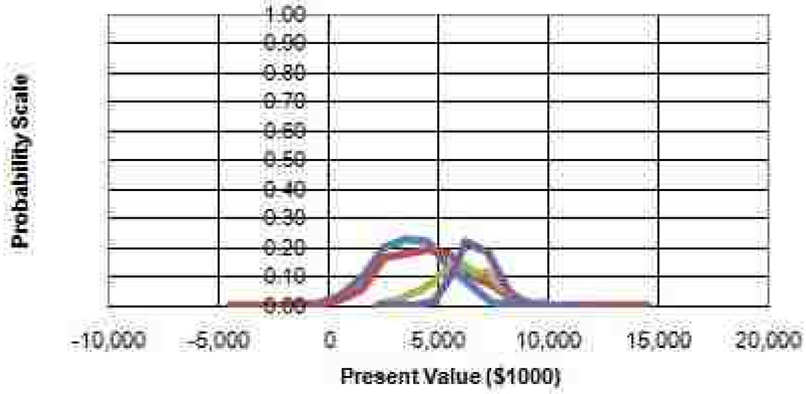


(a) NPV Histogram

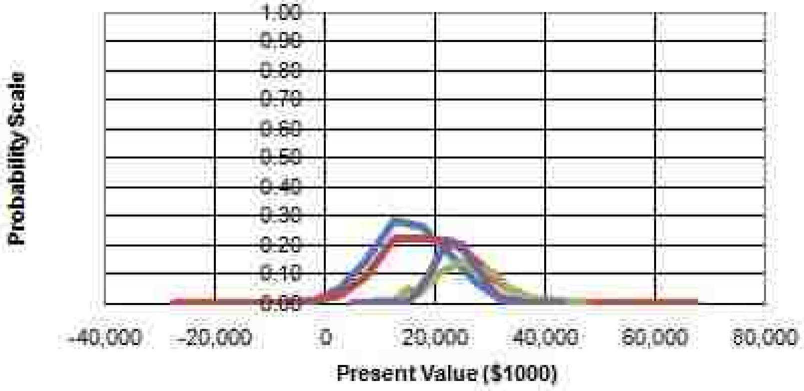


(b) Cumulative Risk Profile

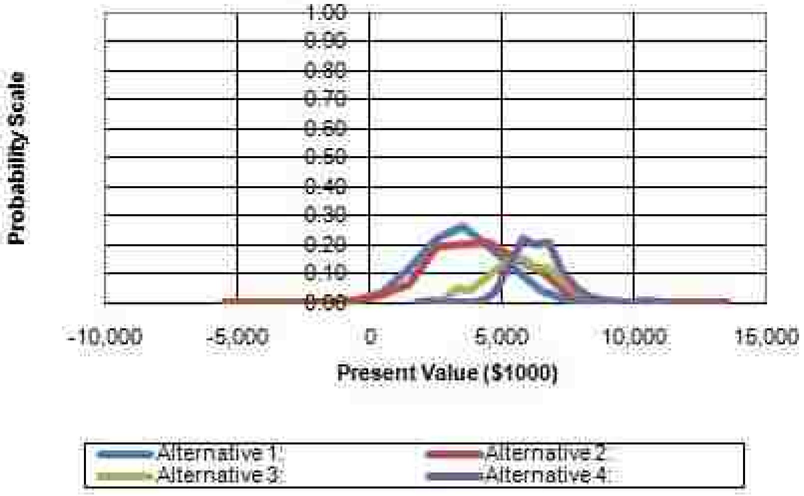
Figure 6.4: NPV Histogram and Cumulative Risk Profile of Artesia



(a) Belen

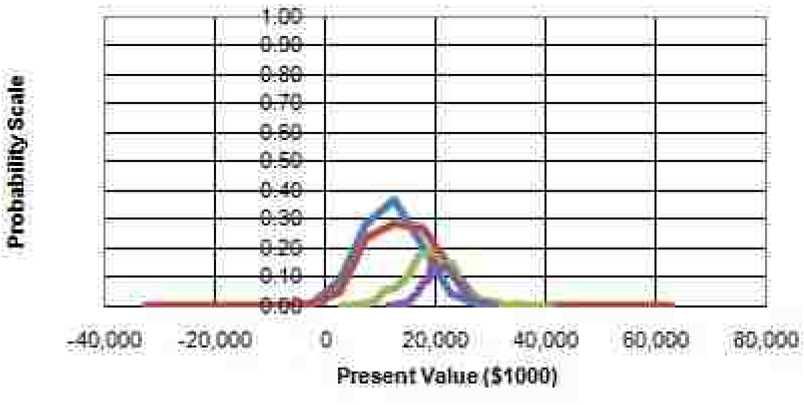


(b) Carlsbad

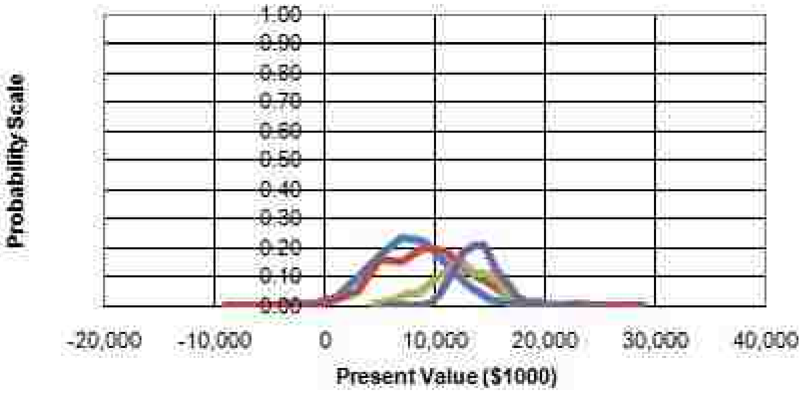


(c) Clayton

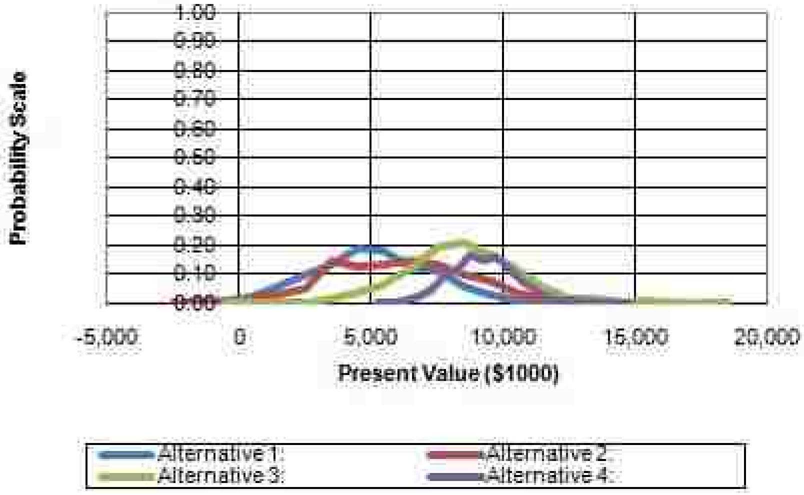
Figure 6.5: NPV Histogram for different Airports



(d) DE II

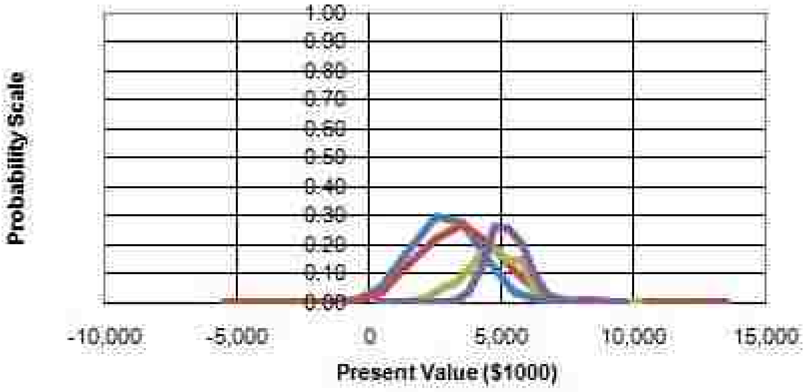


(e) Deming

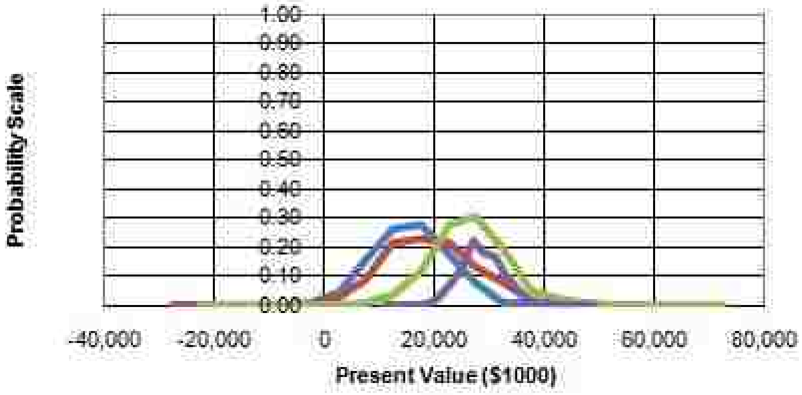


(f) Fort Sumner

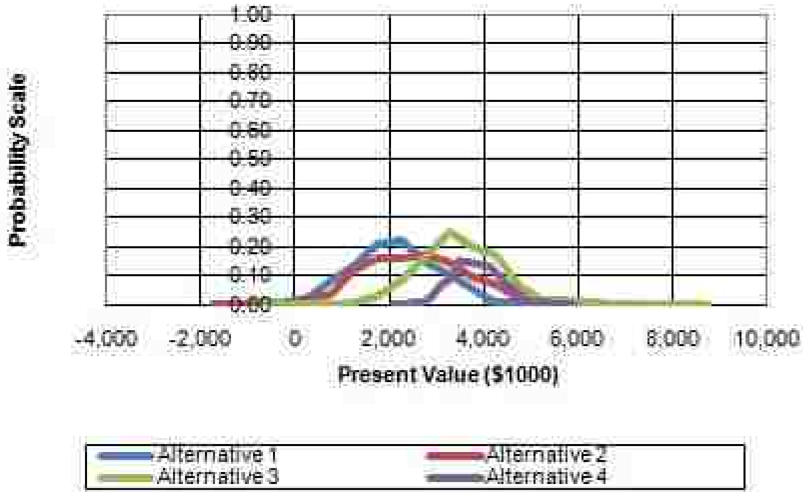
Figure 6.5: NPV Histogram for different Airports



(g) Grants

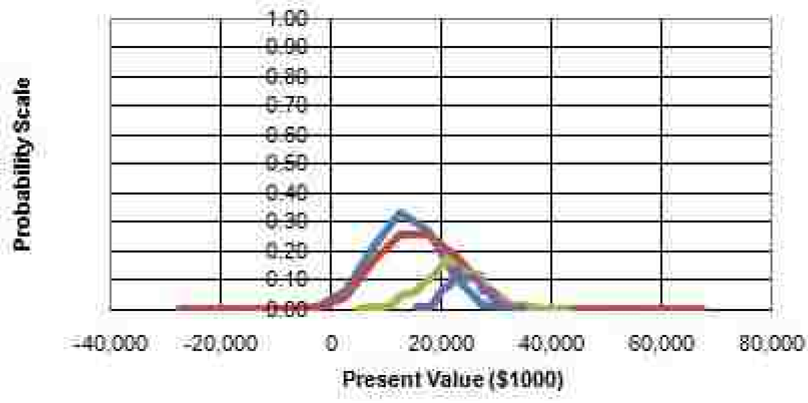


(h) Hobbs

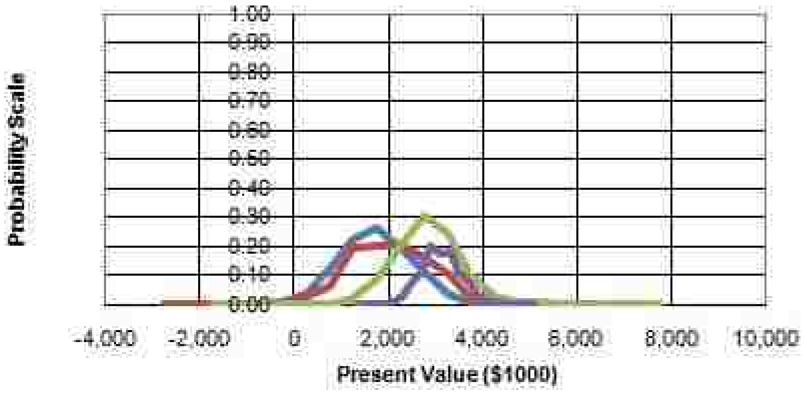


(i) Jal

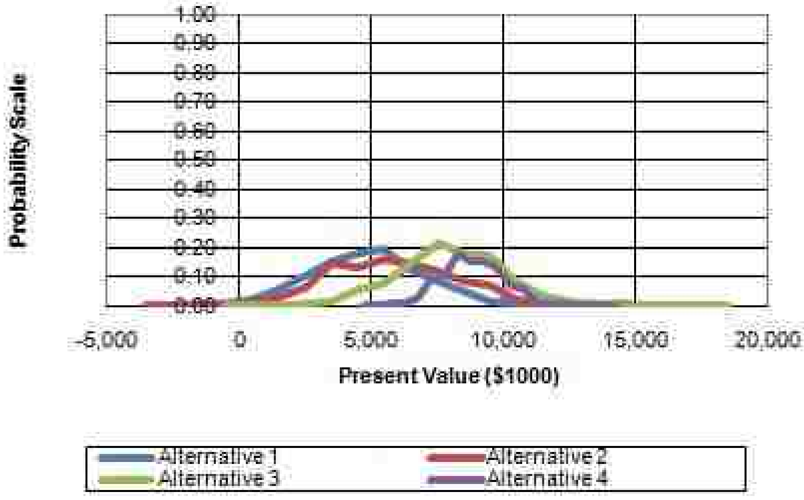
Figure 6.5: NPV Histogram for different Airports



(j) Las Cruces

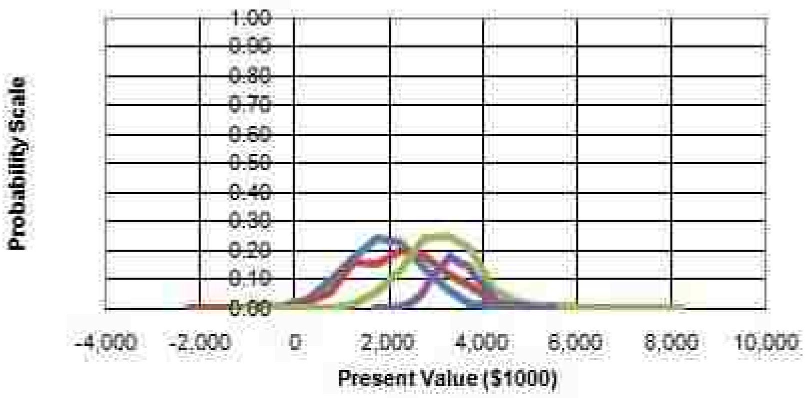


(k) Lordsburg

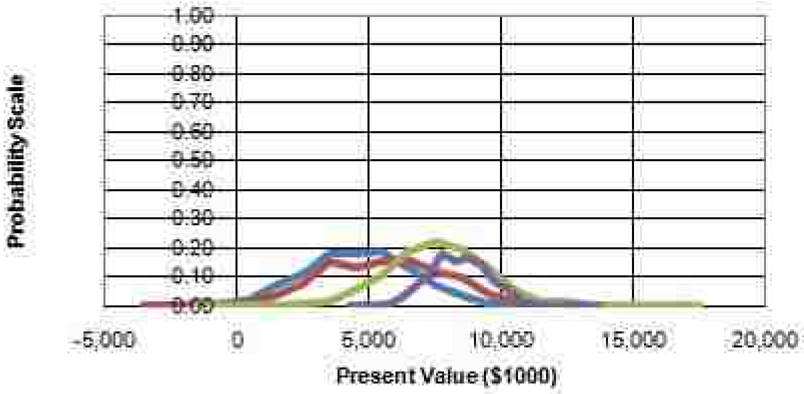


(l) Moriarty

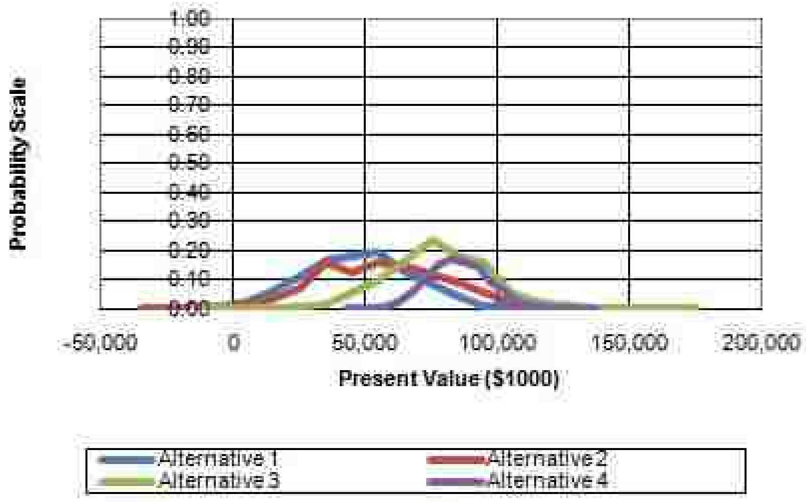
Figure 6.5: NPV Histogram for different Airports



(m) Questa

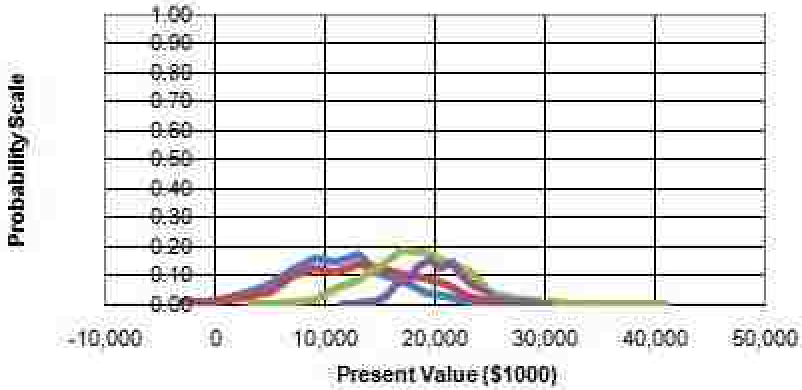


(n)Raton



(o) Roswell

Figure 6.5: NPV Histogram for different Airports



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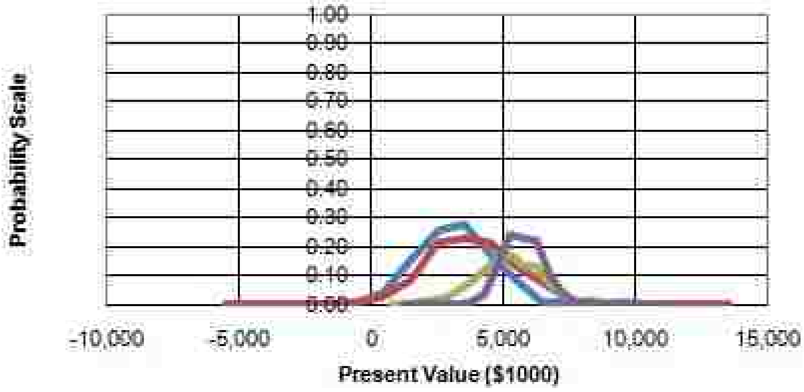
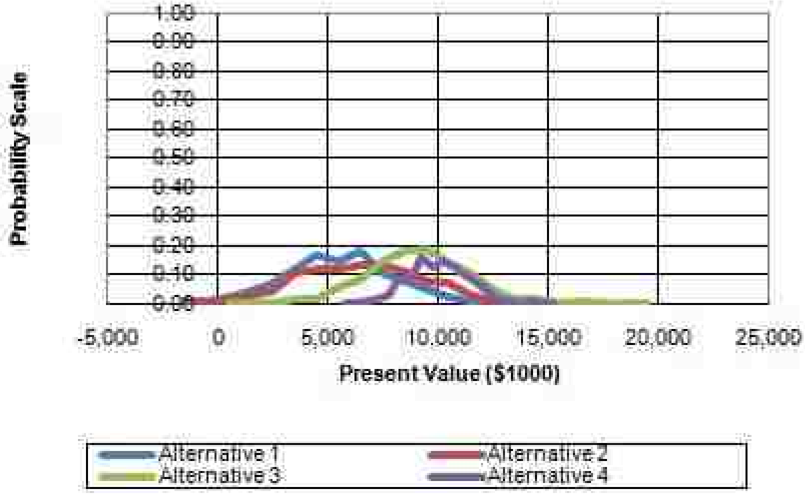
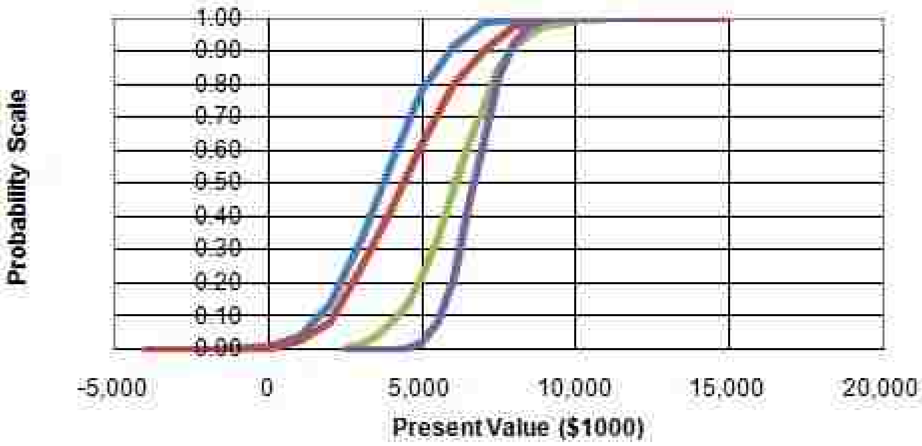


(q) Santa Rosa



(r) Silver City

Figure 6.5: NPV Histogram for different Airports



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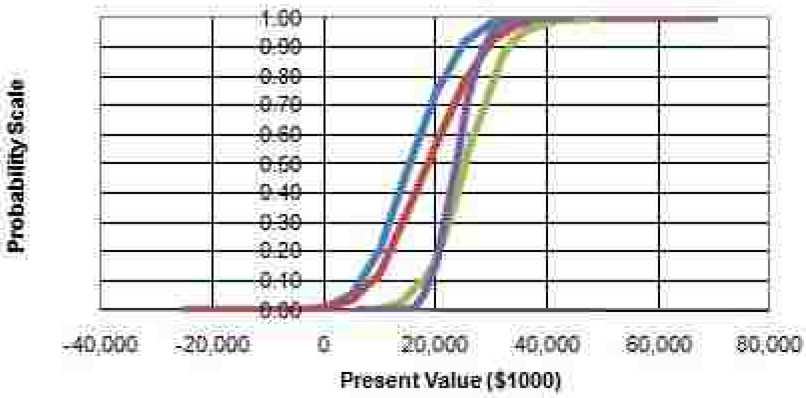
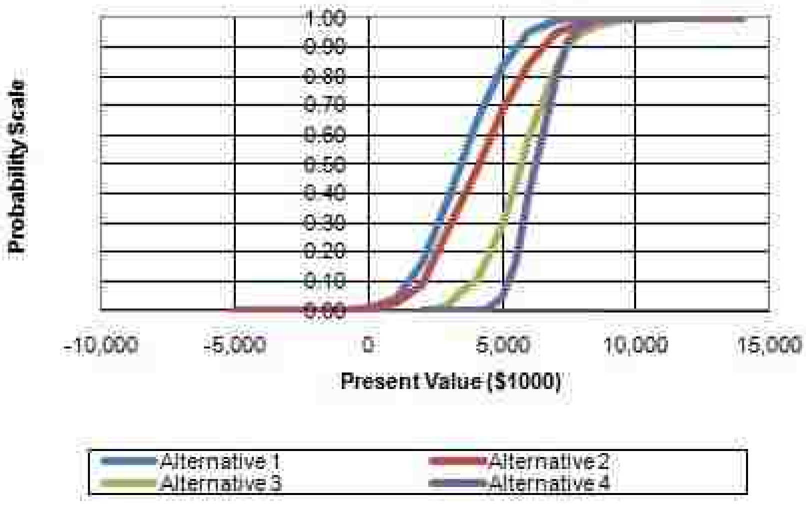
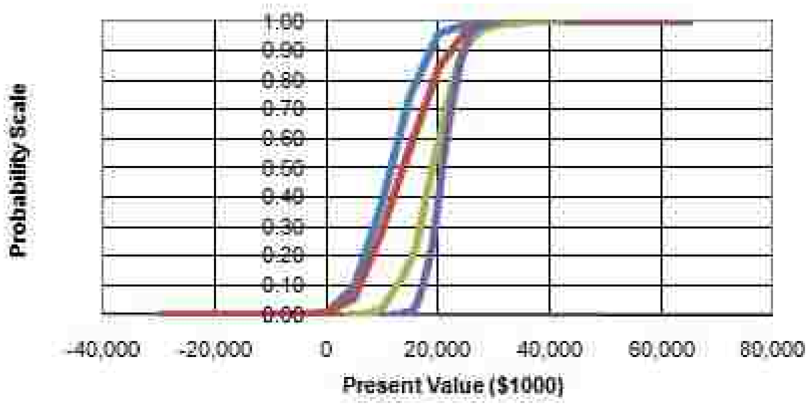


(b) Carlsbad



(c) Clayton

Figure 6.6: Cumulative Risk Profile for different Airports



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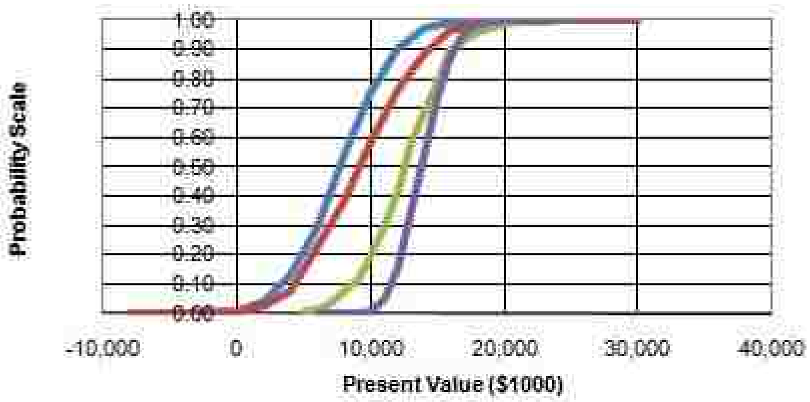
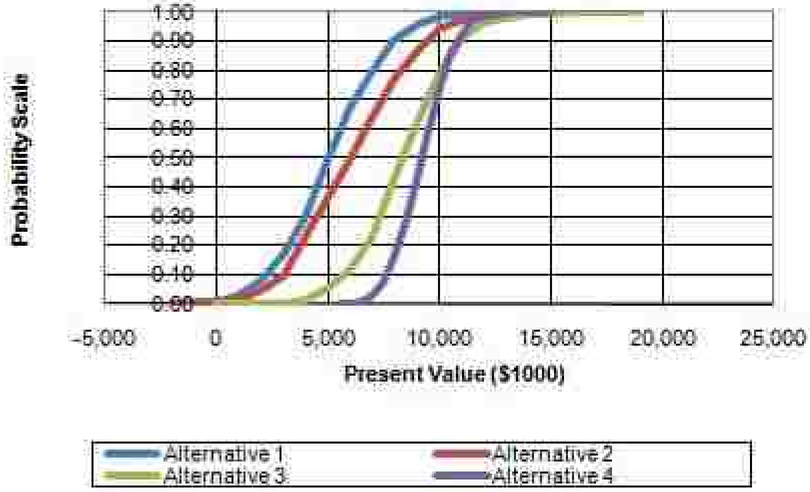
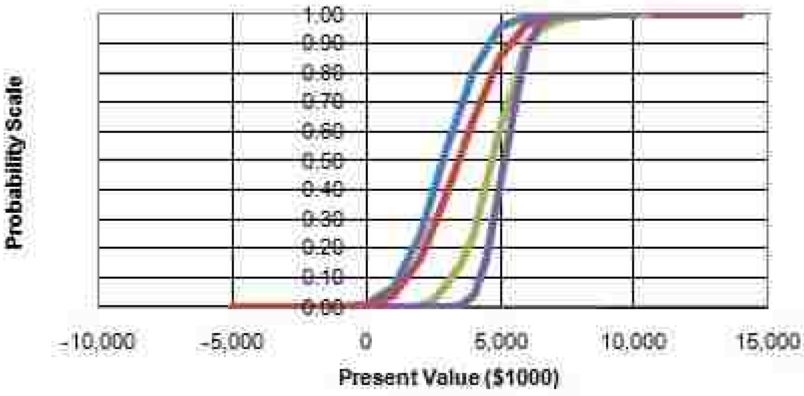


(e) Deming

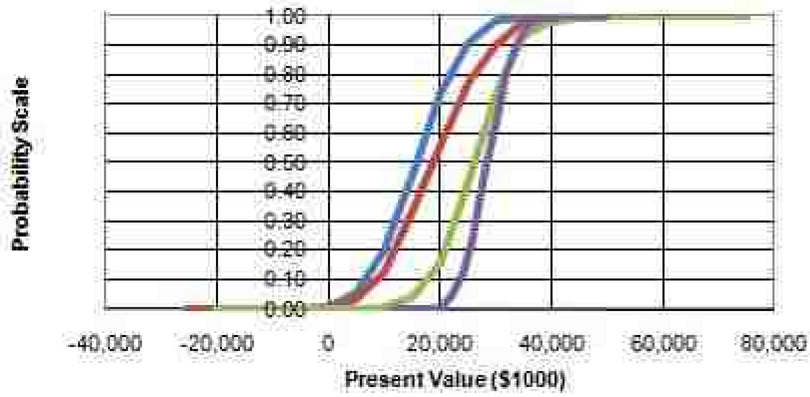


(f) Fort Sumner

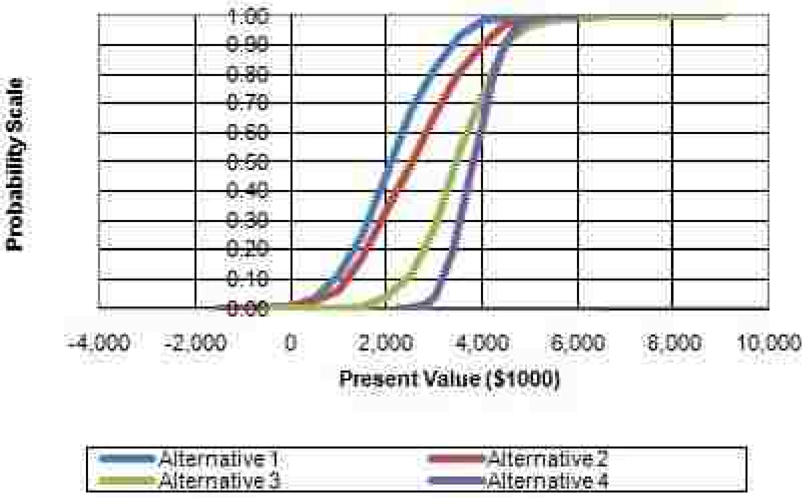
Figure 6.6: Cumulative Risk Profile for different Airports



(g) Grants

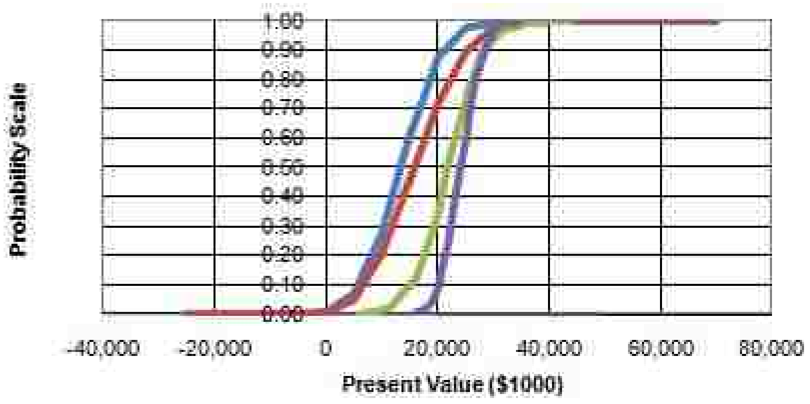


(h) Hobbs

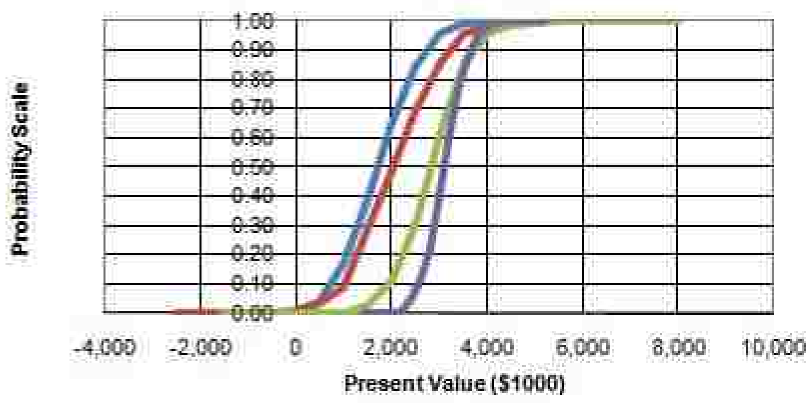


(i) Jal

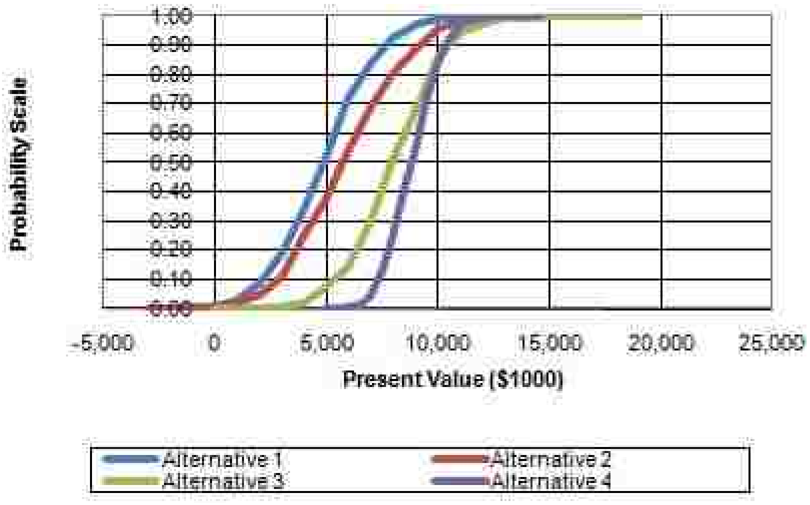
Figure 6.6: Cumulative Risk Profile for different Airports



(j) Las Cruces

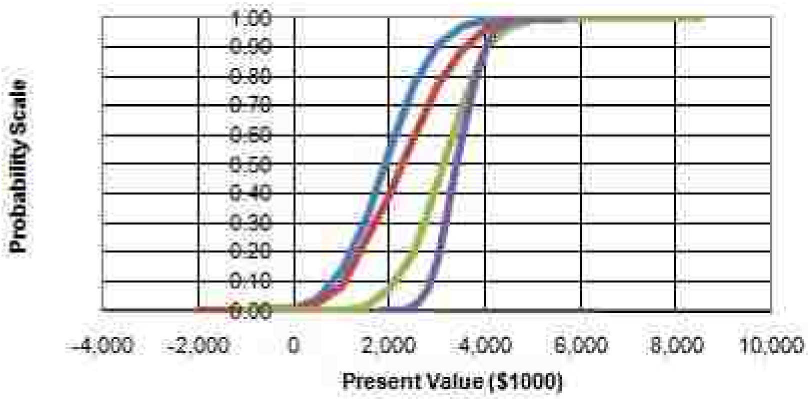


(k) Lordsburg



(l) Moriarty

Figure 6.6: Cumulative Risk Profile for different Airports



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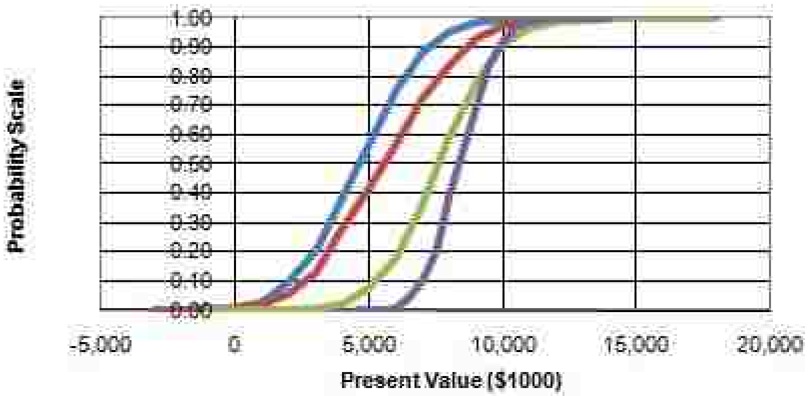
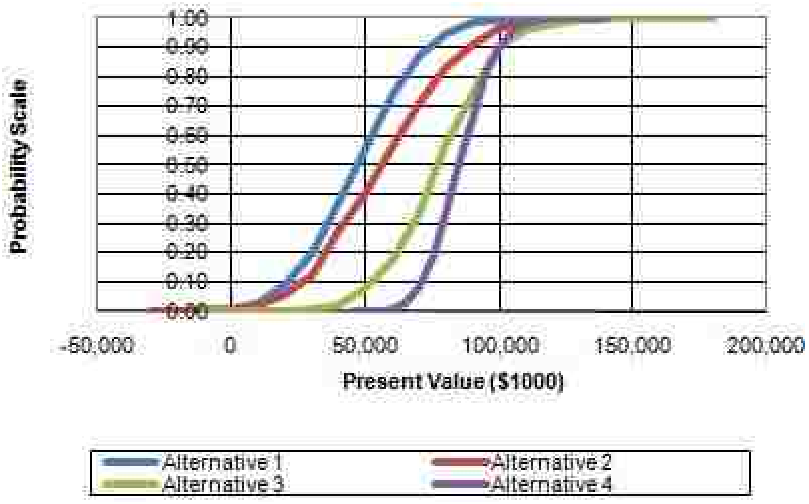
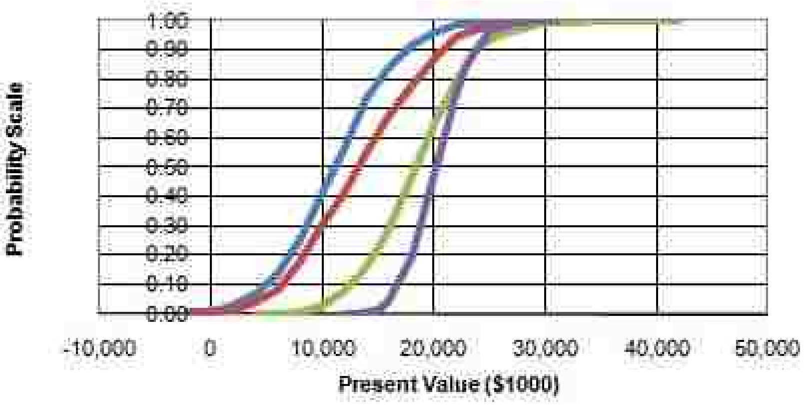


(n) Raton



(o) Roswell

Figure 6.6: Cumulative Risk Profile for different Airports



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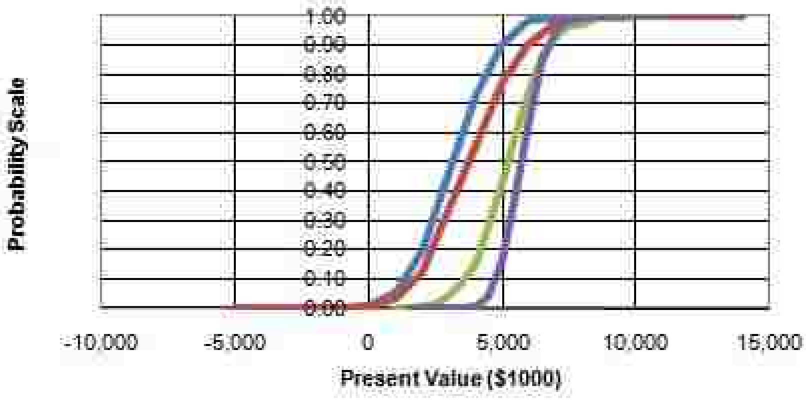
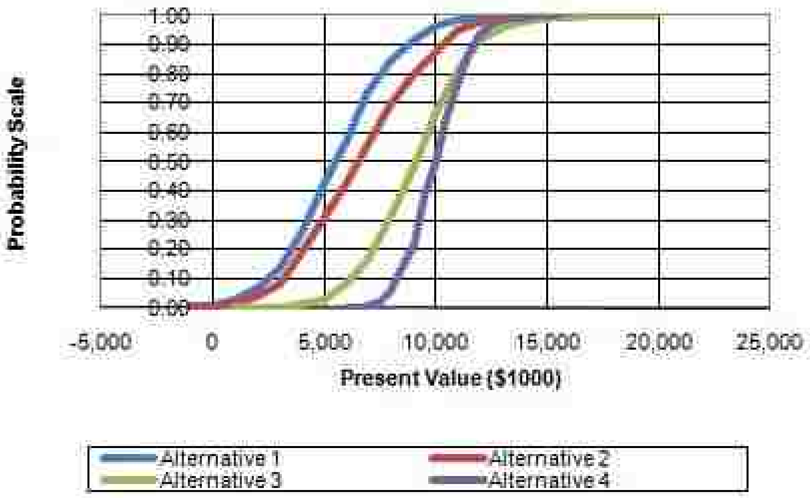


(q) Santa Rosa



(r) Silver City

Figure 6.6: Cumulative Risk Profile for different Airports

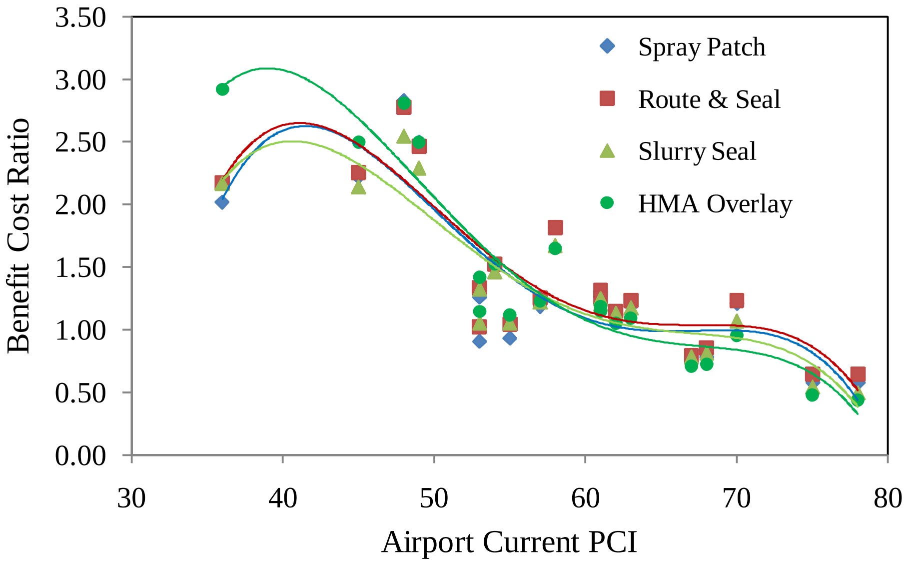


Figure 6.7: Benefit Cost Ratio of Different Alternatives

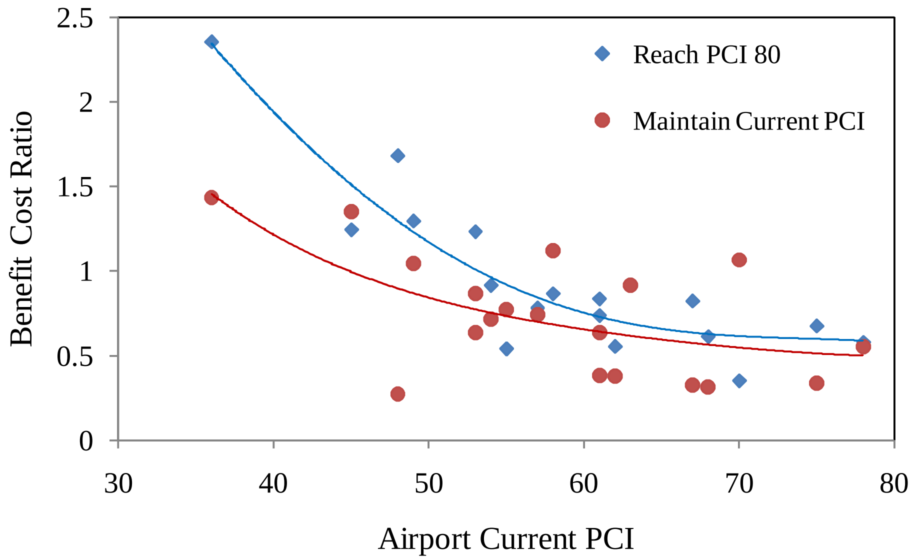


Figure 6.8: Benefit Cost Ratio of Different MicroPAVER Approach

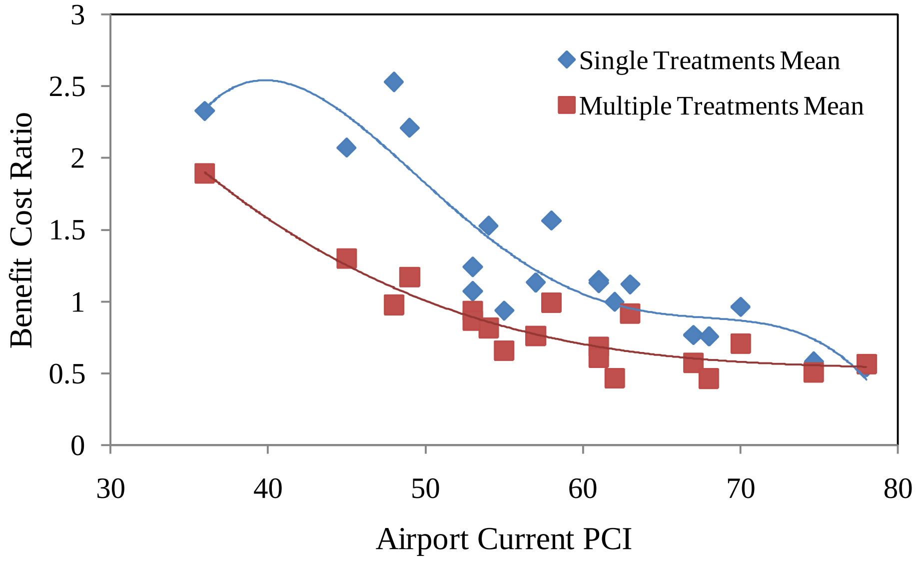


Figure 6.9: Benefit Cost Ratio of System Dynamic Model and MicroPAVER

CHAPTER 7

CONCLUSIONS

7.1 Summary

The first part of this study focuses on the Pavement Condition Index (PCI) and the Structural Condition Index (SCI) based pavement evaluations of the selected 19 general aviation airports of New Mexico. Deterministic and probabilistic Life Cycle Cost Analysis (LCCA) of various maintenance alternatives based on PCI with or without considering SCI has been performed and hence significance of SCI in LCCA of airport pavements has been studied. The second part of this study focuses on developing a new System Dynamic Model (SDM) which predicts PCI as a function of time after various maintenance treatment applications and to compare life cycle cost of different maintenance techniques developed in system dynamic modules. These alternatives are also compared with two different management goals of critical PCI methods developed in a pavement management tool named MicroPAVER.

7.2 Conclusions

PCI and PCI-SCI based pavement evaluation has given the following conclusions:

- Among 19 airports, Artesia has the lowest value of weighted average PCI and Carlsbad has the lowest value of weighted average SCI.
- Belen, Grants, Lordsburg and Moriarty have shown very bad runway skid resistance; hence special measure may be required in these runways.

- Roswell has the maximum percentage of load related distresses; hence structural measure may be needed.
- Among 413 sections, there were 15 failed sections in the inspection year (2006-07) and it has increased to 46 in 2012. If no maintenance were to take place during the next 20 years, almost half of the sections will be in failed condition.
- In the inspection year, more than half of the total pavement areas were of satisfactory and good condition considering all 19 networks.
- A good correlation can be drawn between SCI and PCI, but Skid Number (SN) does not show any correlation with any of the other indices.
- Carlsbad has two runways in the forth coordinate or in the coordinate of the shadow of ignorance. The other 13 runways show PCI-SN such that PCI is satisfactory but SN is below critical value, hence special attention is needed.

The study on alternative treatments to the PCI based maintenance solution has given the following results:

- PCI-SCI based maintenance treatment has shown a significant difference in benefit value comparing PCI based maintenance for airports having SCI close to PCI.
- As investing the same money in the 20 years analysis period for Carlsbad Airport, we can achieve higher functional benefit from the PCI–SCI approach, recommending use of the approach for that airport.
- System dynamic modules give the flexibility to apply maintenance treatment to the pavement at any minimum acceptable condition level.

- In the PCI based approach, benefit has been plotted against current PCI which shows an optimum PCI point where maintenance application can give the maximum Benefit to Cost Ration (BCR).
- BCR has been studied for both approaches and the effect of cutoff PCI, PCI rise and initial PCI on BCR has been plotted to develop various design charts.
- Benefit Cost Analysis has been performed for both linear ad non-linear deterioration rates and design charts are developed of BCR versus cutoff PCI for different initial PCI and PCI rise.

The following conclusions can be made based on the study on alternatives to the MicroPAVER critical PCI based maintenance solution:

- For different maintenance alternatives in the system dynamic module, Spray Patching is the most cost effective and Hot Mix Asphalt (HMA) Overlay has shown highest functional benefit.
- For the different MicroPAVER critical PCI methods, ‘reach PCI 80’ has shown the highest benefit and highest life cycle cost. If we want to maintain the current PCI, MicroPAVER gives the lowest benefit and lowest life cycle cost.
- If we apply a single treatment in different intervals not maintaining the pavements each year of the analysis period, it will give a higher BCR.

7.3 Future Recommendation

- Different non-linear equations should be studied and analyzed for this study.
- Statistical significance test should be performed for different maintenance alternatives.

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