Development and Implementation of an Airfield Pavement Management System for the Winnipeg International Airport

by

Jared Mitchell, B.Sc., EIT

A Thesis

Submitted to the Faculty of Graduate Studies in Partial Fulfillment of the Requirements for the Degree of

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Department of Civil Engineering
University of Manitoba
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THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES

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ABSTRACT

A Pavement Management System (PMS) is a tool that aids in determining the most effective application of maintenance and reconstruction (M&R) work for a given pavement network. The purpose of this research is the development and implementation of an Airfield Pavement Management System for the Winnipeg International Airport (WIA) that expands on the capabilities and usefulness of conventional systems.

The system developed in this research utilizes geo-referenced pavement distress data collected using a GPS receiver. Time required to complete Pavement Condition Index surveys has been reduced, minimizing the impact on airport operations of conducting an airfield inspection. Using geo-referenced distress data leads to a multitude of new analysis techniques that allow for optimum management of the pavement network.

Several pavement deterioration models have been created using the collected pavement condition data. These models aim to predict pavement condition at points in the future to aid in M&R planning. Models were created using the least-squares regression technique as well as neural network modelling. The use of neural networks appears promising as they are not constrained to a single regression parameter and can account for the interaction between parameters and nonlinear relationships.

The WIA PMS represents a significant improvement to the functionality of current PMSs by expanding the analysis and modelling capabilities while reducing the effort associated with data collection.

ACKNOWLEDGEMENTS

I would like to take this opportunity to acknowledge the support of the people who made this research possible. First of all, my advisors, Dr. Ahmed Shalaby of the University of Manitoba and Mr. Bill Tipper of the Winnipeg Airports Authority, your guidance and assistance on this project was invaluable. Also this research would not have been possible without the generous financial assistance of NSERC, The Transportation Association of Canada, and the Winnipeg Airports Authority. Finally I would like to thank my family and friends for their continued support and encouragement.

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LIST OF ACRONYMS

AASHO	American Association of State Highway Officials
AC	Asphalt Concrete
ACN	Aircraft Classification Number
AMS	Asset Management System
ANN	Artificial Neural Network
APMS	Airfield Pavement Management System
ASTM	American Society for Testing of Materials
CAPTG	Canadian Airfield Pavement Technical Group
FAA	Federal Aviation Administration
FOD	Foreign Object Damage
GIS	Geographic Information System
GPS	Global Positioning System
HWD	Heavy Weight Deflectometer
IRI	International Roughness Index
M&R	Maintenance and Rehabilitation
MSE	Mean Squared Error
NCHRP	National Co-operative Highway Research Program
NN	Neural Network
PCC	Portland Cement Concrete
PCI	Pavement Condition Index
PCN	Pavement Classification Number
PMS	Pavement Management System
UTM	Universal Transverse Mercator Grid
WAA	Winnipeg Airports Authority
WIA	Winnipeg International Airport

Chapter 1

INTRODUCTION

A Pavement Management System (PMS) is a tool that can aid in determining the most effective application of maintenance and reconstruction (M&R) work for a given network. Airfield Pavement Systems (APMS), which deal specifically with airfield pavements are the focus of this research. Airport authorities, like highway agencies are tasked with the job of managing infrastructure networks worth millions of dollars. Budget cutbacks, shortfalls and changing priorities over several decades have led to rapidly increasing infrastructure deficits, driving agencies to find better approaches to infrastructure management. A properly designed and implemented PMS will assist an agency in making the best use of the money available for maintenance and rehabilitation by providing the ability to monitor existing performance and predict the condition of the network at points in the future.

A major driving factor behind widespread PMS implementation in the United States was legislation. Public Law 103-305, which was passed in 1994, requires state aviation agencies to have a PMS in place as a condition for receiving public funding. In Canada, airport authorities that operate the larger commercial facilities receive no ongoing federal funding for infrastructure maintenance and rehabilitation, and as such the implementation of PMSs has not proceeded as rapidly. Another factor affecting not only the implementation, but also the updating of a PMS is the time consuming nature of pavement condition inspections. Although airfields are small in comparison to provincial highway networks, gaining access to critical areas such as busy runways or taxiways at an airfield with 24-hour operations is a major issue.

1.1 Research Objectives

The focus of this research is the development and implementation of a network level Airfield Pavement Management System (APMS) for the WIA with the following objectives:

- Minimize impact of PMS implementation on airport operations
- Integrate construction history and pavement cross-section data collected by WAA and Transport Canada
- Optimize collection of pavement distress information
- Utilize GIS and GPS technologies during data collection and analysis stages
- Address problems and concerns raised regarding industry standard Pavement Condition Index inspection
- Develop deterioration models for the WIA pavement

To accomplish these objectives a partnership was formed with the Winnipeg Airports Authority (WAA) that allowed access to the WIA's facilities and resources.

1.2 Background

The Winnipeg International Airport dates back to the Stevenson Aerodrome, which was opened in May 1928. By 1938, there were 3 hard surfaced runways each measuring 960m in length. Continuing to grow and expand, the facility was officially named the Winnipeg International Airport in 1958 at the request of the Department of Transport (www.waa.ca). To this day, infrastructure created in the 1940s, 50s and 60s provides the base for a great deal of the airfield. After decommissioning a small portion of the airfield in 2005 to make way for the new terminal building, today's WIA is comprised of 2 runways, 12 taxiways and 7 aprons with a total area approaching 1 million square metres and it serves over 3 million passengers and over 149000 tonnes of cargo per year (www.waa.ca). The Canadian Air Force also routinely uses the facilities of the WIA as 17 Wing Winnipeg is located adjacent to the airport property. 17 Wing operates their own apron and two taxiways, but uses the runways and taxiways of the WIA to conduct their operations.

A facility the size of the WIA needs to track the performance of its airfield in such a manner that will allow it to optimize, in terms of both cost and condition improvement, the timing of maintenance and rehabilitation (M&R) work. A PMS provides a tool for this purpose and through its implementation and continual updating can be used to build a knowledgebase of effective treatments and triggers for M&R work.

1.3 Organization of Thesis

The thesis has been organized as follows:

Chapter 2: Literature Review

A review of current and past work on pavement management systems with particular attention paid to airfields. A definition of a PMS is provided along with descriptions of the basic components common to all systems. Pavement condition assessment and deterioration models, two critical components are investigated thoroughly. Experiences with different types of automated collection techniques, the integration of GIS and GPS into pavement management and other advances to the state-of-the-art are also presented.

Chapter 3: WIA Pavement Management System Development and Implementation

This chapter details the components of the WIA system. A description of the work involved with developing and implementing the new system is presented. The software and equipment that were used are described as well as the pavement inspection procedures that were followed. This chapter also includes the results of an environmental scan that was conducted to assess the extent of PMS implementation at Canadian airfields.

Chapter 4: Results of 2005 Pavement Condition Survey

Chapter 4 presents the results of the initial Pavement Condition Index (PCI) inspections completed during 2005. These inspections were completed using a new method for locating, collecting and storing pavement distress information developed as part of this research. Several Condition maps, as well as the experiences encountered using the new procedures included are included. Pavement distress information is also analyzed to assess the foreign object damage (FOD) potential of each pavement section.

Chapter 5: Pavement Deterioration Modelling

Data obtained during the 2005 condition surveys forms the baseline conditions for deterioration models used to predict future pavement performance. Several pavement deterioration models were created using the constrained least squares regression modelling technique. Alternative modelling techniques were explored leading to the creation of Advanced Neural Network (ANN) models based on the 2005 PCI data. A comparison of the two modelling techniques is included. Finally, an investigation into the applicability of using deterioration models created for other airfields to model the condition of the Winnipeg airfield pavement was conducted.

Chapter 6: Results and Discussions

A discussion of the major findings and results of this research are presented in Chapter 6. The unique aspects of airfield pavement management systems in general, as well as the system that was developed for the Winnipeg International Airport are presented. Experiences gained during the development and implementation of the WIA system are presented followed by a summary of the results of the analysis and modelling stages. Finally recommendations and guidance for further implementation and expansion of the WIA system are discussed.

Chapter 7: Conclusions and Recommendations

Chapter 7 contains a summary of the project and the conclusions of this thesis as they relate to the original objectives. Also included are recommendations for future research on development and implementation of pavement management systems at Canadian airports.

Chapter 2

LITURATURE REVIEW

2.1 Background

The field of pavement management evolved as highway agencies emerged from the road building boom of the 1950s and 60s that saw the creation of the interstate system in the United States. As budgets became tighter, and the network was not expanding at the same rate, the focus shifted to preserving the existing network. Systems theory was first introduced into pavement engineering in the 1970s (Haas 94) and the term pavement management system (PMS) first started to appear in the late 1960s and early 70s and encompassed all the activities involved in "providing pavements" (Haas 78).

Early pavement management systems consisted of little more than a database of inventory and condition data. Condition data usually was based on subjective ratings such as the present serviceability index (PSI) developed at the AASHO Road Test (HRB 62). The systems employed simple data processing techniques to evaluate and rank rehabilitation projects on present condition (Kuklarni 03). This usually led to the 'worst first' approach, since future pavement condition or the application of maintenance at differing times in the life cycle was not considered. Today's systems on the other hand, are used to predict future pavement condition and determine optimum allocation of limited financial resources. They employ objective condition indices that reduce or eliminate the subjective nature of past systems.

2.2 Components of a Pavement Management System

There are many possible definitions of a pavement management system, and nearly as many miss-conceptions about the potential uses for such a system. Some people feel that PMS is simply a collection of 'buzz words' strung together to garner attention, while others feel a PMS is the "panacea for all pavement problems" (Haas 94). Of course, both of these opinions are false. A PMS can be defined as follows:

> "A pavement management system provides a consistent objective and systematic procedure for setting priorities and schedules, allocating resources, and budgeting for pavement maintenance and rehabilitation. It can also quantify information and provide specific recommendations for actions required to maintain a pavement network at an acceptable level of service while minimizing the cost of maintenance and rehabilitation." (FAA 88)

The definition of a PMS can be further supplemented depending on its intended use as both network and project level systems exist. Network level pavement management is broad in nature, and focuses on creating the most effective use of budgetary resources for an entire network. Whereas project level management is concerned with evaluating several alternatives for specific projects identified as priorities by the network level system. The main difference between the two levels is their size and detail of information. Project level systems provide detailed information (often providing a 100% pavement inspection rate) about a single project, and network level systems provide a general condition report for the entire pavement network by sampling only a small portion of each section. Some PMSs employ a third level in the hierarchy referred to as the "Project Selection" level (Haas 94). Most of the time however, the project selection is completed as part of a network level analysis.

To achieve the functions described in the definition above, every PMS utilizes the same basic components. Figure 2.1 shows these basic components and how they relate to each other.

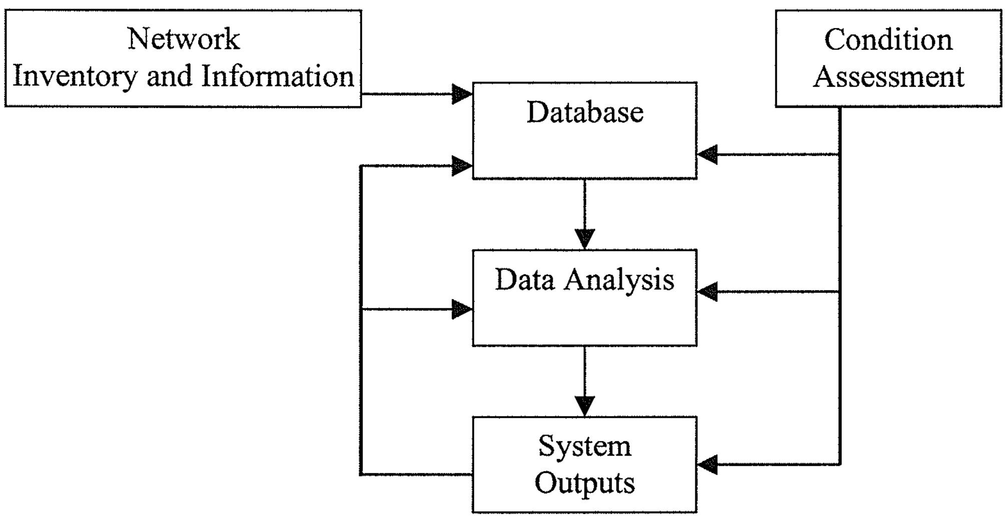


Figure 2.1: Components of a Pavement Management System

The first component necessary for a PMS is the network inventory. All information regarding the pavement construction history, traffic, environment, maintenance, and past condition data is collected, compiled and stored in the database. This work, while very time consuming, is crucial as it forms the foundation of the PMS (Broten 98). For example, incorrect or unreliable information regarding pavement age, leads to erroneous outputs from pavement condition prediction models that are created using this data.

Another important element of a PMS is the pavement condition assessment. This information is used to create deterioration models for predicting future pavement condition and also provides useful data on current pavement needs. The different options available for pavement condition assessment are discussed latter in this chapter.

A database is used to house the volumes of information that are a part of a modern PMS. Historically this information might have been stored on paper-forms or keyed manually on an electronic form. This is no longer possible or practical with the volume of data present in today's systems. The database must be flexible enough to accommodate varying user queries and present the data in a format that is easy to understand. The ability to add new variables of interest, or easily change the network inventory information is also important.

The data analysis and system output stages will vary depending on if a project level or a network level analysis is desired. Data analysis at the network level produces such deliverables as the network condition at the time of last inspection, condition forecasting, and budget forecasting for the network needs (Shahin 94). At the project level, the analysis generally focuses on the evaluation of several alternatives for a project that has been identified through a network level assessment.

The final component of a PMS is the system outputs, which deliver the desired information about the pavement network to the user. Numerous outputs from a PMS are possible. Traditionally graphs, charts, and tables were produced, but modern PMSs are utilizing geographical information systems (GIS) to add a geo-referenced graphical component to the output. A further description of the uses for GIS in a PMS will follow later in this chapter. The data generated during the system output stage is inputted back into the system as historical information completing the cycle illustrated in Figure 2.1.

2.3 Pavement Condition Assessment

Information regarding the present condition of the network pavement is critical to the functioning of a PMS. Without condition data, a PMS would be little more than an electronic version of a pavement inventory binder. Pavement condition assessments vary from a simple drive by of a pavement section to detailed measurement of every distress observed. The most widely implemented type of assessment involves the quantification (extent and severity) of surface distresses. This section will summarize the benefits and disadvantages of different condition assessment methods, both past and present.

In the past, agencies used a panel of experts to rate the condition of their pavements. One example of this type of system was the Pavement Quality Index (PQI), developed in Alberta in the early 1980s (Karan 83). In this system, two vehicles containing 4 raters each would travel the sections being studied, while recording values (scale of 0 to 10) for the Riding Comfort Index (RCI), Structural Adequacy Index (SAI), and Surface Distress

Index (SDI). These values were then combined together to create the PQI value (Haas 94). Analysis of variance techniques have been used to show that the only significant source of variation was due to the sections (which was to be expected) and not due to factors related to the raters (Haas 94). However, using expert opinion is still very subjective since it is not based on any measured quantities of distress. These tests also require the time of 8 experienced pavement engineers to act as the raters.

The advantages of this system are the speed at which it allows the surveys to be completed, and it is safer for the raters as they do not exit the vehicle. Both of these advantages are of great importance to highway agencies that have vast networks to inspect, usually while the roads are open to traffic.

Expert opinion can also vary depending on the qualifications of the expert. In an airport setting, the primary users of the facility are pilots, who are experts in the safe operation of their planes. One study of particular interest found that a group of pavement engineers ranked the importance of certain distresses differently than a group of pilots (Gadallah 00). This finding is important because it shows that where pavement engineers are focused more on the structural integrity (how long will the pavement last) of a pavement, the pilots (primary users) are focused more on the functional integrity (how safe is this pavement). An important distinction exists between highway pavements and airfield pavements in this regard. Airfield users expect a much higher degree of attention be paid to distresses that pose a Foreign Object Damage (FOD) potential than do highway users. FOD is defined as "a substance, debris, or article alien to a vehicle or system which would potentially cause damage," according to the National Aerospace FOD Prevention Inc. (NAFPI) a group of aerospace professionals dedicated to the elimination of FOD. It is estimated that FOD costs about $4 billion annually in aircraft repairs. Distresses that pose a FOD potential are easier to detect during surveys that require evaluators to walk the pavement. Engineers must take this into account when deciding which pavement condition assessment method to implement in an airport setting.

To eliminate the subjective nature of the expert opinion inspections, it is desirable to use a condition assessment that is based on measured distress quantities. The most common distress survey used by airport agencies in North America is the Pavement Condition Index (PCI). Developed by the US Army Corps of Engineers, PCI has gained widespread acceptance and is recommended by Federal Aviation Administration and the American Public Works Association (Shahin 94). Detailed procedures for completing a PCI test on both Concrete and Asphalt surfaced pavements will be contained in Chapter 3.

There are several advantages of using the PCI, the primary of which is the repeatability and non-subjective nature of the inspection. ASTM D5340 details how each distress is to be measured and recorded, leaving little room for subjective opinion. This allows agencies to compare PCI values from different facilities even if collected by different inspection crews and in different years. Another advantage is that a PCI inspection does not require the mobilization of large teams of experienced pavement engineers as with the previously described panel tests.

There are some disadvantages associated with the PCI test that have been identified over the years. A thorough description of the limitations and potential misapplications of the PCI test was completed by Broten and De Sombre in 2001 (Broten 01). A summary of some findings from that paper are presented here:

- The way longitudinal and transverse cracks are evaluated in AC pavements allows for cracks greater in 3" in width to be classified as low severity if these cracks are sealed and the sealant is in good condition. FAA regulations on the other hand require such cracks be repaired immediately.
- Difficult to prepare maintenance programs using PCI data due to the manner in which PCI is calculated and reported for both PCC and AC sections. For PCC pavements, results are reported on a section-by-section basis, where repairs are usually done on a slab-by-slab basis. For AC pavements, no distinction is made between narrow unsealed cracks and sealed cracks in good condition, which does not allow for easy computation of quantity required for joint sealing program.
- The method of computing PCI values for a pavement section can produce misleading results unless sample unit values are consistently sized. Meaning the average section PCI is calculated from the average of the sample unit PCI values (not weighted).

Similar to the previously mentioned findings (Broten 01) a study by McNerney and Harrison (McNerney 98) identified some potential areas of improvement for the PCI inspection procedure. One main drawback they identified was lack of distress location information. Since the PCI tests only reports results at the section level (Chapter 3 contains a description of the classification levels in a PCI based PMS), information regarding the exact location of individual distresses is not collected. The focus of this research will be the implementation of a PMS that utilizes the PCI while addressing the limitations and concerns identified regarding this procedure.

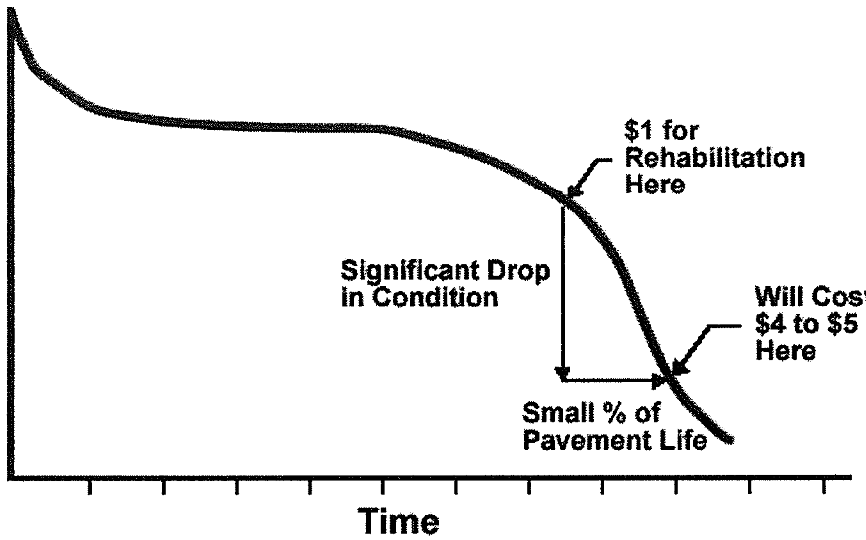
Other indices can also be compiled from the distress data collected during pavement inspections. As mentioned earlier, FOD is of great concern in the airport environment, giving rise to the creation of the FOD potential index. This index is a representation of the distresses most likely to cause FOD and is compiled using some of the distresses from the PCI survey (Shahin 04).

As the PCI deals only with visible surface distresses, many agencies collect additional information about their network as part of a PMS. Several non-destructive tests (NDT) are possible and can assist in giving a better picture of the overall condition of the airfield pavement. Deflection testing using machines like the Heavy Weight Deflectometer (HWD) can assess the structural condition of an in-service pavement (Shahin 94). The HWD data can also assist in determining the Pavement Classification Number (PCN) which is used by many airfields to represent the structural capacity of a given pavement (Shahin 04).

Runway friction is also a very important measure of safety that many airport agencies evaluate on a regular basis. Friction is measured using Continuous Friction Measurement (CFM) devices. Although many different types of CFM devices exist, the basic principle is the same. They work by having a wheel of some sort constantly in contact with the pavement providing a continual friction measurement. The use of friction index measurements is much more widespread amongst the airfield community than on streets and highways. On the other end of the spectrum, many more highway agencies collect roughness data (using the International Roughness Index) than do airport agencies. Do in part to a shift in the user's priorities, but also the lack of an appropriate method for reporting roughness. The IRI is based upon the Quarter-Car simulation (Shahin 94), which does not accurately model the range of stiffness, speeds, and axle spacing of aircrafts travelling the same section.

2.4 Pavement Deterioration Models

Several methods of collecting and presenting information regarding pavement condition have been presented. Regardless of what index or property is measured however, one thing stays certain, without intervention (maintenance/repair), the condition of a pavement will deteriorate with time. Variables such as age, along with traffic, weather, construction quality, and use affect the rate of deterioration and as such there is no simple relationship for forecasting a pavements life. At the heart of any pavement management system exists models used to predict the future deterioration of the pavement. Pavement deterioration models are what allow PMSs to function. Without information about future pavement condition it is not possible to know the optimal application time for M&R work. The concept of a pavement deterioration model is presented in Figure 2.2.



Source: http://www.cecer.army.mil/paver/

FIGURE 2.2: Sample Pavement Deterioration Model

An example of how pavement deterioration models are used is contained in Figure 2.2. In this case if the rehabilitation is undertaken while the pavement is still in the "Fair" condition state it will only cost $1, but if the pavement is allowed to deteriorate to the "Serious" condition state the cost of rehabilitation will now be 4 to 5 times as much. The determination of where the accelerated deterioration will begin is the main objective of pavement deterioration models.

There are numerous types of pavement condition models available. These include straight-line extrapolation, regression (empirical), mechanistic empirical, polynomial least square, probability distribution, Markovian, and neural network models. Obviously the most simplistic model would be straight-line extrapolation, used when only limited information regarding the rate of deterioration is available. This technique is not very accurate and should be used for predicting only short periods into the future (Shahin 94).

2.4.1 Regression Models

Regression models can be used to create empirical relationships between observed variables. The most basic model would be linear regression between two variables (Shahin 94). Purely mechanistic models are not used, as primary response variables (stress, strain) are not used as a measure of pavement condition (Haas 94). However, mechanistic variables such as strain can be used as input variables for regression models creating mechanistic-empirical models (Shahin 94).

A polynomial constrained least squares regression model is a very useful model for predicting pavement condition due to the effect of one variable (Shahin 94). These models fit polynomials to predict the values of Y (PCI or other condition assessment) as a function of x (age, traffic, etc) by using the least squares technique. To make the models more effective at modelling real world behaviour, constraints are often placed on them. For example, when using the PCI as the measure of distress, a value greater than 100 is not possible, yet an unconstrained model might very well predict a value greater than 100. In order minimize the least squares error; the model might also predict an increase in condition with age, something that will not typically be seen in the field (without maintenance work). Figure 2.3 shows the difference between constrained and unconstrained models created from the same data set.

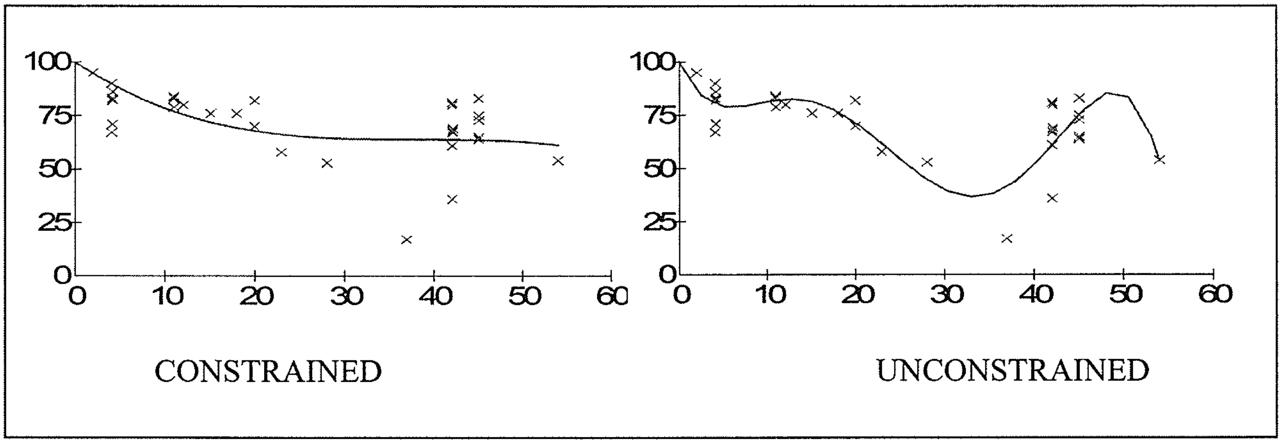


Figure 2.3: Constrained vs. Unconstrained Deterioration Models

Pavement performance is clearly affected by more than one variable, which might lead some to suggest the constrained polynomial method is therefore not practical for modelling pavement deterioration. To overcome this obstacle, the Family Method has been proposed (Shahin 94). This method works by clustering similar pavement sections together, eliminating the need to use their common variables in a prediction model. Families can be created for numerous variables including use, surface type, location, last construction date, rank and PCI (Shahin 94). This model allows for subsets of data for which condition vs. age models can be generated. Using the family technique, it is possible to create deterioration models with as little as one year of inspection data (at the network level). If all the sections grouped together to form a family are the same age (time since last construction date) this technique will not work. The reason for this is that all the points would be the same x value on a plot, not allowing a model to be calculated from the data.

2.4.2 Probability Distribution

Probability distribution can also be used to model a pavement condition measure such as PCI or IRI. The purpose of a probability distribution model is to find the probabilities associated with each of the values of a random variable. Since this technique requires knowledge of the statistical distribution for the variable or condition in question it is recommended that it only be used for individual distress prediction (i.e. Joint Spalling, not PCI) (Shahin 94).

2.4.3 Markovian Modelling

Markovian models divide a variable (PCI, IRI) into discreet condition states, and function by determining the probabilities that a pavement in a given condition state will move to another condition state (Shahin 94). One particular advantage of Markovian models is that an improvement in condition can be forecast (increase in PCI) thereby modelling the effect of maintenance works (Abaza 04). Using matrices of present condition states and probability matrices that predict the chances a pavement in each state will improve, decrease or remain in the same condition state, pavement performance can be quite accurately modelled. Obviously a great deal of work is involved with calculating the probability matrix, and large models with numerous condition states (especially ones that allow the possibility of increasing condition) can become quite complex (Abaza 04). An example of a Markovian model is presented in Figure 2.4. The example network contains only 3 condition states (Good, Fair, Poor) but does contain probabilities of pavement sections improving in condition.

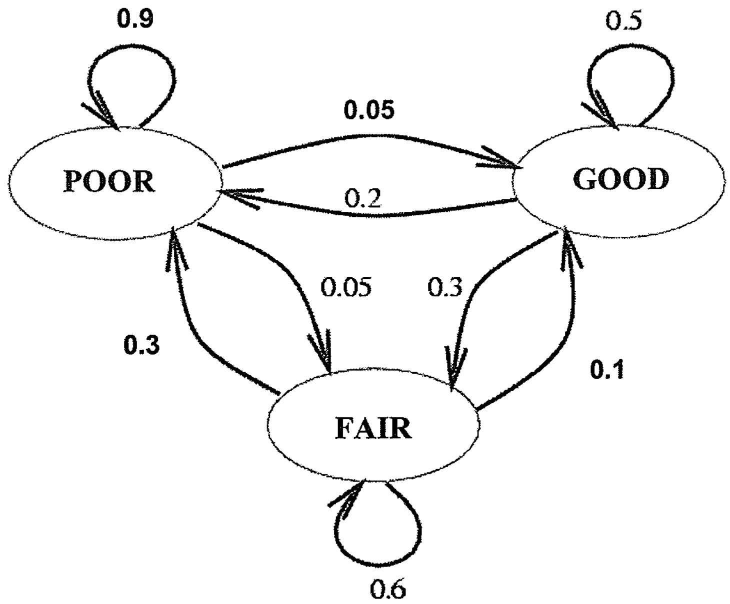


Figure 2.4: Example Markovian Model

2.4.4 Neural Networks

Modelling pavement deterioration is not a simple task, as no straight forward relationship exists between inputs (age, traffic, and environment) and pavement performance. This has led to the study of Artificial Neural Networks (ANNs) as a tool for modelling pavement performance. Neural networks are modelled on the current understanding of the brain, although on a much lesser complexity (Shekharan 00). An ANN is 'trained' to 'learn' the relationship between a set of given inputs and outputs. The benefit of ANNs is that the relationship between the inputs and outputs, which is often complex, does not have to be known before the modelling stage is begun (Shekharan 00). The typical structure of an ANN contains input, hidden and output layers, and is presented in Figure 2.5.

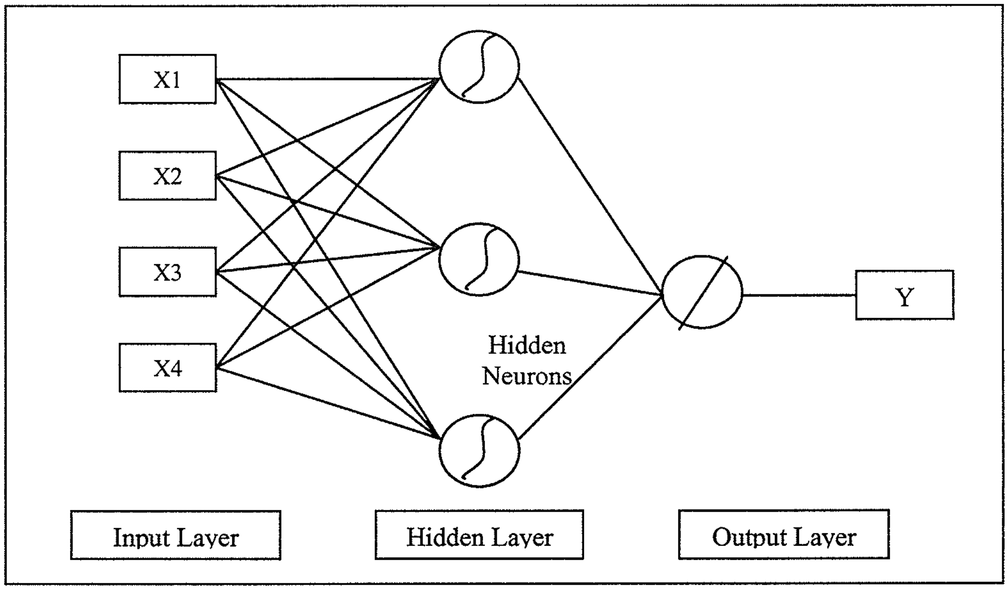


Figure 2.5: Typical Neural Network Architecture

Each layer consists of nodes, or neurons that function like biological neurons in the brain, they receive stimuli (input), process the signal, and deliver a response (output). Different weights and biases are assigned to the links between the neurons. These weights affect how the data is processed between the layers. The detailed workings of ANNs are much more complex than what is described here and beyond the scope of this research, but a general idea has been given. Research has been completed into the applicability of using ANNs in place of other more traditional pavement deterioration modelling techniques. This work has shown that ANNs are better at predicting pavement deterioration than regression techniques (Shekharan 00). Another study explored using different types of ANNs for predicting IRI based on several input variables, and showed that certain forms of ANNs produced better results than others (Roberts 98).

Use of neural networks looks promising, especially for agencies with large amounts of historical condition data available for modelling. If there is not enough data available to create both a training sub-set and validation sub-set, the possibility exists that the ANN will simply memorize the data set and be ineffective at predicting responses not present in the original data.

2.5 Advances and Future Trends

Pavement management systems have evolved considerably over the years and with further investment in research and development will continue to do so. New methods of collecting, storing and analyzing pavement condition data are being developed. Other advances are making the output of PMSs easier to understand by staff outside the engineering realm. This is an extremely important enhancement as the decision to fund the implementation and continual upkeep of a PMS often rests with senior non-engineering staff.

The use of automated data collection technology is of great interest to many agencies. Provincial highway departments are especially interested in utilizing these technologies as their networks cover vast regions with thousands of lane kilometres worth of data to collect. While the ability of automated systems to collect roughness and rutting data while travelling at highway speeds has been demonstrated, many airport agencies have not yet adopted this technology (Wang 02). One reason is that the cost of these surveys on such small network (in comparison to a highway network) makes them less attractive than manual surveys. The main reason for the lack of implementation is the inability of these vehicles to collect information that would allow the calculation of PCI values (Wang 02). As explained earlier, PCI is the preferred method for reporting airport pavement condition in North America and agencies are not likely to abandon this practice. Research into using automated survey data to calculate a PCI value was completed but researchers were unable to capture all distress types listed in ASTM D5340 using automated equipment (Wang 02). If in the future this technology can be demonstrated to reliably calculate a PCI value its use amongst the airport community would certainly grow.

Incorporating GIS into pavement management systems has been occurring rapidly for the last 10 years and is greatly expanding their capability (McNerney 98, Lee 04, and Hede 01). The ability to store location-referenced information about the pavement in graphical form is making PMSs more user-friendly. Retrieving information regarding construction history of a particular section of pavement is now as easy as clicking on that section in a map. GIS based systems also allow for a myriad of graphical outputs to be created from the PMS data. As previously mentioned, this helps to sell the concept of a PMS to senior executives. Whereas engineers might be used to reading and interpreting tables, lists and graphs, non-engineering staff usually find a map or picture easier to understand. A study of US airport executives in 1999 showed that over 60% were using (or had planned implementation within 3 years) GIS for such things as infrastructure management, environmental analysis and airport operations (McNerney 00).

Use of GIS amongst state DOTs is also widespread. A 2004 study indicated that 60% used GIS to support their pavement management activities (NCHRP 04). Several of the remaining agencies have implemented GIS, but reported only using it for map generation. One interesting finding of this study was that despite widespread use, only a small percentage were using the full spatial analysis tools available in a GIS based platform. One reason for this is that some have questioned if the expense (monetary and time) involved with fully implementing/utilizing the spatial analysis tools is worth the effort. Reports from two of the states that have developed such systems (Florida and Illinois) indicate that within 5-7 years the "estimated efficiency and effectiveness benefits clearly outweighed the costs" (NCHRP 04).

Building on the successful incorporation of GIS into PMSs, the use of global positioning system (GPS) technology is now being researched as part of a "state-of-the-art" system (McNerney 00). Using a GPS receiver, distress location information can be stored along with the standard extent and severity values. The distress information collected in the field is then transferred to the GIS system allowing for individual distress maps to be created. The time required to complete field inspections is also expected to be much less using this type of system, as the need for traditional paper forms is eliminated (McNerney 00, Huang 04).

Pavement management systems provide valuable information to many levels of an organization. GIS based systems, supplemented with more data than just the PCI values can provide some added capabilities that increase their usefulness. Examples include maintenance crews sealing cracks identified during a GPS survey to management viewing the latest condition maps giving them a complete visual of the airports condition. In the past this might have required each person to have the appropriate software on their computer, and the knowledge how to use that software. One recent development that addresses this problem is the creation of web-based PMSs. Highway agencies wishing to share information with regional offices and regional aviation authorities can all benefit from the connectivity of a web-based system. A case study in Oklahoma showed that through the implementation of a web-based PMS for the 88 general aviation airports, they were able to drastically increase efficiency (Mooney 05). Efficiency in this case is measured as the ratio of management costs to airport funding, which was cut by over 50%. Even within a single facility, the potential for such a system is immense. For example, maintenance crews could log onto the system from their vehicles (equipped with wireless internet access and a GPS receiver) and locate distresses that require immediate attention, or update the system as they complete repairs. Currently, this type of small repair would likely go untracked as no record of its location is kept.

The term integrated, or enhanced is being applied to pavement management systems that employ many of the enhancements mentioned in this section (Hede 01). These systems supplement standard surface distress information (PCI) with a range of additional objective measurements (structural, friction, and roughness). This allows for a more complete reporting of the pavement condition, as three condition indices (structural index, frictional index, and surface distress index) are used (Hede 01). To store, analyze and display this information, these integrated systems make extensive use of GIS software and GPS technology.

2.6 Summary

Pavement management systems have evolved considerably from the initial systems developed in the early 1970s to the systems being implemented by agencies today. The major components of a standard PMS were described in this chapter, along with descriptions of several types of pavement condition inspections and pavement deterioration models. The latest advances being made in the field of pavement management were also described.

The focus of this research is on creating and implementing an APMS that expands on the works presented in this chapter. Limitations identified regarding the most widely used pavement condition procedure, the PCI, are addressed in the newly developed system. In addition much work went into the extensive integration of GPS and GIS technologies into the APMS. Finally deterioration models were created using two of the methods described in this chapter, the Family modelling technique and Neural Network modelling.

Chapter 3

WIA PAVEMENT MANAGEMENT SYSTEM DEVELOPMENT AND IMPLEMENTATION

Prior to this project the Winnipeg International Airport did not have a PMS. Pavement inspections were not based on measurable distresses and most often decisions on which sections to repair or replace were based on the opinion of the senior airfield engineer. This situation is far from ideal, as without the extensive knowledge of the airfield engineer the airport would have no basis for decision-making.

Before a proper PMS can be implemented, an organization needs to determine what deliverables and features the system should be capable of. Pavement management systems vary from one agency to the next and have many different features as discussed in Chapter 2. This chapter will deal with the work that went into taking the WIA airfield pavement management system from the conception stage to completion of the initial pavement condition inspections.

3.1 Site Description

The Winnipeg International Airport has evolved greatly since its inception in 1928. Today the airport has 2 runways, 18-36 at 3350 m and 13-31 at 2650 m in length. Airfield operations are carried out on 7 aprons connected to the runways through a system of 14 taxiways. Connected to the passenger terminal, Apron 1 is the main apron on the airfield, with the remainder of the aprons being used for cargo, general aviation, de-icing, and maintenance operations. Figure 3.1 contains a labelled site plan.

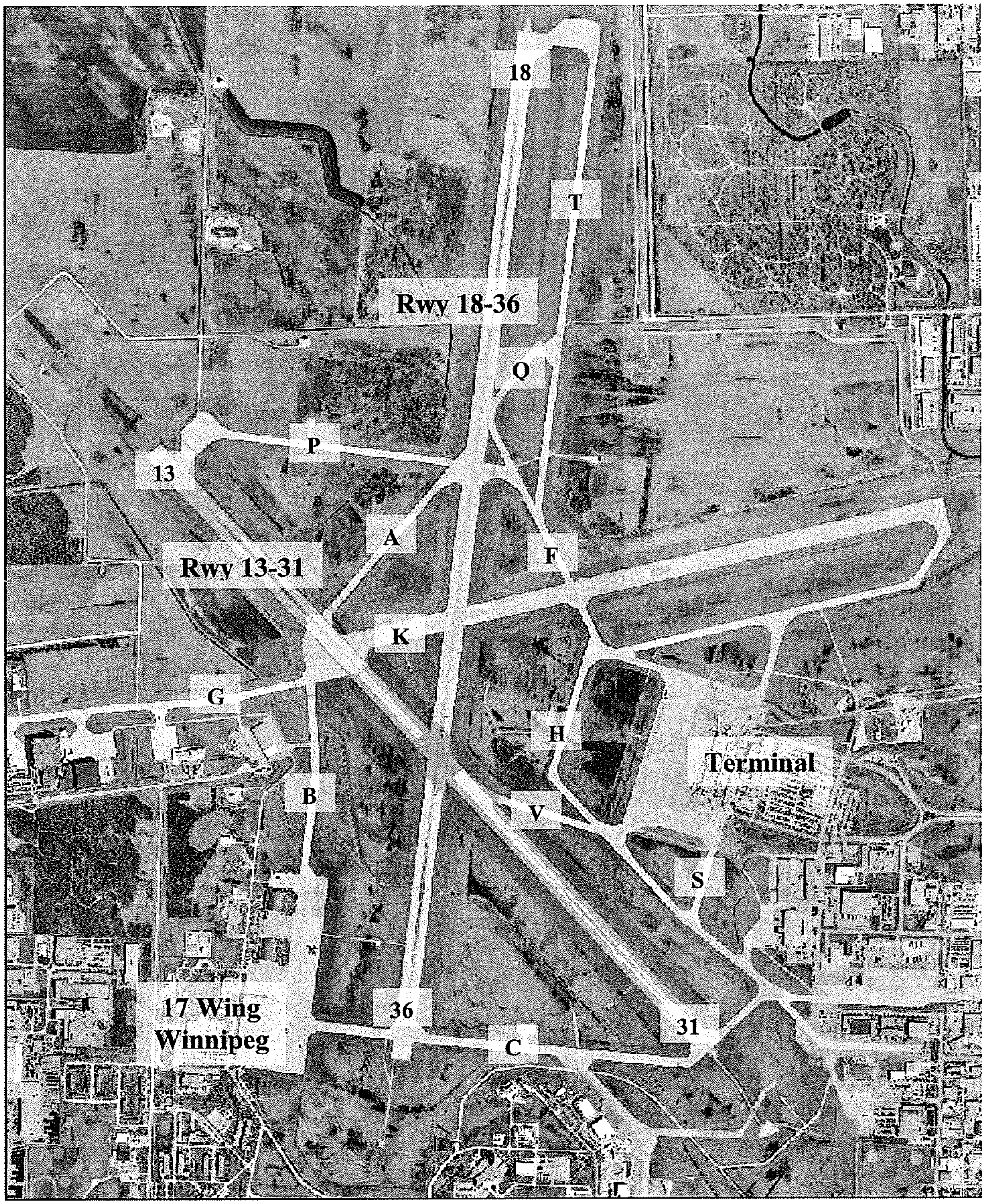


Figure 3.1: WIA Site Plan

3.2 Explanation of Airport Facility Designation

Runways are named using a 2-digit code such as 13-31 or 18-36 at the WIA. A letter such as R or L indicating left or right is also added to the numbers in the case of parallel runways. The process for naming a runway involves taking the compass heading of one end, and rounding it to the nearest 10 degrees to obtain the first number. The second number is simple the reciprocal of the other, meaning the two numbers differ by 180 degrees on the compass. For example, the compass reading on one of the Winnipeg runways might have read 129 degrees; this is rounded to 130, the reciprocal of which is 310. For simplicity sake the zero is dropped and the runway is named 13-31. To avoid any possible confusion regarding which end of a runway to land on, pilots are given instruction to land on either runway 13 or runway 31.

Taxiways are named using a single letter designation, with a unique letter being used for each new taxiway. If multiple parallel taxiways exist, then numbers may be added to the letter (A1, A2, and A3 for example). When taxiways are discussed over the radio, they are referred to using the standard military alphabet. This means each letter is assigned a word, for example, Taxiways A, B, and C would be referred to as Taxiways Alpha, Bravo and Charlie.

3.3 Network Classification

Once the needs of an organization have been identified, the task of implementing a PMS begins with classification. The purpose of classification is to break a network down into a manageable scale. Within a PMS there exists four levels of classification: Network, Branch, Section and Sample Unit. Network level classification treats an entire facility, in this instance the Winnipeg International Airport, as one entity. This is particularly useful for agencies that manage several facilities such as the military or Transport Canada with the smaller regional airports. This means that in a single database, agencies could store several networks.

Another advantage of an airfield network is that in relative terms, it covers only a single geographic location when compared to a provincial highway network. This eliminates the need to study impacts of different climatic zones as possible sources of accelerated deterioration in one section of the airfield over another, as it can be assumed that the entire airfield is subjected to the same climatic conditions.

The broadest classification level within a given network is the branch, comprised of an entire segment of infrastructure such as a runway or taxiway. For the purposes of this PMS, the airside network was subdivided into 3 types of branches based on functional classification: runways, taxiways and aprons. This research only focused on airside pavements. Groundside pavement can be incorporated into the PMS in the future as additional branch types (service-road, parking lot, etc.) if an airport authority manages such pavements. Figure 3.2 displays the branch network created for the WIA and Table 3.1 contains the approximate total area of each branch type. Calculating total area per branch type is important as different branch types are often inspected at different percentages. Therefore an approximate total area that must be surveyed during the pavement inspection process can be computed.

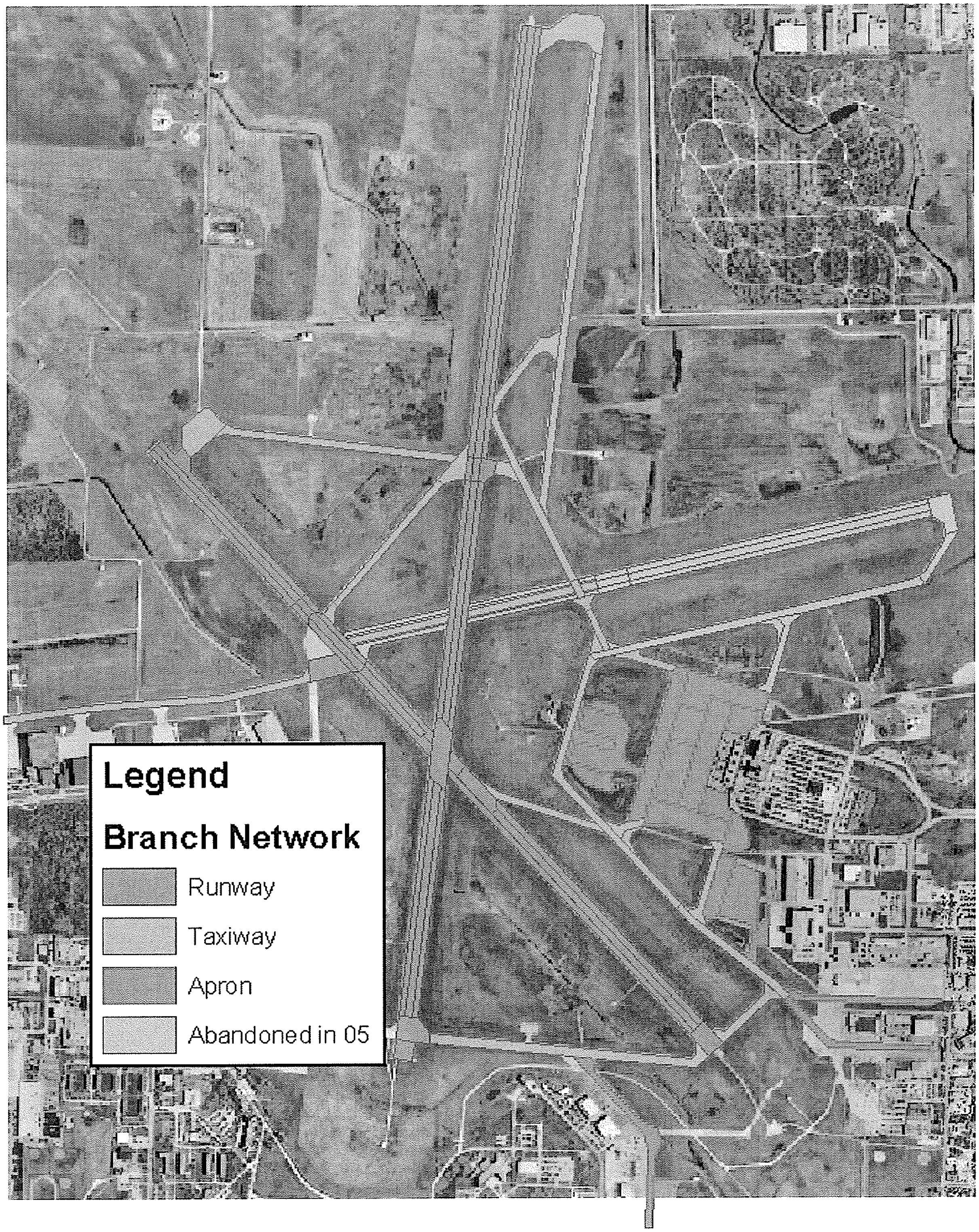


Figure 3.2: Branch Network for WIA Airfield Pavement Management System

Table 3.1: Approximate Quantities of Each Branch Type in Winnipeg APMS

Branch Type	**Quantity (m^2)**
Runway	380,222
Taxiway	269,526
Apron	270,061
Abandoned in 2005	142,658
Total	**1,062,466 m^2**

The next stages of classification were critical to the proper functioning of the PMS. Using the existing Pavement Inventory Binder, contract drawings, and as-built drawings, each branch was broken into homogenous functional use or pavement type sections. Sectioning is extremely important as variables that might account for differing rates of deterioration, such as traffic or pavement surface type must be isolated properly. For example, since taxiways generally see the same traffic across their width (usually 23m) changes in pavement cross-section were most often used to create sections. Runways, being 60m wide see different traffic loadings across their width. The outer edges see less traffic than the centre of the runway. Creating sections containing the entire width of the runway would therefore be inappropriate, even if the pavement cross-section remained uniform across the runway.

Appropriately defined sections allow for the results of pavement inspections from similar sections to be grouped together to form families as described in Chapter 2. These families are then used to create deterioration models for the different pavement types or branches present on the airfield as will be described in a later chapter. Figure 3.3 shows the 93 sections, each one a different colour, that have been created for the WIA.

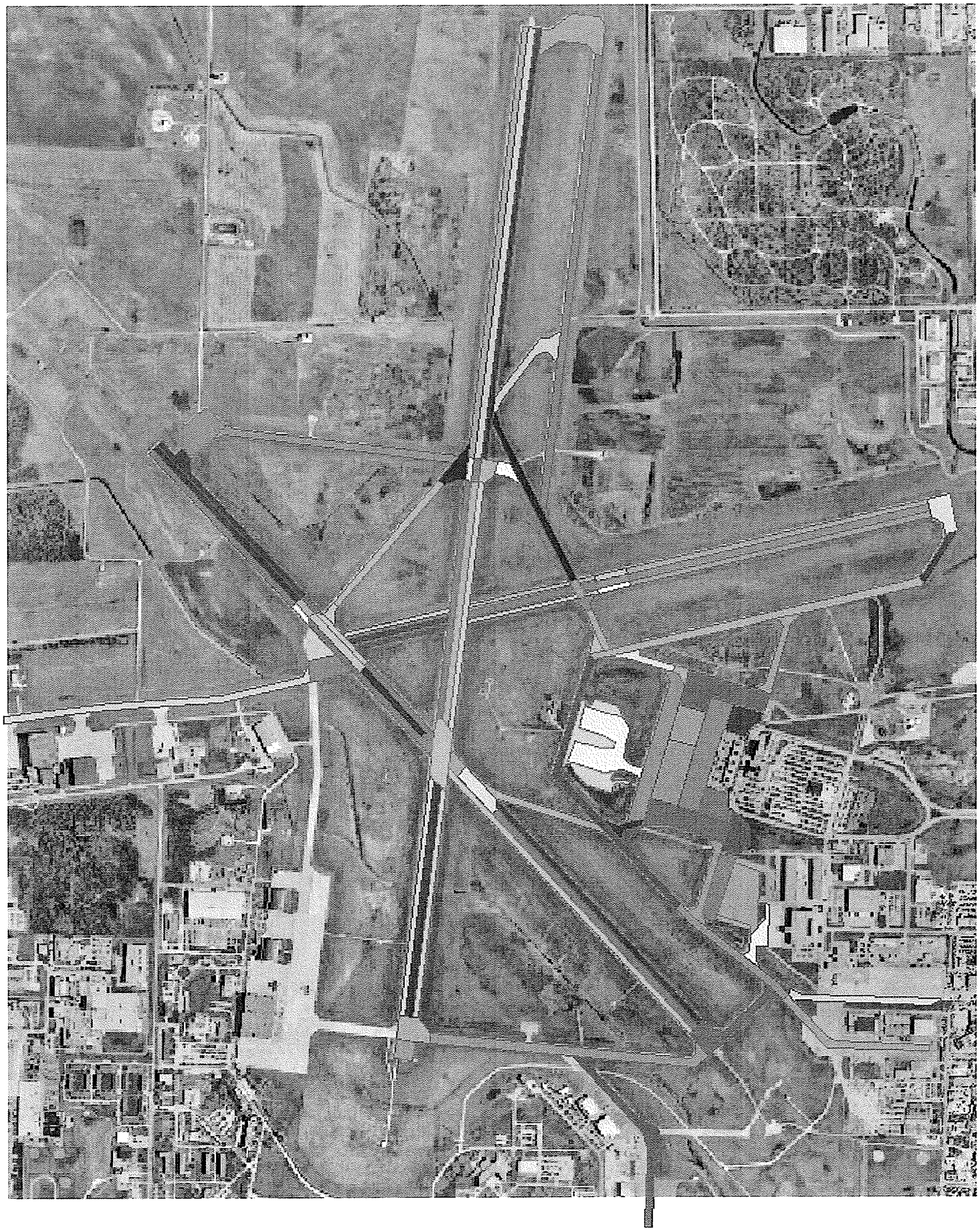


Figure 3.3: Results of Section Level Classification on Winnipeg Airfield

Time and budget constraints prohibit the inspection of every component of the network, so each pavement section is further divided into sample units for inspection purposes. The sample units are sized such that each AC unit has an area of $450m^2 \pm 180m^2$ and each PCC unit consists of 20 ± 8 slabs.

Using the above guidelines a sample unit map was created using the existing site base plan and air photos. In AutoCAD each section was manually divided into an appropriate number of sample units. The resulting map contains 1844 sample units and is presented as Figure 3.4. Attention was paid to ensuring the sample units were uniformly sized and kept within the allowable ranges. The reasoning behind this is to allow for pavement condition information at the section level to be reported as the average of the sample units that were inspected. If the sample units were drastically different in size and a weighted average was not used, the reported section level pavement condition may not be representative of the actual condition.

Table 3.2 summarizes the network classification completed for the Winnipeg International Airport. The table can be used to identify branch names, sections within each branch, the number of sample units each section contains and what surface type each section is. It should be noted that a portion of a section of pavement (half of former section Rwy0725-01) was removed during 2005, and this is why the number of sample units in Table 2 does not add up to 1844, but 1828 as it reflects the new total number of sample units on the airfield. The remaining portion of section R0725-01 has been renamed to TaxiG-02 in Table 2.

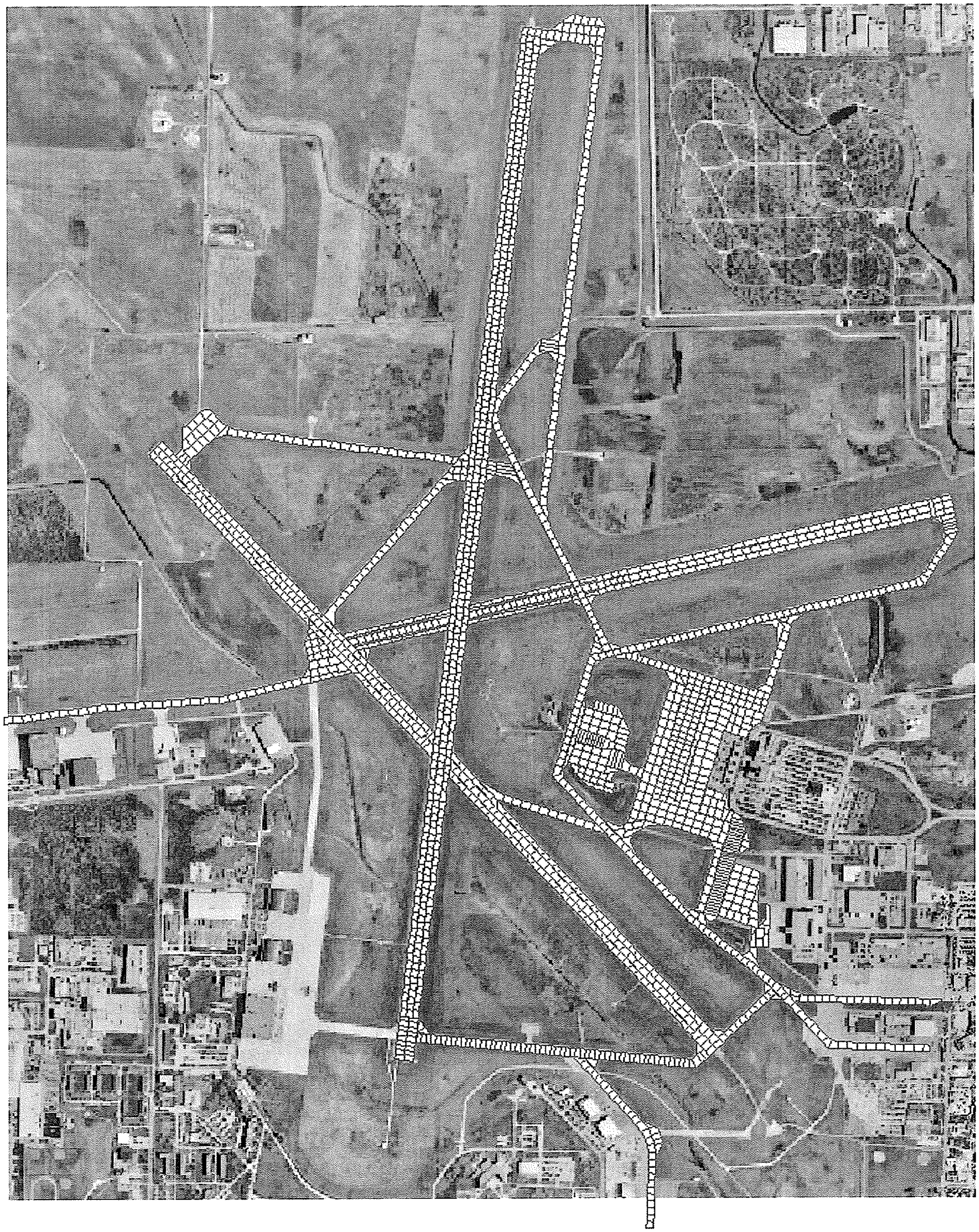


Figure 3.4: Sample Units Created to Facilitate Inspection of WIA Airfield

Table 3.2: Network Classification for Winnipeg Internatioal Airport

a) Runways

Branch	Sections	Surface Type	No. of Sample Units
Rwy 13-31	R1331-01	APC	30
	R1331-02	APC	31
	R1331-03	APC	26
	R1331-04	APC	3
	R1331-05	APC	3
	R1331-06	APC	3
	R1331-07	PCC	11
	R1331-08	PCC	9
	R1331-09	PCC	9
	R1331-10	PCC	13
	R1331-11	APC	13
	R1331-12	APC	14
	R1331-13	APC	4
	R1331-14	PCC	9
	R1331-15	APC	43
	R1331-16	PCC	32
	R1331-17	APC	37
	R1331-18	PCC	8
Rwy 18-36	R1836-01	APC	54
	R1836-02	APC	64
	R1836-03	APC	54
	R1836-04	APC	3
	R1836-05	APC	3
	R1836-06	APC	7
	R1836-07	APC	30
	R1836-08	APC	35
	R1836-09	APC	31
	R1836-10	APC	22
	R1836-11	APC	30
	R1836-12	APC	34
	R1836-13	APC	28
	R1836-14	APC	15
	R1836-15	APC	8

b) Aprons

Branch	Sections	Surface Type	No. of Sample Units
Apron 1	Apr1-01	PCC	12
	Apr1-02	PCC	11
	Apr1-03	APC	36
	Apr1-04	APC	43
	Apr1-05	PCC	30
	Apr1-06	PCC	27
	Apr1-07	APC	22
	Apr1-08	AC	16
	Apr1-09	PCC	33
	Apr1-10	APC	3
Apron 2	Apr2-01	AC	34
Apron 4	Apr4-01	PCC	18
Apron 5	Apr5-01	PCC	20
	Apr5-02	APC	1
Apron 7	Apr7-01	PCC	8
Apron 7A	Apr7A-01	PCC	27
Apron 7A	Apr7A-02	AC	21
ApronCDF	AprCDF-01	PCC	37
	AprCDF-02	AC	38

c) Taxiways

Branch	Sections	Surface Type	No. of Sample Units
Taxi A	TaxiA-01	APC	1
	TaxiA-02	PCC	21
	TaxiA-03	APC	11
Taxi C	TaxiC-01	APC	57
	TaxiC-02	APC	14
Taxi F	TaxiF-01	PCC	6
	TaxiF-02	APC	4
	TaxiF-03	APC	3
	TaxiF-04	PCC	21
Taxi G	TaxiG-01	PCC	34
	TaxiG-02*	APC	9
Taxi H	TaxiH-01	APC	21
	TaxiH-02	PCC	40
	TaxiH-03	PCC	3
Taxi P	TaxiP-01	PCC	16
	TaxiP-02	PCC	26
	TaxiP-03	APC	4
Taxi Q	TaxiQ-01	PCC	13
Taxi S	TaxiS-01	PCC	10
Taxi T	TaxiT-01	PCC	49
	TaxiT-02	PCC	25
Taxi V	TaxiV-01	PCC	12
	TaxiV-02	PCC	4
	TaxiV-03	PCC	2
Taxi W	TaxiW-01	PCC	9
Taxi K	TaxiK-01	PCC	14
	TaxiK-02	APC	18

d) Abandoned

Branch	Sections	Surface Type	No. of Sample Units
Abandoned	TaxiE-01	PCC	8
	TaxiE-02	PCC	45
	TaxiN-01	PCC	10
	TaxiN-02	PCC	2
	R0725-02	APC	9
	R0725-03	APC	4
	R0725-05	APC	4
	R0725-06	APC	10
	R0725-07	APC	10
	R0725-08	APC	5
	R0725-10	APC	6
	R0725-11	APC	11
	R0725-12	APC	4
	R0725-13	APC	5
	R0725-14	APC	4
	R0725-15	PCC	23
	R0725-16	PCC	32
	R0725-17	PCC	23
	R0725-18	PCC	13

e) Summary

Branch Type	No of Sample Units
Runways	716
Taxiways	447
Aprons	437
Abandoned	228

As previously described, both network and project level pavement management are possible, and depending on the level, differing quantities of sample units per section are inspected. One method that is available for project level surveys is to select the number of sample units that would provide a statistically adequate estimate (95% confidence) of the Pavement Condition Index (PCI) for a particular section using equation 3.1 (ASTM D5340):

$$n = \frac{Ns^2}{(e^2/4)(N-1)+s^2} \tag{3.1}$$

Where:

e = acceptable error in estimating the section PCI (industry standard value of 5 is used)

s = standard deviation of the PCI within a given section

N = total number of sample units in the section

Obviously, before the initial years inspections were completed the standard deviation values for each section were not known. One approach is to use assumed values of 10 for AC pavements and 15 for PCC pavements as suggested in ASTM D5340. Network level surveys require only a general overview of the condition and a sample unit inspection rate of 10% is usually sufficient for highway networks (Shahin 94). Airfields are usually held to higher standards than highway networks and therefore require a greater rate of inspected samples. The WIA inspections were carried out with the intent of creating a network level condition report so the inspection ratio was chosen based on branch type.

For the 2005 inspections the following breakdown was used: 40% for runways, and 20% for taxiways and aprons as proposed in the literature (Shahin 94). Table 3.3 shows the number of sample units that needed to be surveyed based on the above percentages.

Table 3.3: Required Number of Sample Units to be Surveyed in 2005

Branch Type	Number of Sample Units	Sample Unit Inspection Rate	No. of Sample Units Required to be Surveyed in 2005
Runway	911	40%	365
Taxiway	480	20%	96
Apron	437	20%	88
		Total	**549**

*note: Above quantities includes sample units that were to be abandoned in 2005.

Once the required number of sample units is determined, the next task is to select the sample units to be inspected within each section. A procedure known as systematic randomization is used for choosing these sample units. The spacing interval is computed using equation 3.2 from ASTM D5340:

$$i = N / n \qquad (3.2)$$

Where:

N = total number of sample units in the section

n = number of sample units to be inspected

The first sample unit to be inspected is randomly chosen between 1 and *i*. These sample units are referred to as 'random samples' during the inspection process. 'Additional samples' may be added during the inspection procedure if sample units that are non-representative of the rest are observed. This may include either much worse, or much better sample units, or sample units that contain an anomaly such as large utility cuts. If a sample unit that was chosen at random is found to have fallen into this category it should be counted as 'additional' and another random sample unit should be chosen.

It should be noted that due to the learning curve associated with conducting proper inspections and some delays in procuring the necessary surveying resources, the entire network was not surveyed during the summer of 2005. Most notably only 3 out of the 18 pavement sections of runway 18-36 were surveyed. In addition, inspections were carried out on pavement sections that were abandoned during the summer of 2005. The reason these inspections were still carried out was to add more data points to the pavement deterioration models.

3.4 Environmental Scan of PMS Implementation

Choosing a pavement inspection procedure was another important task that needed to be completed before airfield pavement condition inspections could be conducted. An environmental scan was conducted to assess the experience of Canadian airport community with PMS. The experience of local municipal and provincial agencies was also investigated.

Much of the growth and widespread use of PMSs has been driven by legislation in the United States. Two wide reaching legislations, known as Governmental Accounting Standards Board Statement #34 (GASB34) and Public Law 103-305 affect the funding of state and federal agencies in the US (highway and aviation), and require, as a condition for federal funding that asset management systems be implemented and that accounting procedures be used to track the value of an agency's infrastructure. In Canada the federal government does not provide funding to provincial or local transportation agencies for infrastructure maintenance and rehabilitation (outside special infrastructure funds used on a case by case basis) so no such program has been developed. Still many agencies in Canada do utilize PMSs to help manage their investment in infrastructure in the most efficient manner.

The environmental scan results varied widely as it was discovered some agencies utilize standard inspections while others created or adapted standard techniques into custom procedures. On a local scale, both the City of Winnipeg and Manitoba Transportation have created or use customized inspection procedures as part of their pavement management systems. Size of network to be surveyed was the driving force behind these agencies developing custom procedures, as most standard procedures were found to be too time consuming for their purposes.

3.4.1 Survey of APMS implementation at Canadian Airports

In order to assess the state of implementation of PMSs at Canadian airfields, a survey was developed and distributed through the Canadian Airfield Pavement Technical Group

(CAPTG). CAPTG was created in response to the decentralization and privatization of Canadian airports to assure the information is shared amongst facilities and research is not duplicated. Their mandate states that CAPTG is "concerned with the planning, design, construction, maintenance, rehabilitation, monitoring, performance evaluation and management of airfield pavements, and all factors that influence their physical behavior, service life and economy" (www.swiftconference.org/captg.htm). Many airport authorities and government airfield engineers are active members of CAPTG.

Responses were received from both large and small facilities across the country and both the survey questions, as well as a summary table of the responses is included in Appendix A. The first four are of particular interest as they are from larger international airports (YYC, YVR, YOW and YYZ). Three out of four of these facilities use the Pavement Condition Index to evaluate their airfields, while the other uses a system developed by Transport Canada (AK-68-32-000). Amongst the responses from regional airport authorities and small airport operators, the response was split 50/50 between PCI and the Transport Canada systems.

The survey also assessed the extent of GIS and GPS use as part of the APMS at each of the facilities. GIS use is not very widespread and is limited to only the larger facilities. Within the facilities that indicated some GIS use, all reported either being in the implementation stage or only using GIS software for creating maps and presenting data. The full spatial analysis capabilities of the GIS software are not currently being employed at Canadian airports. Also, no facility reported utilizing GPS equipment as part of the pavement inspections either. One facility (YOW) indicated they are beginning the incorporation of GPS technology into their system.

3.5 Selection of Inspection Procedure

The WIA had several criteria for any inspection procedure that was going to be implemented as part of their PMS. Most important of which was, an inspection procedure that was simple to conduct, repeatable, and based on measurable quantities/distresses. Also, selecting an inspection procedure that eliminated as much of the subjective nature of past procedures would minimize the variability due to operator bias.

After considering all of the above criteria, along with the knowledge gained through the environmental scan, the decision was made to adopt a standard inspection procedure as opposed to creating a custom one. Logistical problems such as expansive networks (provincial highway network) that led other agencies to develop their own procedures do not exist in the airport environment. This means it is possible to conduct inspections that require the detailed evaluation of selected sample units.

The decision was made to implement the Pavement Condition Index (PCI) inspections as detailed in ASTM D5340. During a PCI inspection evaluators that traverse the sections on foot measure the quantity and severity of 15 distresses for concrete surfaces and 16 for asphalt surfaces. Table 3.4 lists the measured distress types and the units they are recorded in for both pavement types. A numerical value is assigned to an inspected sample unit based on the quantities and severity of distress measured during an inspection.

Table 3.4: Distresses Measured during PCI Inspections for Asphalt Surfaced and Concrete Pavements

a. Asphalt Surfaced Pavement	
Distress	**Units**
Alligator Cracking	Sq.M
Bleeding	Sq.M
Block Cracking	Sq.M
Corrugation	Sq.M
Depression	Sq.M
Jet Blast	Sq.M
Jt. Reflection (PCC)	M
Long. & Trans. Cracking	M
Oil Spillage	Sq.M
Patching	Sq.M
Polished Aggregate	Sq.M
Raveling/Weathering	Sq.M
Rutting	Sq.M
Shoving from PCC	Sq.M
Slippage Cracking	Sq.M
Swell	Sq.M

b. Concrete Pavements	
Distress	**Units**
Blow up	Number of Slabs
Corner Break	Number of Slabs
Long/Trans/Diagonal Crack	Number of Slabs
Durability Crack	Number of Slabs
Joint Seal Damage	Number of Slabs
Small Patch	Number of Slabs
Large Patch	Number of Slabs
Popouts	Number of Slabs
Pumping	Number of Slabs
Scaling/Map Cracking	Number of Slabs
Settlement/Faulting	Number of Slabs
Shattered Slab	Number of Slabs
Shrinkage Crack	Number of Slabs
Spalling-Joints	Number of Slabs
Spalling-Corner	Number of Slabs

Under this system, a newly rehabilitated or constructed pavement, free from any surface distresses is assigned a PCI value of 100. Distress data from each surveyed sample unit is used to compute a PCI for each pavement section in subsequent years. For each sample unit, the density of each distress is first computed. For example, if a corner-break was found in 4 slabs of a 20 slab sample unit that would be a density of 20. For each distress type there exists a graph of deduct values vs. densities which is used to obtain the effect of each distress on the PCI of that sample unit. If more than one of the individual deduct values is above 5 then a procedure must be followed to obtain the maximum Corrected Deduct Value (Max CDV). This procedure is contained in ASTM D5340 and will not be described here. A final PCI value for each sample unit is computed and if only randomly selected sample units are inspected, the average of the sample unit PCI values is used as the section PCI. This is why great care was taken during the network classification stage to ensure sample units were created with uniform sizes. However, when additional sample units are inspected then a weighted average must be used as described in section 11.1 of ASTM D5340.

3.6 Data Collection Equipment and Software

At the centre of any PMS is software and equipment to collect, store, analyze, and display the distress and deterioration information in a clear and concise manner. In order to simplify the implementation process at the WIA, it was decided to use existing software that has customizable features as opposed to writing new software. The software program obtained was MicroPAVER. Originally developed by the US Military, MicroPAVER has become one of the most widely used pieces of pavement management software for North American airfields. MicroPAVER puts a graphical user interface on the database that contains all the construction history and inspection data. It can also run simple prediction modelling, generate budget forecasts based on a set condition or a condition forecast for a fixed budget or certain spending policy.

Since visualization of asset and distress information is also an important component of an asset management system, GIS software was needed to visually display and interpret the distress information. The ArcGIS suite of software developed by ESRI was chosen for this purpose due to its ability easily transfer information to and from MicroPAVER and the GPS survey equipment. The GIS software allows nearly all of the information stored in the MicroPAVER database to be displayed graphically and was used to produce all of the maps in this thesis.

Every map created during the classification stage made use of high quality aerial photographs of the airport. Advances in the technology used to capture and process these photos have increased their usefulness for PMS applications. These photos helped answer questions that arose regarding the pavement inventory without leaving the office. As well, they aided in the creation of PCC sample units which are based on slabs since information regarding slab layout is often not kept on the base plan CAD drawings. In 2005, WAA acquired a new set of air photos at a resolution of 10cm. Figure 3.5 was created to demonstrate the difference in available resolutions. Included are 160cm, 80cm, 40cm, 20cm and 10cm resolutions. The resolution indicates the size that each pixel in the drawings represents. Each photo is 625 x 625 pixels, which depending on the resolution, represents from 62.5m x 62.5m to 1000m x 1000m. Each block was created with the aerial photograph displayed at 100% of its original size. This figure demonstrates that the greater expense of higher resolution air photos is offset by the increased usefulness of the photos in the pavement management process. At the highest resolution it is possible to identify pavement joints and the quality of markings, making these images useful for PMS applications.

Several instruments were also acquired to aid in the data collection process. In accordance with ASTM D5340 a hand odometer wheel, 10ft (3m) straight edge, 12 in (300mm) scale, layout plan, and data recording sheets are required to perform a PCI survey. In addition to this equipment, a rugged field computer and a mapping grade GPS receiver were acquired for this project for locating sample units and collecting distress information.

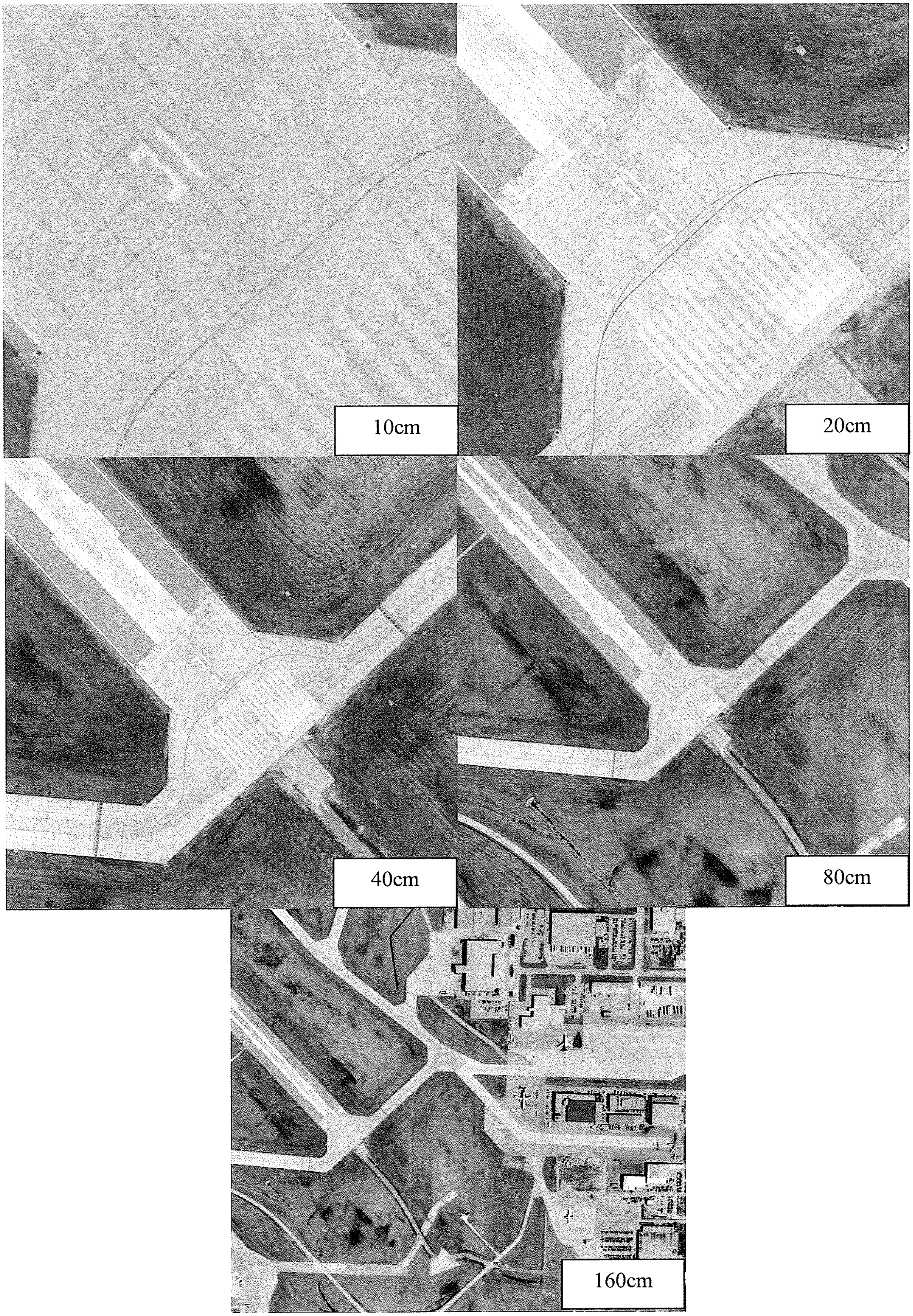


Figure 3.5: Comparison of Different Aerial Photo Resolutions

3.7 Pavement Condition Data Collection

Pavement Distress information can be collected in numerous ways, from pen and paper to electronic forms on laptops. One challenge that was faced at the airport, was locating the selected sample units in the field. The City of Winnipeg uses residential street addresses to assist them in locating a sample section that is being surveyed. Unfortunately airfields are open spaces without enough distinct features to assist in sample unit locations. Runways that are 60m wide and over 3000m long contain little to assist in locating any individual $450m^2$ sample unit. As could be seen in Figure 3.3, most airfield branches contain several sections and many sample units and therefore present a unique challenge for locating the sample units in the field. Furthermore, traditional layout methods with stakes or paint are not acceptable in the airfield environment due to the FOD potential and lack of productivity.

Several solutions to this problem were researched, and it was decided that a mapping grade GPS unit could be used to locate the sample units in the field with sub metre accuracy. A Trimble ProXT unit along with a Recon field computer were acquired to complete this task. Figure 3.6 shows the purchased units. The decision was made to go with two separate devices as opposed to an all-in-one unit so that the GPS unit could be used with several different computers (laptop, PDA, etc) depending the desired application. The GPS antenna communicates with the field computer using Bluetooth or a serial RS232 cable. When completing the PCI surveys the equipment is attached to a range pole, with the ProXT on top, and the Recon attached mid-length down the poll so the recorder only has to carry one piece of equipment. Being one of the first users of this equipment in Canada, there were some initial problems such as improperly manufactured battery and problems with the Bluetooth communication hardware. Once these issues were resolved the sample unit map was loaded onto the field computer and the PCI inspections were commenced.

Figure 3.6: GPS Receiver and Field Computer used for Pavement Distress Information Collection

A data collection utility supplied with MicroPAVER, can be run on the field computer and is used to eliminate the paper survey form. The initial field surveys were completed in this manner, with the GPS being used only for sample unit location. Pavement distress lengths and areas were measured manually and recorded on the field computer. A shortfall of this system was that distress locations were only recorded to be in the particular sample unit, and their exact location is not identified. Secondly the nature of the survey was time consuming, especially for AC pavements because each crack had to be measured with a rolling measuring device and recorded individually.

A solution to both these problems was quickly found. Since the GPS unit was of mapping quality (sub-metre real time and 0.1-0.5m post-processed) it is possible to use the device to map out the location and record the quantity (length or area) of the pavement distresses simultaneously. This method decreased the time necessary to complete each PCI inspection because only one device was used to locate the sample unit, measure lengths/areas and record the information.

In order to facilitate the collection of the distress information, a custom data dictionary was created that contained all distress types and severities that are part of a PCI inspection. This data dictionary was loaded into the GPS software program on the field computer.

In the field when a distress was found, the operator traced the distress along its length or area and selected the appropriate severity. This information is then automatically stored within that Sample Unit on the map. By using this paperless method, the completion and subsequent storing of over 500 inspection sheets (one per inspected sample unit) was eliminated. Figure 3.7 shows the results for an asphalt-surfaced sample unit.

Figure 3.7: Asphalt Sample Unit Before and After Condition Survey using GPS Aided Data Collection

For concrete surfaced sample units, the distresses are recorded on a slab-by-slab basis as the PCI uses a 'count' instead of a quantity such as linear metres. Figure 3.8 shows the results for a concrete surfaced sample unit.

a) Sample Unit

b) GPS-Based Condition Assessment

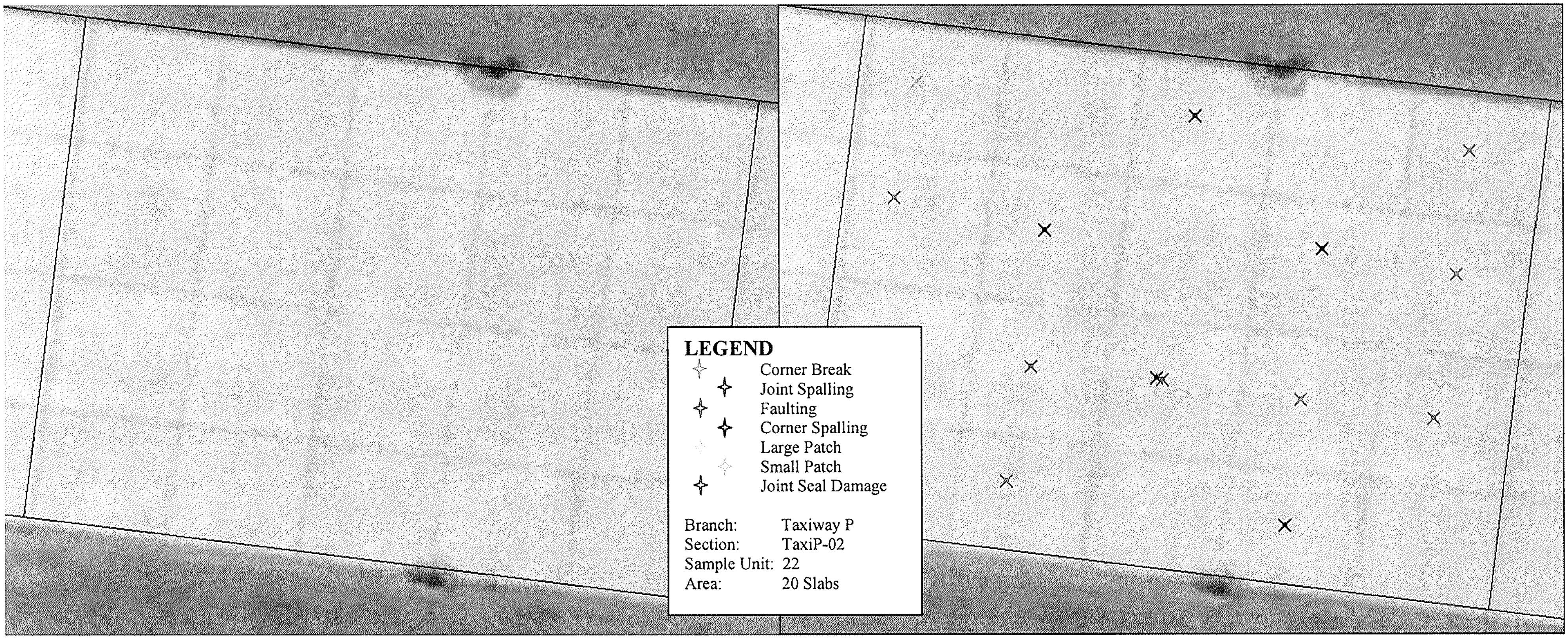


Figure 3.8: Concrete Sample Unit Before and After Condition Survey using GPS Aided Data Collection

After several inspections were completed it was observed that a great deal of time was still being spent traversing the individual distresses while logging them with the GPS unit. In a severely distressed section the distance covered added up quite fast. A unique solution to this problem was found, inline skates. They were used to increase the speed at which the recorder could travel over the distress, thereby drastically reducing the survey time again. In order to keep things moving along as fast as possible, a two person team was deployed. The evaluator would travel ahead, on foot, and rate each distress as to type and severity, using chalk to mark the pavement. Following behind, the recorder would travel on inline skates, with the range pole that had both the GPS receiver and the field computer mounted on it. The recorder, with the aid of the codes on the pavement would log all distresses in the sample unit by rolling over them holding the range pole vertically over the distress. This system proved to be extremely effective and efficient in minimizing the time the inspection crew had to be on the airfield, which is a critical concern particularly on runways or taxiways. The average survey time for each of the sample units was between 5 and 10 minutes.

At the end of each day, the raw survey data was downloaded from the handheld computer to the office to computer using the Trimble software. Differential correction was then applied to the data to improve its accuracy. On average this step brought the data down from approximately 1m accuracy to the sub-0.5m range. The result of the condition surveys was then transferred to the MicroPAVER program manually.

This manual transfer between the two programs provided an opportunity to evaluate the quality of the inspection data. Obvious data errors or mistakes were eliminated, ensuring only high quality data was inputted into MicroPAVER.

A graphical representation of the distresses observed in each sample unit survey is created, and can be viewed in the GIS program or the Trimble software. The advantage of using GIS programs such as ArcView is that maps and spatial queries can be created from the survey data (as will be discussed in Chapter 4). Each distress type is stored as a different layer in the GIS map, meaning it is possible if one wanted to see where faulting was occurring, such a map could be created by turning on the appropriate layer. Storing information about the individual distresses is a significant improvement over the traditional method of simply reporting the PCI for each section. Two sections with the same PCI values can have drastically different distresses occurring, and this system will provide graphical evidence that can assist the pavement engineering in deciding on the appropriate remedial action.

Conducting PCI inspections affords the evaluators an opportunity to observe the entire airfield in more detail than is normally obtained. Despite only a few sample units out of each section being inspected, the inspector walks from sample unit to sample unit in case any 'additional' sample units (as defined earlier) are noticed. During this time on the airfield, occasionally distresses that need immediate attention are discovered. Missing corners of PCC slabs along the wheel path of high traffic areas or cracks which pose a FOD hazard can be extremely dangerous and need to be repaired as soon as possible.

Another benefit of completing the PCI surveys with the GPS equipment is the ability to record the locations of such problems. When these urgent distresses are encountered, they are logged using the GPS unit just as the regular inspection data would be logged. The UTM coordinates of these distresses can then be transferred to the maintenance crews who have GPS equipped vehicles. Having the exact locations of these distresses ensures that there will be no difficulty in locating the area in need of repair. The same procedure could be used for such items as damaged lights or manhole covers.

3.8 Validation of GPS Data Collection

While the GPS enabled system dramatically reduced the time required to complete the PCI surveys, the quality of the data needed to be verified, as it is only useful if it produces results similar or better than traditional surveys. An extensive field trial was completed that compared the length and area measuring capabilities of both the GPS system and the rolling wheel specified in the ASTM standard. Benchmark values were established using a total station, which was used to establish a grid on the test section (4x4 slabs) as seen in Figure 3.9. The points were marked out on the pavement to ensure all the devices would begin and end at the same points.

As part of this procedure, 23 lengths and 6 areas were measured, including 1 manhole cover and 1 non-straight crack. These last two measurements were not recorded with the total station, so no benchmark information exists for them; however the values are compared to each other. The full results, including GPS results overlaid on the air photo are contained in Appendix B. Table 3.5 contains the average percentage each device was off for both area and length measurements. An average using absolute differences as well as the true differences is presented.

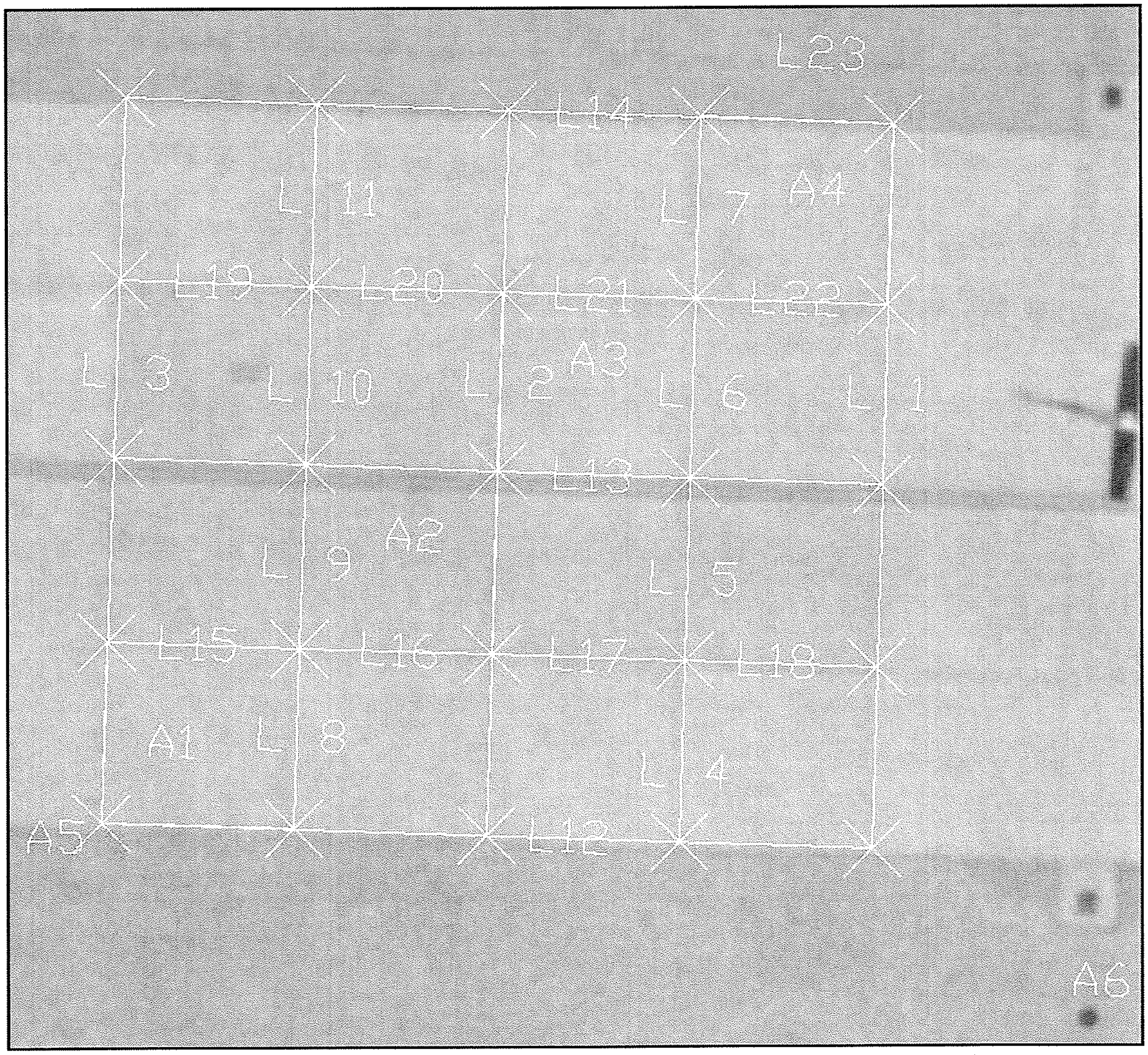


Figure 3.9: Grid Layout for GPS Data Collection Validation Experiment

Table 3.5: Summary of GPS Data Collection Validation Experiment Results

	GPS		Rolling Wheel	
	Mean Absolute (GPS – T.S.) Errors	Mean Arithmetic (GPS – T.S.) Errors	Mean Absolute (R.W. – T.S.) Errors	Mean Arithmetic (R.W. – T.S.) Errors
Length	2.46%	-1.60%	0.96%	0.55%
Area	8.02%	0.44%	0.60%	-0.60%

Note: T.S. = Total Station R.W. = Rolling Wheel

While the rolling wheel produced better results (less than 1% off the total station values at all times), the magnitude of the error in the GPS measured lengths was still minor. When absolute differences were used, the lengths were off by an average of 2.46%, but when the actual differences were used the difference only averaged -1.6%. This second value is the one of interest, as for a given sample unit (like the trial section), some lengths will be calculated too short, some too long, but the average is what we are concerned with as the PCI value for the sample unit is computed from the sum of distresses. The same situation applies for the area measurements.

When dealing with information collected using the GPS system, the standard procedure is to post-process the data upon return to the office. This brings the accuracy of the data down to the 0.1-0.5m range. Unfortunately during the field exercise, base station data (used for post-processing) was only available for a small portion of the points collected (32%) due to an equipment malfunction. The malfunction was only learned about after returning to the office, and at first it was assumed that the trial would have to be run again, but after reviewing the data it became clear this was not the case.

The fact that only a portion of the data was post-processed was actually a benefit to this exercise. It demonstrated that post-processing simply improves the accuracy in terms of position on the earth, leaving the relative distances between the points the same (less than 2% average difference). Figure 3.10 shows the measured distances between the uncorrected GPS, corrected GPS, and total station points. Since the purpose of using the GPS for data collection is to get lengths and areas of observed distresses, we are only concerned with the relative measurements taken between the GPS points. Although the corrected GPS points are located closer to the actual locations recorded with the total station. This does indicate that post-processing should still be completed upon returning to the office to ensure the collected distress data is positioned properly in the GIS map.

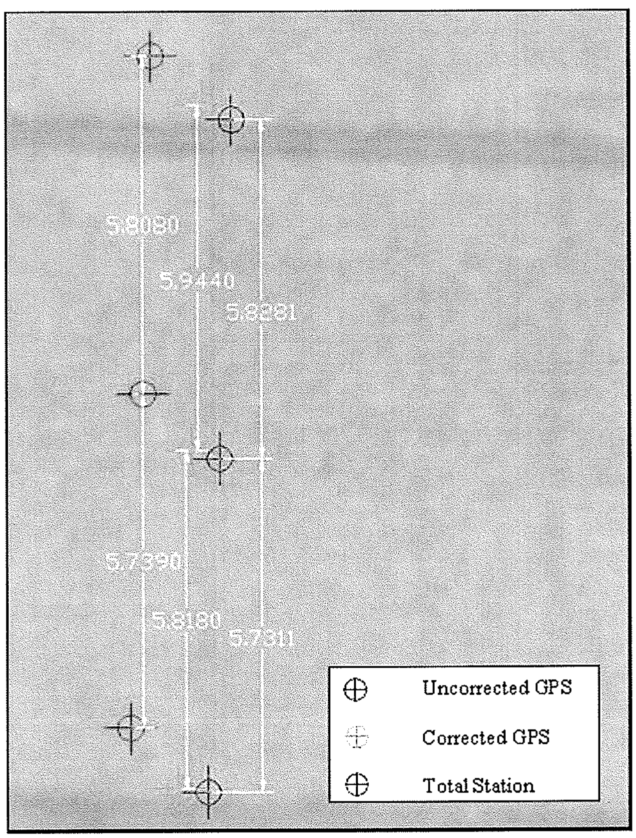


Figure 3.10: Effect of Post-Processing GPS Data on Measured Lengths

The next task was to determine the sensitivity of the PCI scale to varying distress quantities. Full results of this exercise are also contained in Appendix B. Data from a single sample unit was taken from the 2005 PCI survey results for this test. This particular sample unit was chosen because it had distresses measured in both area and length. Since initial PCI for this sample unit was known (from the 2005 survey) the distress data was simply varied by ±5, ±10, and ±15% to observe the impact this had on the PCI. The maximum change in the PCI that was produced by varying the inspection quantities by 15% was only 2 (on the 100 point PCI scale). Since none of the average differences came close to 15% it is safe to say there is no significant impact on PCI values from using the GPS system developed for this project.

3.9 Summary

Implementation of a network level airfield pavement management system for a facility like the Winnipeg International Airport is a large undertaking. The processes followed from the conception through the selection of the pavement condition assessment methods were detailed in this chapter. Over 1 million square metres of airfield pavement was classified into branches, sections and sample units using standard pavement management practices.

A survey developed for this research, was distributed through the Canadian airport community to assess the extent of APMS implementation at Canadian airports. Nine responses were received from both large and small airport operators providing valuable insight from a Canadian perspective. One important observation was that despite fairly widespread APMS implementation, advanced technologies like GIS and GPS are not widely utilized; proving the need for the kind of system this research aims to develop.

Finally this chapter detailed the new method of collecting and storing pavement distress information. This new method utilized a mapping grade GPS receiver with portable field computer to make the data collection process more efficient and reduce the operational impact of PMS implementation on an airport. Data collection with the GPS based system was validated in a field trial to assure the distress information collected in this manner could be relied upon.

Chapter 4

AIRFIELD PAVEMENT CONDITION SURVEY

Upon completion of the network classification and development of the data acquisition system described in Chapter 3 an initial round of pavement condition surveys was completed in 2005. This chapter will present the results of those inspections, first employing the standard reporting methods currently used by airfields throughout North America. In addition, new methods of reporting and analyzing the pavement condition data have been developed as part of this research. These new methods are only possible because of the new GPS data collection and its integration with a GIS based pavement management system.

4.1 Standard Method of Reporting Pavement Condition

4.1.1 PCI Results

Pavement Condition Index inspections were completed during the summer of 2005, with over 300 PCI inspections being carried out across the airfield. MicroPAVER was used to compute a PCI for each section that was surveyed. A weighted average PCI, which takes into account the area of each section, was also calculated for each branch. Figure 4.1 displays the PCI values computed at a section level, while Figure 4.2 displays the average branch PCI values. Results from the PCI inspections on a section-by-section basis are included in Appendix C. When analyzing the first year results, the standard PCI rating

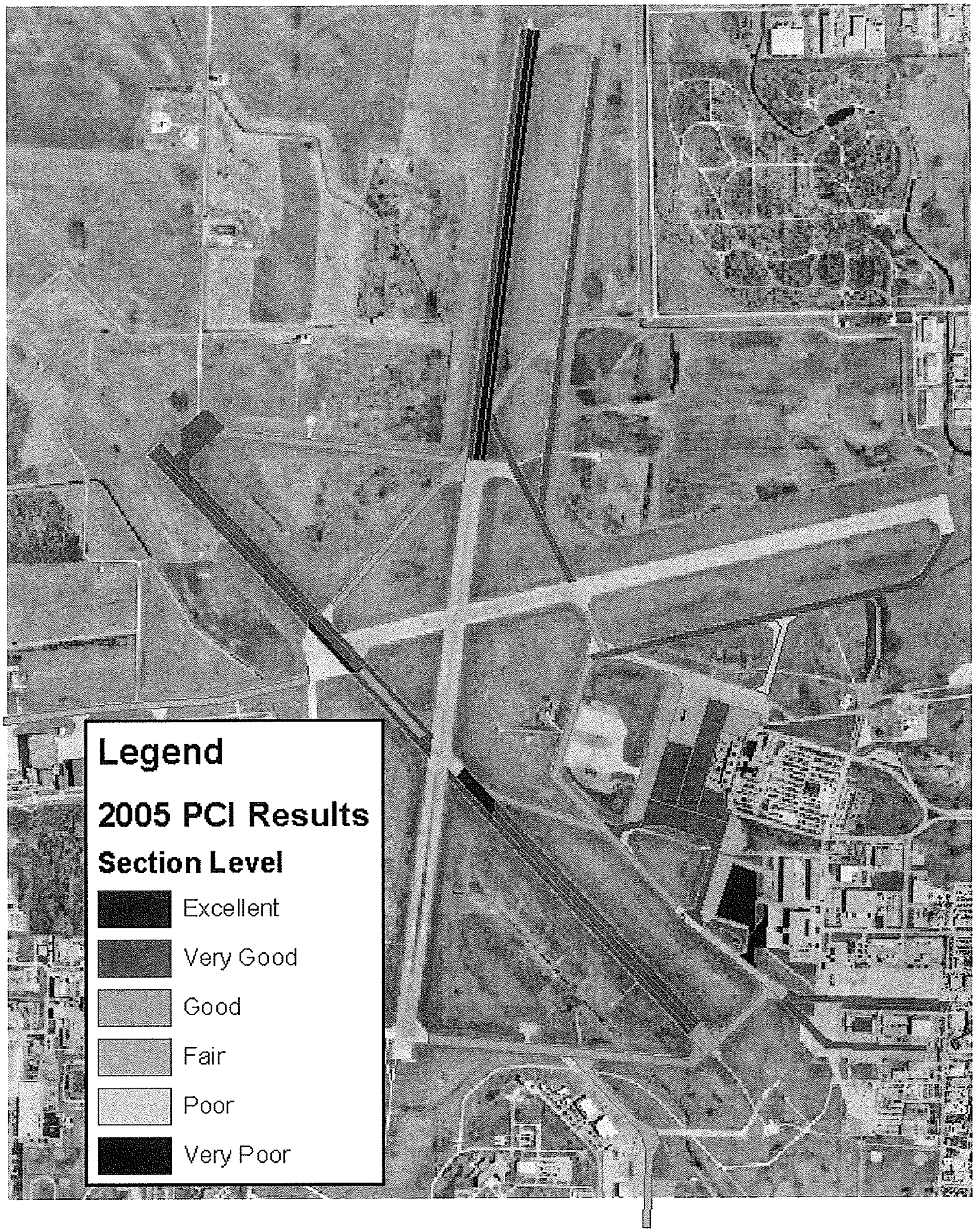


Figure 4.1: 2005 Section Level PCI Results for WIA

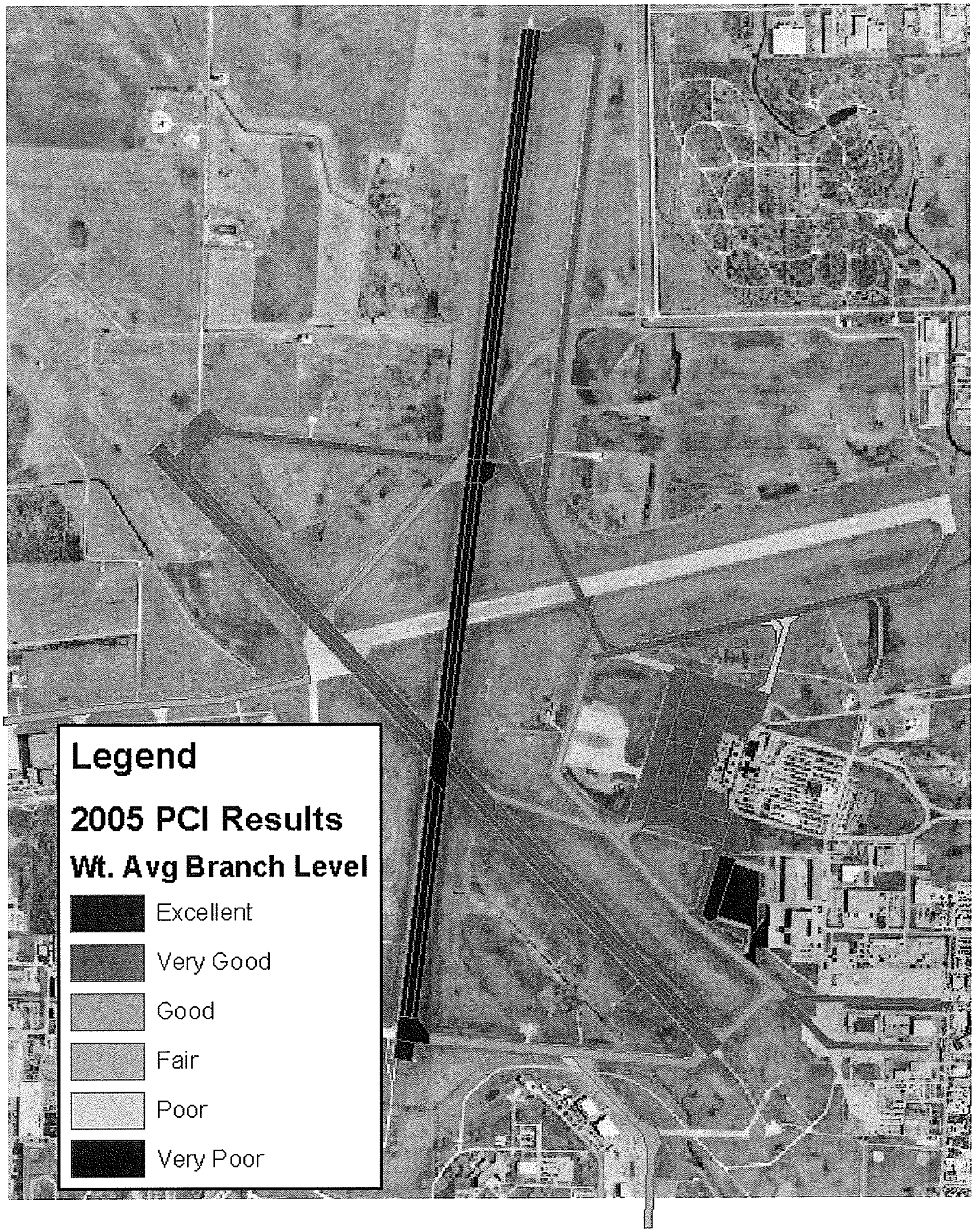


Figure 4.2: 2005 Average Branch PCI Results for WIA

scale (ASTM D5340) shown in Table 4.1 was used. Later, the use of a custom distress scale will be discussed.

Table 4.1: Standard PCI Rating Scale

PCI	Rating
86 - 100	Excellent
71 - 85	Very Good
56 - 70	Good
41 - 55	Fair
26 - 40	Poor
11 - 25	Very Poor
0 - 10	Failed

Figures 4.1 and 4.2 provide a graphical representation of the airfield condition in the summer of 2005. Looking at Figure 4.1, two pavement sections were rated as very poor and these have been abandoned (Taxi N) or do not see plane traffic (Apron 7). Of the sections rated in the fair category, two (Taxi A and Apron 2) have received major rehabilitation since the surveys were completed and will no longer score in this category. A great deal of infrastructure renewal has taken place at the WIA over the last 5 years, and as such the majority of Apron 1 and both runways have scored in the Very Good (PCI > 71) category or higher. Table 4.2 contains the PCI numbers, for the sections surveyed broken down by branch type.

Table 4.2: 2005 WIA Average PCI Results Broken Down by Branch Type

Branch Type	Sections Inspected	Weighted Average PCI	Rating
Runway	20	81.53	Very Good
Taxiway	19	67.24	Good
Apron	11	72.22	Very Good

To help put the data from the above figures and tables into perspective the ages of the pavement sections that were inspected must be known. Since the pavement inventory and construction history data have been integrated into the GIS database this information is readily available. With this system many different attributes, such as age and pavement type can be queried and mapped with ease. In this case, age of a particular section is defined as the time since the last major reconstruction or rehabilitation. Figure 4.3 displays the average ages for each section in the WIA network.

After analyzing the data contained in the figure, it becomes clear the taxiways are the oldest segments of the network, with an average branch age of 31.8 years. These taxiways are performing very well with an average PCI of 67.24 which is still in the Good range on the traditional PCI rating scale. The average age of the runways (18-36 and 13-31) is 4.3 years, and they have an average PCI value of 81.53 (it should be noted that a significant portion of Rwy18-36 was not surveyed during 2005 as can be seen in figure 4.1). The Aprons averaged 16.5 years of age and a PCI of 72.22.

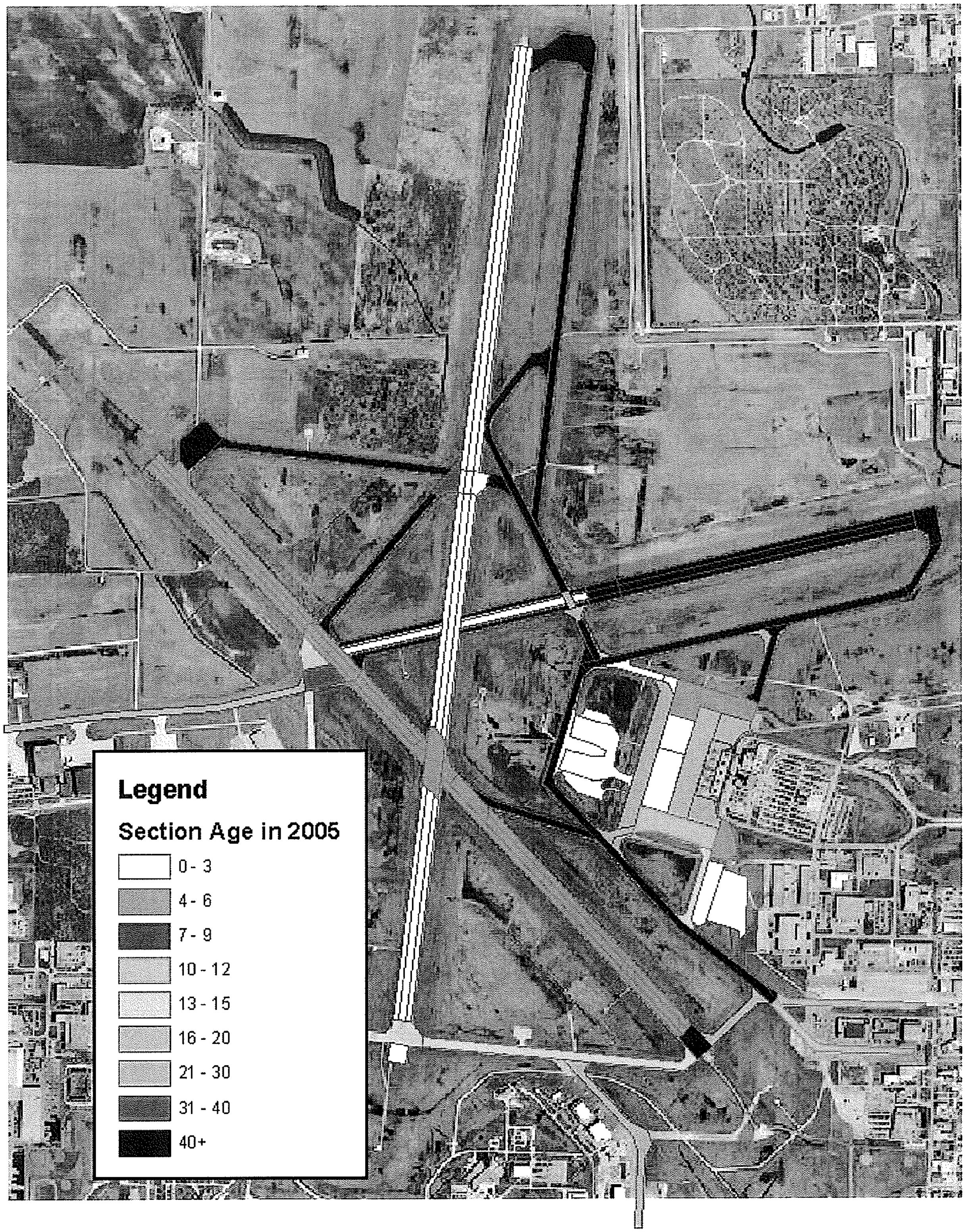


Figure 4.3: Age of Sections Measured from the Last Major Rehabilitation or Reconstruction

The above results follow a logical pavement deterioration trend, meaning the branch type with the oldest average age, had the lowest average condition. But as will be shown in the next chapter, when the results within each branch type are investigated further this is not always the case.

4.1.2 FOD Potential Condition Rating

Foreign object damage (FOD) is a serious problem that requires airport staff to constantly inspect the airfield for debris and foreign objects. Aircraft engines can be seriously damaged by FOD, which poses both an expensive maintenance problem and a serious safety risk if the damage goes unnoticed. As discussed in Chapter 2, pilots often feel distresses that have a potential to cause FOD are the most crucial to repair. Given this, a FOD potential condition rating is determined on the basis of a calculated FOD index, the pavement type, and the aircraft using the pavement (Shahin 04). The FOD index is calculated using the quantities of only certain distresses (10 for AC and 13 for PCC) that have demonstrated a FOD potential.

It needs to be mentioned that the FOD potential condition rating is actually a subjective measure. While the FOD index is calculated, what constitutes a Good score from a Fair score was decided upon by expert opinion based upon the above-mentioned variables (aircraft type and surface type).

From the 2005 PCI inspection data the FOD potential rating for each pavement was calculated. Since different plane options were available, a worst-case scenario was run,

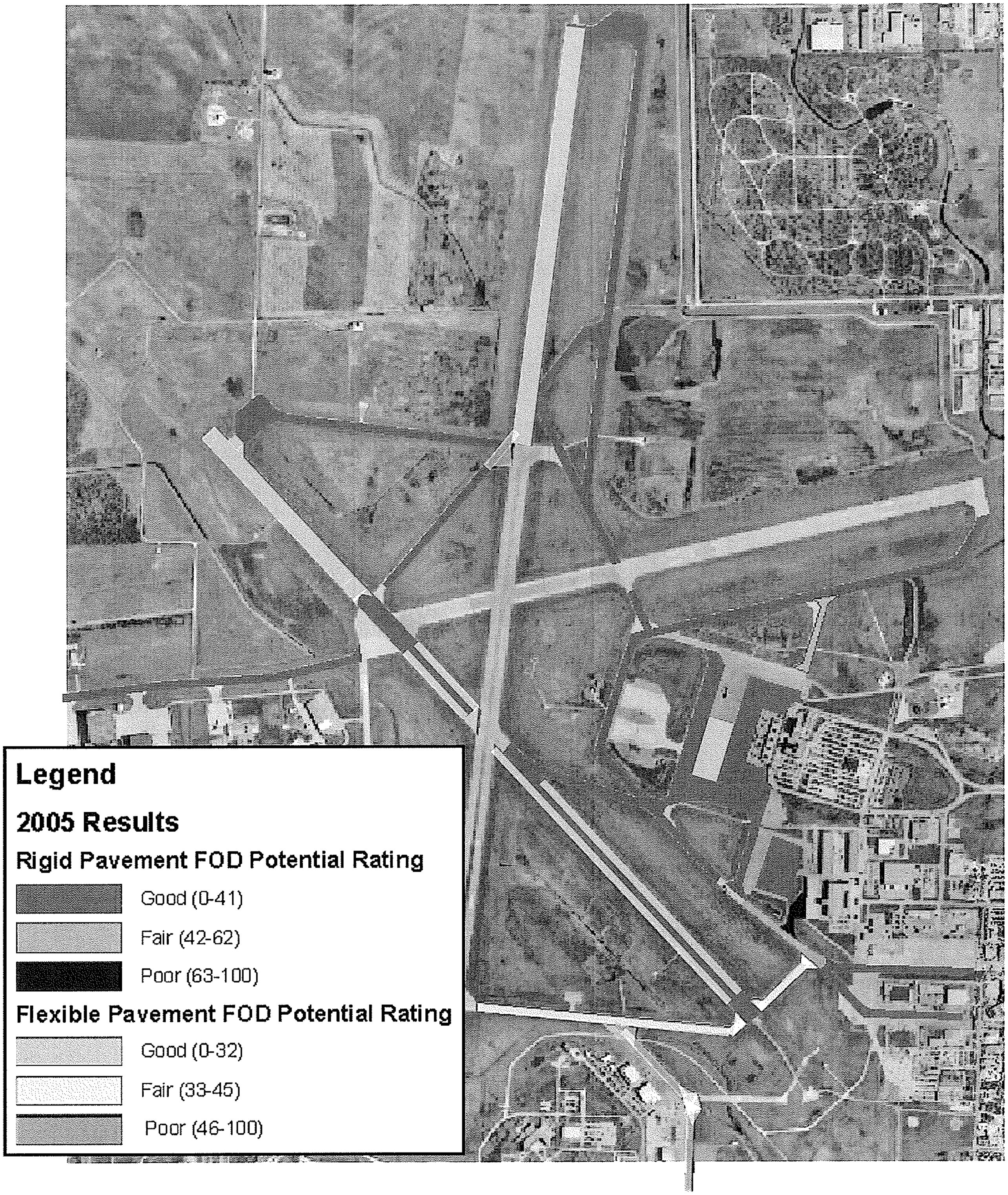


Figure 4.4: FOD Potential Index Calculated from 2005 Condition Inspection Data

4.2 New Methods of Reporting Pavement Condition Data

In the previous section, the standard method utilized by airport agencies across North America for reporting the condition of their pavement was presented. This method does have its advantages. It provides a single number to summarize the pavement condition, allowing for an objective comparison between different pavement sections or even different airports. Clearly this method is effective at providing a general overview of pavement condition; however any information about individual pavement distresses is not conveyed.

As discussed in Chapter 2, researchers have identified some drawbacks and limitations to the PCI procedure. One such drawback is that two pavement sections with the same PCI values can have drastically different distresses. Another limitation is that PCI values are reported for the section and branch levels only, where repairs are generally done on a smaller scale. This is especially true on PCC pavements where repairs are often completed on a slab-by-slab basis.

The time saving benefits of the GPS data collection procedure developed for this project were detailed in Chapter 3. Decreasing the time required to complete the PCI inspections was vital to reducing the impact of PMS implementation on airport operations and streamlining the efficiency of the data collection. Additional benefits of this system can also be realized during the data analysis and reporting stages.

Since all the distress information was recorded using the GPS device, it was easily imported directly into the GIS map. This allows for further analysis of the data that is not possible under the standard system. In order to make informed decisions regarding maintenance and rehabilitation work, the engineer must know the types of distresses present in a given location and their quantities. Viewing each section on the GIS map gives an indication of what distresses are present, their severity and quantity all at once.

Presented below is an example analysis that was conducted using the data from the WIA data. A figure of the distresses observed in the section along with the summary statistics about the distresses is included. This analysis can be used for distresses on both AC and PCC pavements. As can be seen from Table 4.3 the most common distress recorded in this particular section of Taxiway C was longitudinal/transverse cracking. Of the other distresses present, the oil spills were seen to be small (mean area of less than 0.5m), the patching is new and in good shape as it was placed during the summer of 2005 to ramp up to a new holding bay that was constructed (not seen on the air photo) and the weathering/ravelling is of some concern, but is still low in severity. Further analysis of the cracking reveals that shorter medium severity cracks are the most prevalent distress in the section as can be seen in Figure 4.6. The traditional analysis generated in MicroPAVER for this same section is included in Appendix D. A comparison of the two analysis techniques clearly indicates the expanded capabilities and usefulness of the new techniques presented in this chapter.

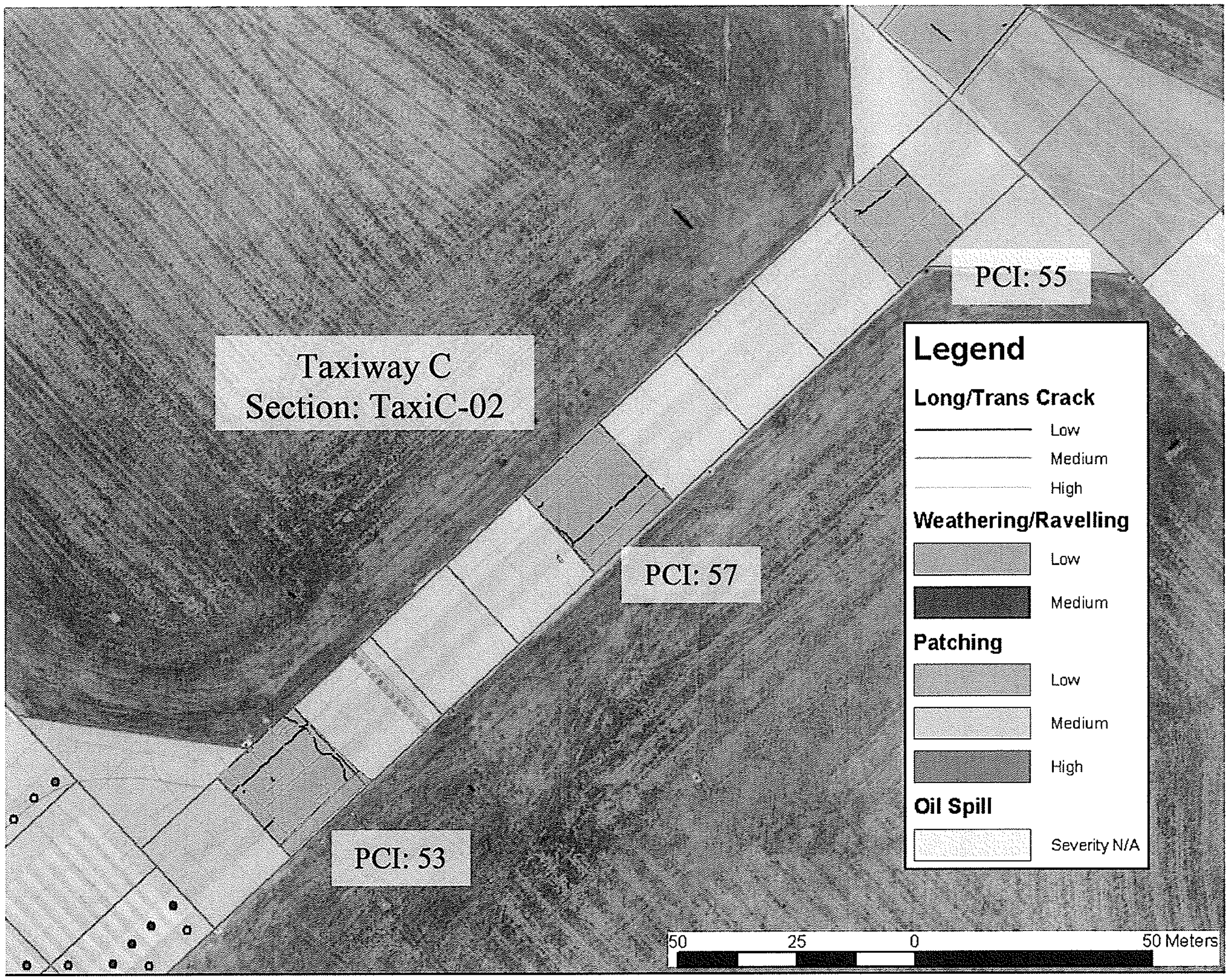


Figure 4.5: Example GIS Distress Analysis using Taxiway C Distress Data

Table 4.3: Distresses Observed in Example GIS Distress Analysis using Taxiway C Data

Distress Type	Times Observed
Long/Trans Cracking	46
Weathering/Raveling	3
Patching	3
Oil Spill	3

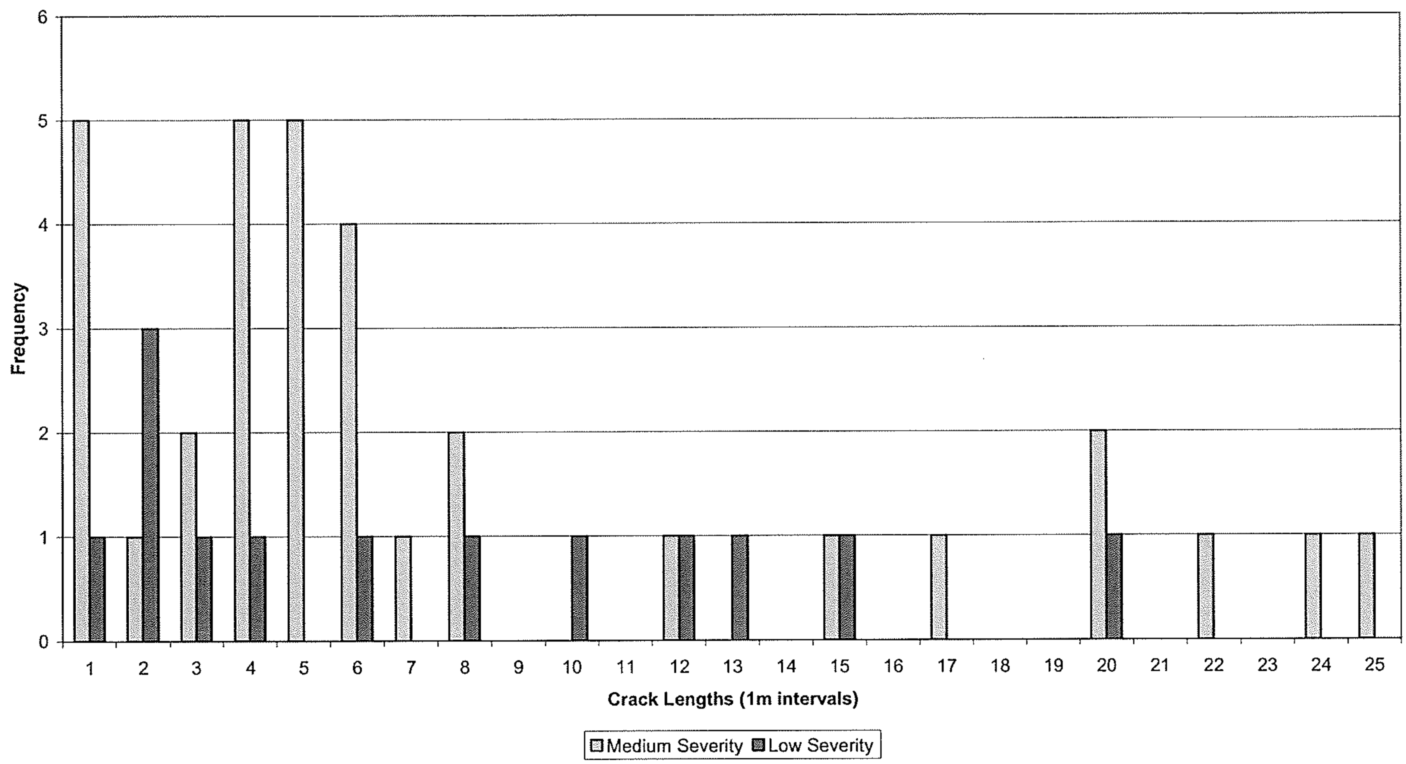


Figure 4.6: Histogram of Longitudinal and Transverse Cracking on Taxi C from Example GIS Distress Analysis

The analysis presented here can easily be completed for each section of the airfield as part of a network level analysis. If a project level analysis is required, completing the inspection surveys with this system will provide the most comprehensive method of displaying, storing, and analyzing the results. The geo-referenced inspections allow for a better understanding of the distresses present making the selection of appropriate remedial action simpler.

Using the GIS distress analysis, it is also easy to address another one of the limitations raised regarding the PCI. Under the standard system, the engineer has no way of identifying sealed cracks vs. unsealed cracks. This is due to the fact the definitions specified in the ASTM standard, allow both unsealed cracks (depending on width) and sealed cracks (depending on condition of sealant) to be rated identically. This problem was overcome by creating another sub-field in the GPS data dictionary for cracks that indicates, "sealed" or "unsealed." This information is then useful for both a PCI analysis and determining quantities for issuing repair contracts. This additional feature does not alter the manner in which cracks are evaluated for severity or type, but simply adds an additional check box, allowing the inspector to identify if the crack is sealed. Back in the office, this information is still inputted into MicroPAVER for traditional PCI analysis.

Further analysis is then completed on the data in the GIS software. By running the same types of queries that were run to create the information in Figures 4.5 and 4.6, the average quantity of unsealed cracks per sample unit is determined. Multiplying this number by the number of sample units in the section will yield an estimate for the engineer to issue a crack sealing tender. For a detailed project level analysis, every sample unit in the section could be surveyed with the GPS equipment providing an accurate account of the distresses present.

Another possible output of this new system is the density of different distresses throughout the airfield. This analysis is similar to the "black spot" analysis commonly used by road safety professionals looking for the most frequent accident locations. The output from this exercise is particularly useful to the airfield engineer when looking for locations most in need of repair. In the output of this analysis the larger and more intense the circles appear, the more frequent the chosen distress is at that location. Figure 4.7 was created to illustrate this point. It contains the results of an analysis that was run to determine where corner breaks are most prevalent on the airfield. This type of distress is important as loose corner pieces of PCC slabs pose a FOD potential and should be repaired as soon as possible.

This analysis can bring to light problem areas on the airfield that might have gone unnoticed with standard analysis methods. For example, upon examination of Figure 4.7 it can be seen that most of the corner break occurrences take place at locations of turning movements and intersecting traffic. These load related distresses are likely due to these areas experiencing the slow moving intersection traffic from two taxiways. These taxiways have each been classified as 1 section during the network classification stage. Since the remainder of each taxiway is relatively free of distress the overall PCI score for each section is still in the good category. Using traditional analysis would allow the areas in need of repair to remain undetected. In this case, using the density analysis shows that there is in fact an area that requires remedial action. Clearly the benefit of this type of analysis is the ability to assess the PCI inspection results on a sample unit by sample unit basis. In the example included in Figure 4.7, the density analysis would alert the engineer to the fact that a new section should be created to account for the increased traffic in the crossover area.

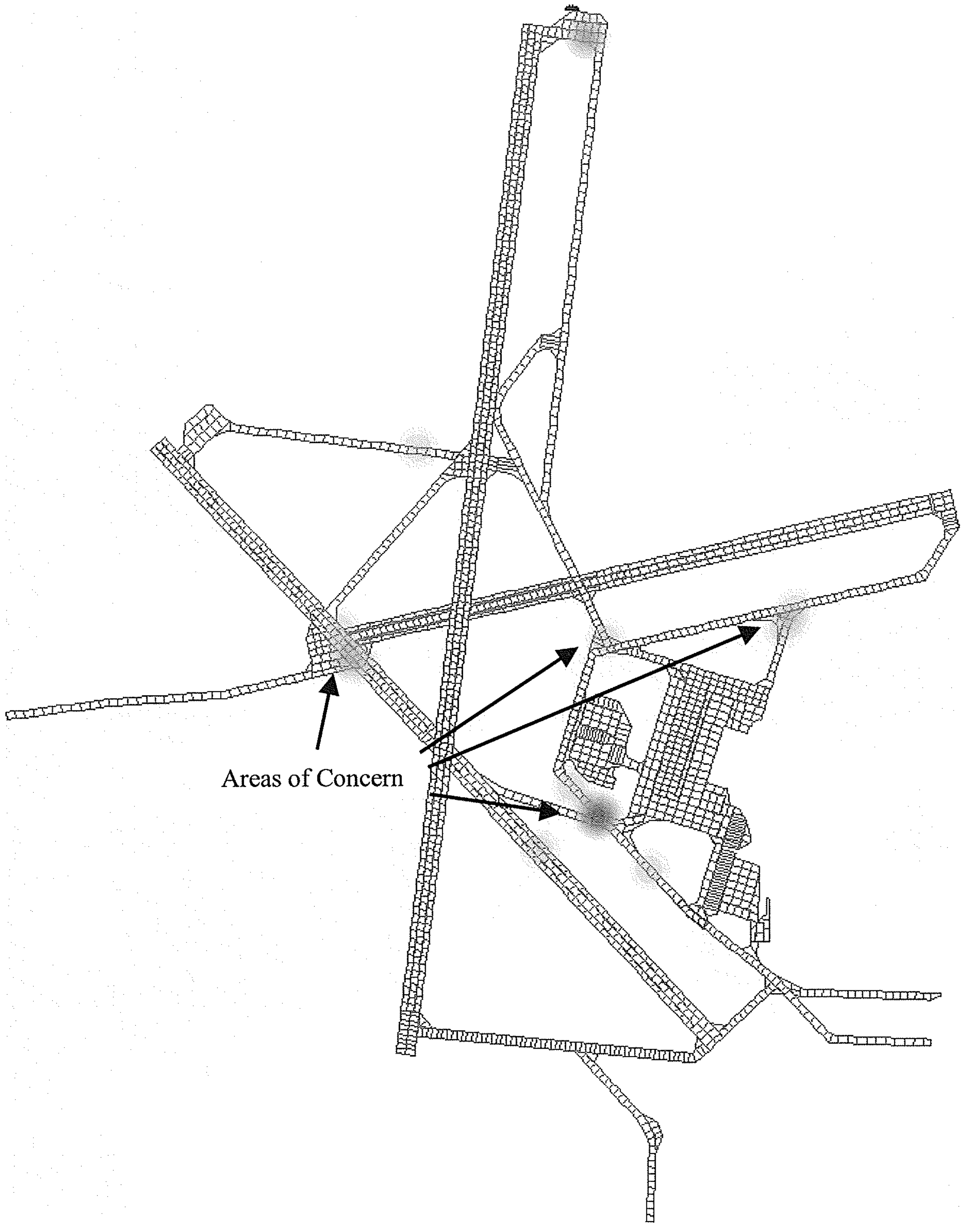


Figure 4.7: Corner Break Density Analysis using 2005 Condition Data

It is common practice to review the raw data from PCI inspections upon returning to the office for obvious errors or anomalies. This process can also be improved with the new system. By loading the day's PCI inspection results on the GIS map, erroneous data can be spotted much easier. If the engineer suspects that data was recorded incorrectly (wrong severity or type) the particular distress in question can be loaded back onto the GPS unit and can be relocated in the field very easily. Using this system allows the engineer to have a much higher degree of confidence in the data collected, as distresses such as an individual crack could be investigated. This also allows for audits to be conducted on inspection teams, or comparisons between teams to check the consistency of their data collection.

4.3 Summary

Results of the 2005 pavement condition index inspections have been presented in this chapter. Both a standard analysis, used by nearly all agencies employing a PCI based inspection system, and an advanced analysis using the spatial analysis tools available in GIS software were included. Using the standard analysis techniques, both runways and aprons received an average PCI score of Very Good, the taxiways received an average score of Good.

Having the ability to store geo-referenced distress information allows for a more detailed analysis than was previously possible. The new types of data analysis possible, such as density analysis for individual distresses and detailed visual and statistical reporting of distresses found in a given pavement section have been presented in Chapter 4.

Managing and interpreting distress information at this level of detail without the visual capabilities of the GIS environment would be nearly impossible. Combining the GIS system with GPS aided data collection system detailed in Chapter 3 further expands the possibilities of the system beyond what is currently standard practice.

Chapter 5

PAVEMENT DETERIORATION MODELLING

The prediction of future pavement condition is an important function of an APMS that aids in the planning of maintenance and rehabilitation activities. To do so, past pavement performance must be collected and studied, allowing deterioration models to be developed. This chapter focuses on developing pavement deterioration models for the Winnipeg International Airport using the family modelling technique described in Chapter 2. Of all the modelling techniques presented in Chapter 2 the family modelling technique represent the most widely used method amongst the airfield community. An investigation into the applicability of using one of the other advanced techniques presented, such as neural networks to model the performance of the WIA pavement is also included. Finally, existing models created for other airfield pavements are compared against the Winnipeg data to demonstrate the importance of creating site-specific localized models.

5.1 WIA Pavement Performance Models

As described in Chapter 3 a requirement of the network classification stage was to create pavement sections that were homogeneous in terms of pavement type, traffic patterns, and functional class. As a result of this, the creation of deterioration models is now possible by grouping inspection results from similar use and/or surface type sections together to form 'families' of sections that have consistent structure and loading conditions.

There are many benefits to using the family modelling technique. Families allow for the identifying of trends in a statistically representative group of sections. By clustering the several sections together the trends are more pronounced and easier to interpret. The use of families also allows for models to be created without waiting for several years' worth of inspection data for each pavement section. Deterioration models can be created from families as generic as 'PCC pavements' which would cover all PCC pavement in the airfield or as specific as 'composite runway centreline pavements' which would be a model comprised solely of composite (AC over PCC) pavements in the middle 23m of the runways. The limiting factor is the amount and quality of available data. A model could be created with as little as two points; this however would not provide a reliable basis for predicting future performance. For this analysis, only families that contained a minimum of 5 points were modelled.

Using the 2005 average section PCI data, several possible models were investigated and six were created. The name of each model created along with the number of pavement sections in the particular family is presented below. Absent from the list below are composite-apron, composite-taxiway, and any asphalt pavement (non-overlay) models as these families did not have the minimum 5 data points.

- PCC pavements (32 sections available)
- Composite pavements (AC overlay) (17 sections available)
- PCC-Taxiway (16 sections available)
- Composite-Runway (13 sections available)
- PCC-Apron (9 sections available)

- PCC-Runway (7 sections available)

Of the 6 models developed, only 4 are presented and discussed in this chapter, the remaining 2 are included in Appendix E but will not be discussed in depth. The reason the runway models (PCC-runway & Composite-runway) have been excluded from this chapter is not lack of available data, but rather lack of spread in the data. Both runways at the WIA have been completely reconstructed within the last 5 years, leading all the collected data for these sections to be located at only 2 points on the AGE (x) axis. It becomes difficult to make deterioration predictions about a family with such little separation in the data.

Each family described above is used to create a deterioration curve, which uses the available historical condition data to develop a mathematical model of pavement condition over time. Figures 5.1-5.4 contain the deterioration curves that were produced for four of the families listed above. The curves are models of PCI vs. AGE, where age is defined as time since the section received major work (ie, new construction or overlay). In each of the figures, the data points represent the observed PCI values while the line represents the model fitted to these points. The equation of each model as well as the R^2 value is provided.

Each of the models was created using Polynomial Least Squares Regression. This has become the standard method used for creating airfield pavement deterioration models and has been described as "one of the most powerful techniques for predicting the change in a variable Y (i.e. PCI) as a function of one variable X (i.e. age)" (Shahin 94). The basis of this technique is the fitting of a polynomial of degree n to the data such that the sum of the squared errors (difference between each individual observed value and corresponding model value) is minimum. Before the modelling is commenced, the value of n is not known, so several values are tested to find the optimum.

To ensure the models created using the Least Squares technique accurately represent experiences seen in the field, they must be constrained. Figure 2.3 in Chapter 2 shows the difference between an unconstrained and a constrained model. Although the unconstrained model will produce a lower error value, it cannot be used to model PCI vs. Age. During creation of these models, two constraints were applied. First the slope of the models must always be negative or 0. This means that the PCI value is always predicted to remain constant or decrease with age as we are assuming that without work the PCI of a pavement section can not increase. Secondly was that at year 0 the models must have a PCI of 100. This assumes that new pavements are constructed free of surface defects and would therefore receive a score of 100. This modified technique is referred to as Polynomial Constrained Least Squares Regression.

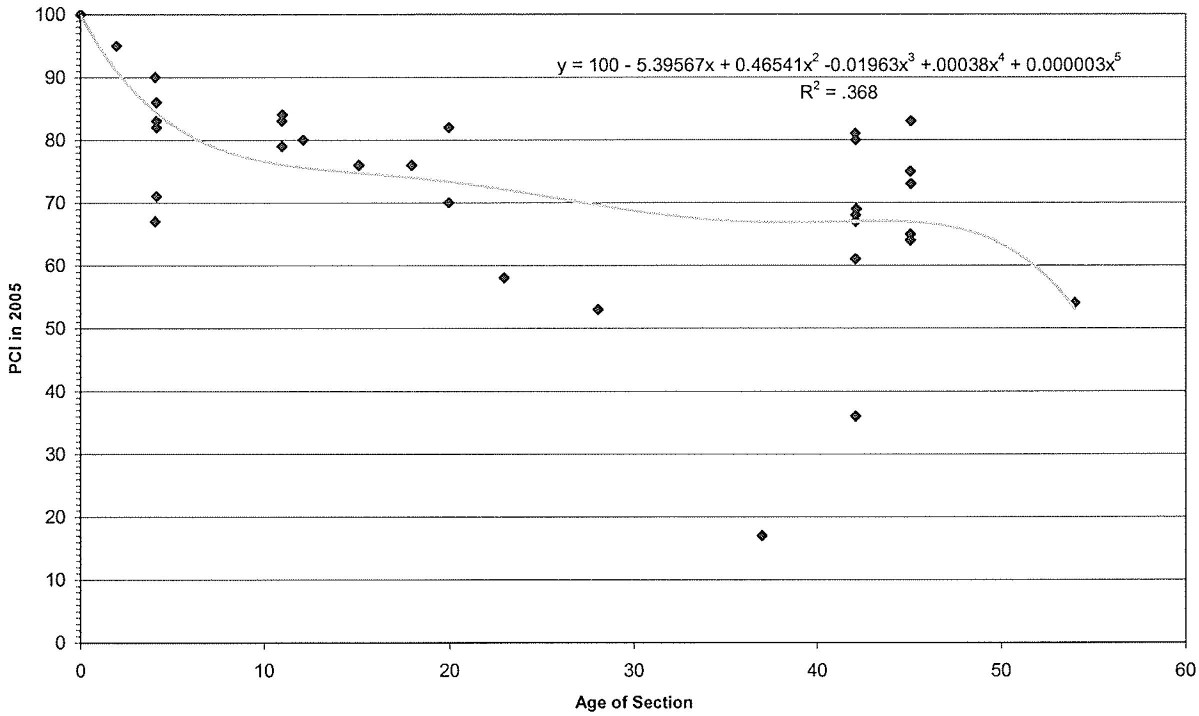


Figure 5.1: PCC Pavement Deterioration Curve

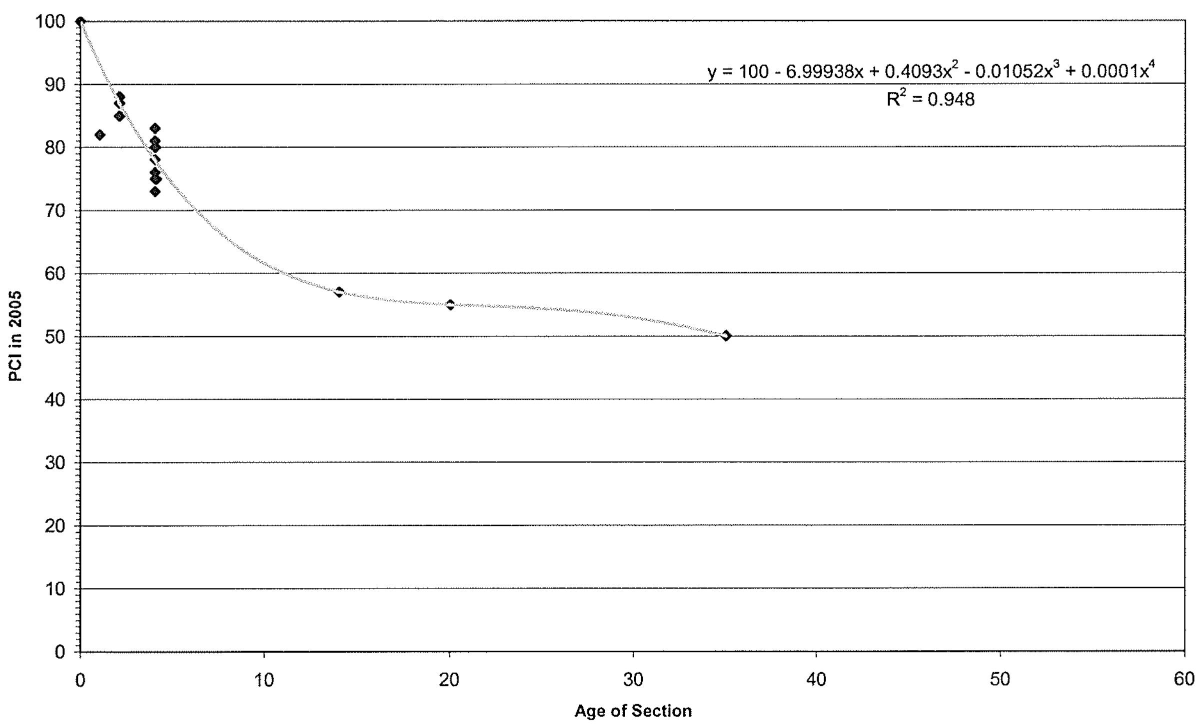


Figure 5.2: Composite Pavement Deterioration Curve

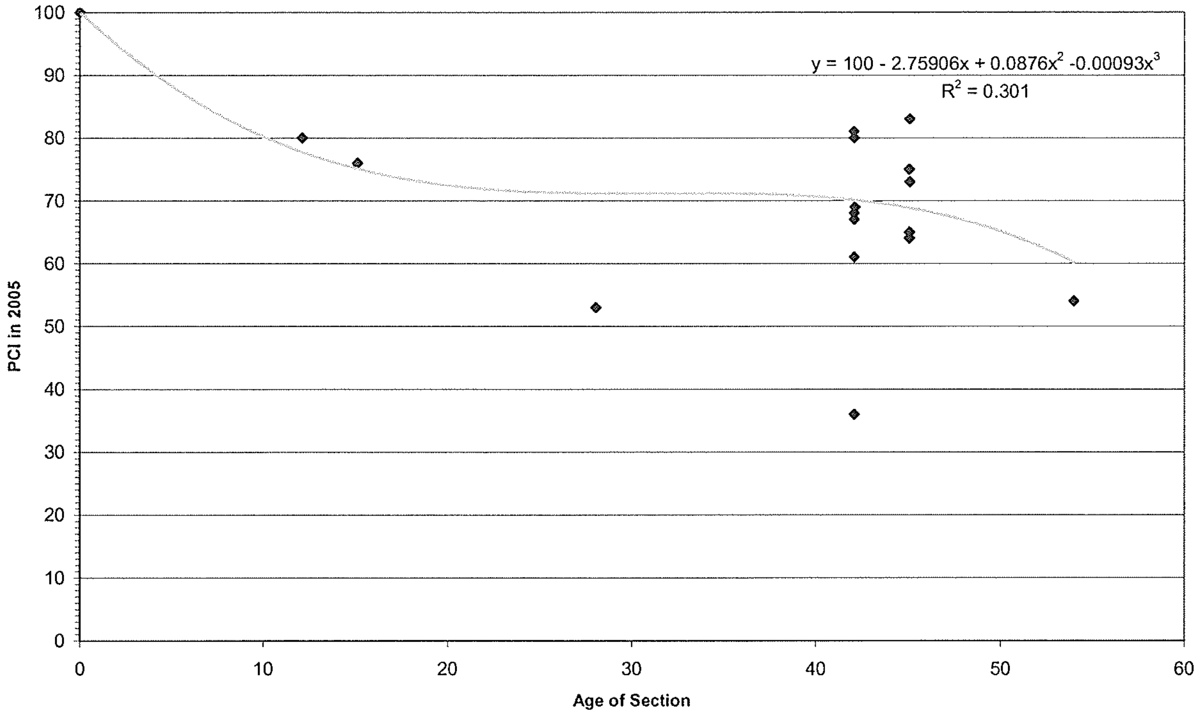


Figure 5.3: PCC Taxiway Pavements Deterioration Curve

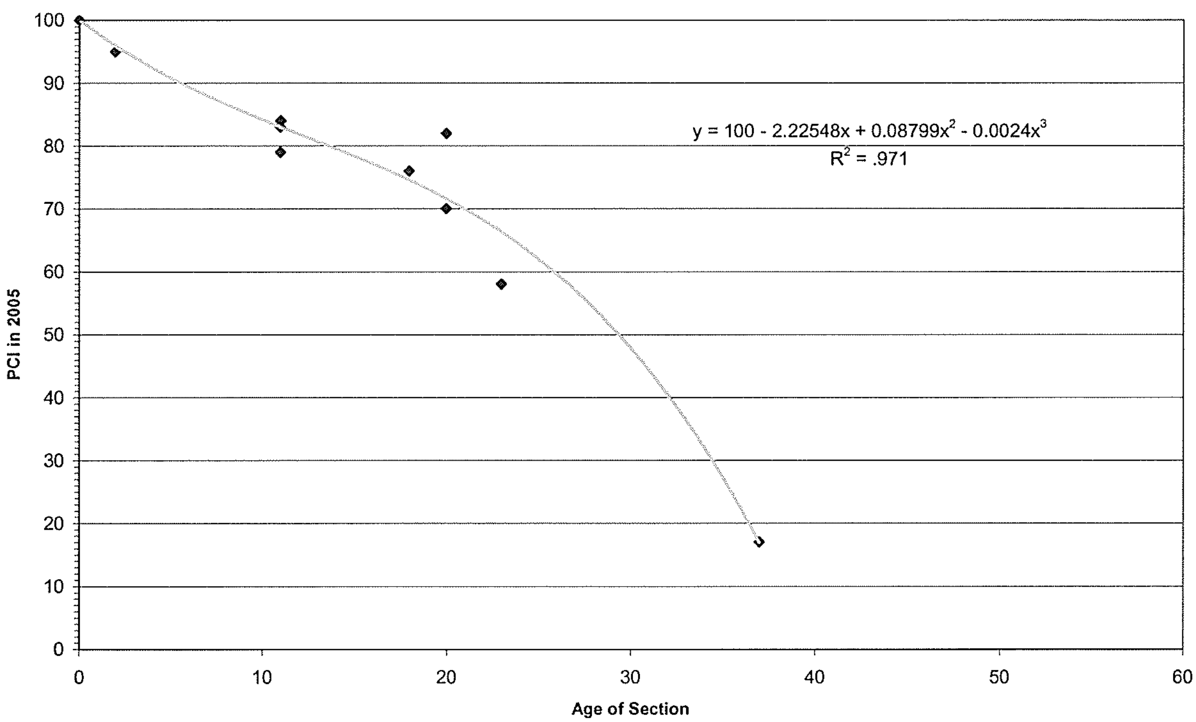


Figure 5.4: PCC Apron Pavement Deterioration Curve

The first two models presented are broad in scope and provide an indication of how a certain type of pavement (PCC or APC in this case) has performed on the Winnipeg airfield regardless of functional use. Analyzing pavement performance on such a level is useful for discovering general trends (PCC lasts longer than AC for example), but may not accurately reflect the performance of all the pavement of that type due to differences in use. The next two models presented are for the same surface type (PCC) but contain pavements that are used differently (Taxiway or Apron). Classifying families in this manner enhances the pavement performance models as another variable (Use) has been removed from the equation.

Included in each of the figures is the R^2 value, which indicated how well the model was able to predict the PCI values. Two of the models, Composite Pavements and PCC Apron pavements had values above 0.9 indicating a very good fit (1.0 being the maximum possible value).

Figures 5.1 and 5.3 show that there are several pavement sections that are performing well after nearly 40 years of service. Sections over 40 years of age were observed to have PCI values above 60 and in a few cases above 80. These results are leading to a large spread in PCI values for older pavements causing the R^2 values for the models to be quite low (0.368 and 0.301). Some possible explanations for this phenomenon exist, including differences in quality of materials available at time of construction (aggregate and cement), construction techniques, or subgrade conditions, however none of these have been verified. Further research beyond the scope of this thesis, will require extracting cores in these sections to examine the pavement structure and underlying subgrade, providing an indication as to why pavement from the 1960s is receiving higher PCI scores than 1980s pavements.

Due to the relative increased performance of these particular pavement sections, the deterioration models that contain these sections will not accurately predict the performance of other PCC pavement sections. To solve this problem, a 'modified' PCC pavement model was created in which the group of older PCC pavements has been excluded and is included in Figure 5.5. The objective is to model the performance of the majority of pavements and this group is relatively small. Excluding these sections is therefore acceptable. The R^2 value for this model was 0.861 indicating the model is more capable of predicting the PCI values in this case.

Family modelling is the most widely used method of predicting airfield pavement performance and has been incorporated into the most utilized software package MicroPAVER. The technique has many advantages, it has been common for well over 15 years, and is relatively easy to implement. However, many variables contribute to pavements deterioration, and it can be argued that modelling performance vs. age does not take into account all possible variables.

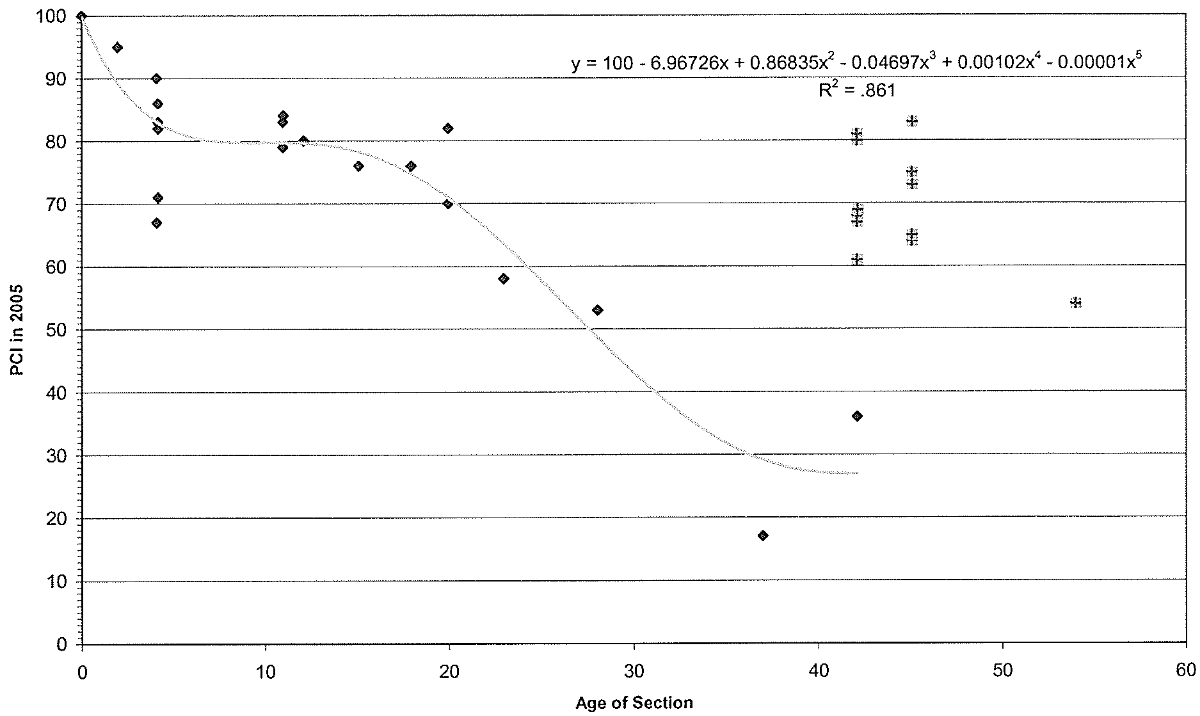


Figure 5.5: Modified PCC Pavements Deterioration Curve

5.2 Neural Network Modelling

In the previous section, models were created using a widely accepted method for predicting a dependent variable due to changes in a single independent variable. In reality, many variables affect the performance of an airfield pavement and the relationship between these variables and pavement performance is complex and unknown. To overcome these limitations, the use of an advanced modelling technique will be investigated in this section. Artificial Neural Networks (ANN) and their applicability to pavement deterioration modelling will be studied. A brief introduction to the concept of neural networks and how they function was included in Chapter 2.

While the focus of this chapter is pavement deterioration modelling, ANNs have been employed in a variety of other uses. Medical diagnosis, handwriting recognition, and fault detection in machinery are a few examples of the many uses for ANN. Within transportation engineering, the uses for neural networks also vary widely, including the prediction of household vehicle choice, planning of maintenance and rehabilitation works, and crack propagation models (Reggin 04, Yang 03).

5.2.1 Neural Network Architecture

Creation of the neural network architecture for each specific problem is a time consuming and complex undertaking. The determination of the input and output variables, along with the number of hidden layers, and the number of hidden neurons in each hidden layer all require a great deal of time and effort and must be determined for each new ANN. Research has shown that while any number of hidden layers could be used, networks with only 1 are employed most often due to significant increases in computation time that follows the selection of additional hidden layers (Yang 03). Both neural networks created as part of this study use only 1 hidden layer based on this finding.

A feed-forward back-propagation algorithm was employed in this research. This type of network was chosen after studying the many possibilities available in the Neural Network Toolbox in Matlab. A feed-forward back-propagation neural network works by first supplying the given input values (training set) into the network; this generates output values which can be compared against the desired output values. There is an error associated with each estimated output value, and these errors are fed back into the network to adjust the weights and biases in the neural network. The network stops the cycle when the output errors fall below some predetermined level or when the number of attempts reaches the set limit.

Back-propagation neural networks are identified as being most suitable for function approximation and determining linear and non-linear relationships between input and output variables (Matlab NN Toolbox User Guide). Another option available when designing a neural network is what transfer functions each layer in the ANN will employ. Three types of functions are available in the Matlab neural network toolbox, "logsig", "tansig" and "purelin". This work utilized "tansig" and "purelin" functions in the hidden layer and output layer, respectively. The "purelin" function was used in the output layer because the output values (PCI values) were outside the range of -1 to 1, something that the other functions could not provide (Matlab NN Toolbox User Guide). The "tansig" function was used in the hidden layer because it provides better function approximation. Finally, the training function that the ANN would employ had to be selected. The 'trainlm' function was chosen as it the fastest algorithm for function approximation of moderately sized networks (Matlab NN Toolbox User Guide).

Every time the training of neural network is commenced, the initial weights and biases are randomly set, which can lead to the prediction of different output values. To overcome this problem, each network configuration was trained 100 times, with 500 epochs each. Past research has shown that these values are sufficient at producing stable ANN with the lowest error values (Reggin 04). Only the weights and biases that produced the lowest error values were retained. Appendix F contains a sample of the

Matlab code that was used for the training of the PCC network to show how this was accomplished.

Prior to the commencement of the modelling, the original data set (input and outputs) was randomly sorted and split into a training set (75%) and a testing set (25%). This represents the first change from the traditional Constrained Least Squares Regression, which used all of the available data to build the model.

To facilitate the creation of the testing and training data sets, it was decided to try the neural network modelling with PCI data at the sample unit level instead of using average section PCI values like the Family modelling technique. It was hypothesised that modelling the actual observed PCI values would yield more accurate results than modelling with average section PCI values. The new data collection system designed as part of this research, as described in Chapter 4, allows for sample unit level data to be utilized with no additional work required.

The main benefit of modelling with sample unit PCI data is that many more data points are available (167 for Composite and 145 PCC). As mentioned in Chapter 2, if a small data set is used, it is likely the neural network will simply memorize the data set and not be useful for any values outside the ones used to create it. This is why both a training set and a testing set must be used for the successful creation of an ANN.

Additional input variables could also now be included in the modelling, as neural network modelling is not restricted to only 1 input variable like the previous regression models. Surface thickness, base thickness, and use (runway, taxiway, apron) are among the possibilities considered for the ANN models.

After each modelling stage (both training and testing) an error is calculated (mean square error), and it is important that both of these errors are minimized. The particular network architecture that leads to the minimum testing error is the most useful for working with values outside the original.

5.2.2 Neural Network Models for WIA Pavements

Two neural network models were created using the 2005 PCI data; one each for Composite and PCC surfaced pavements. The basic architecture (algorithms and learning functions) of each model was chosen during the process described in the last section, leaving two remaining factors to be decided; which input variables would be included, and how many neurons would be in the hidden layer. Since both of these factors have an effect on the ability of the model to predict the PCI value of a given sample unit, several scenarios were run with different combinations of variables and neurons.

Deciding which input variables to include was completed through the training of several neural networks with different combinations of variables. It was discovered that models trained with Age, Surface Thickness, and 3 Use variables (one each for runway, taxiway, and apron) as the inputs returned the lowest error values. Age and Surface Thickness were created as continuous variables measured in years and mm respectively. The Use variables are not continuous and can only take on the values of 0 or 1 depending on the use of each pavement section. Including these Use variables in the modelling allowed for all pavements of a given surface type to be modelled together.

Neural networks were then trained using these input variables with many different numbers of hidden neurons to determine the optimum number. Figures 5.6 and 5.7 contain both the training error and testing error for a variety of hidden neuron values. For PCC pavements the optimum was a network with 6 hidden neurons and for Composite pavements it was discovered that after 3 hidden neurons the error remained constant and did not change with increasing the number of neurons.

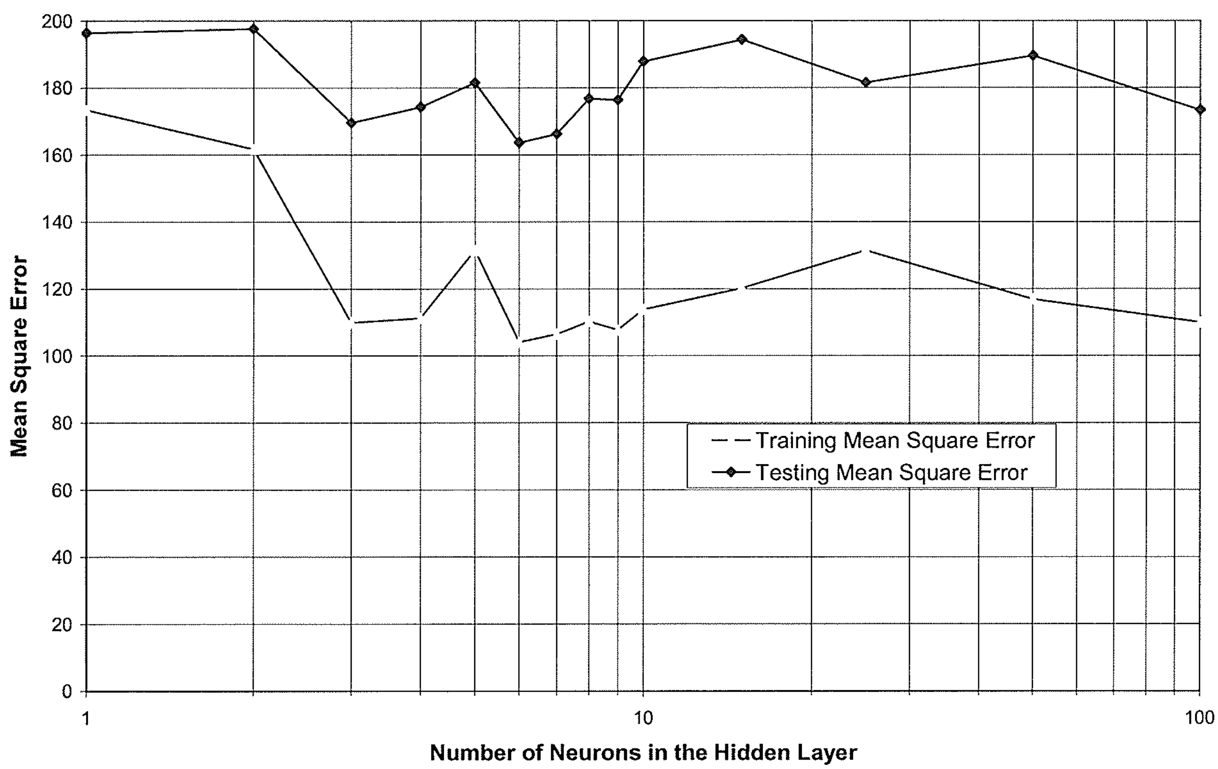


Figure 5.6: Training and Testing Errors from Concrete Pavement ANN

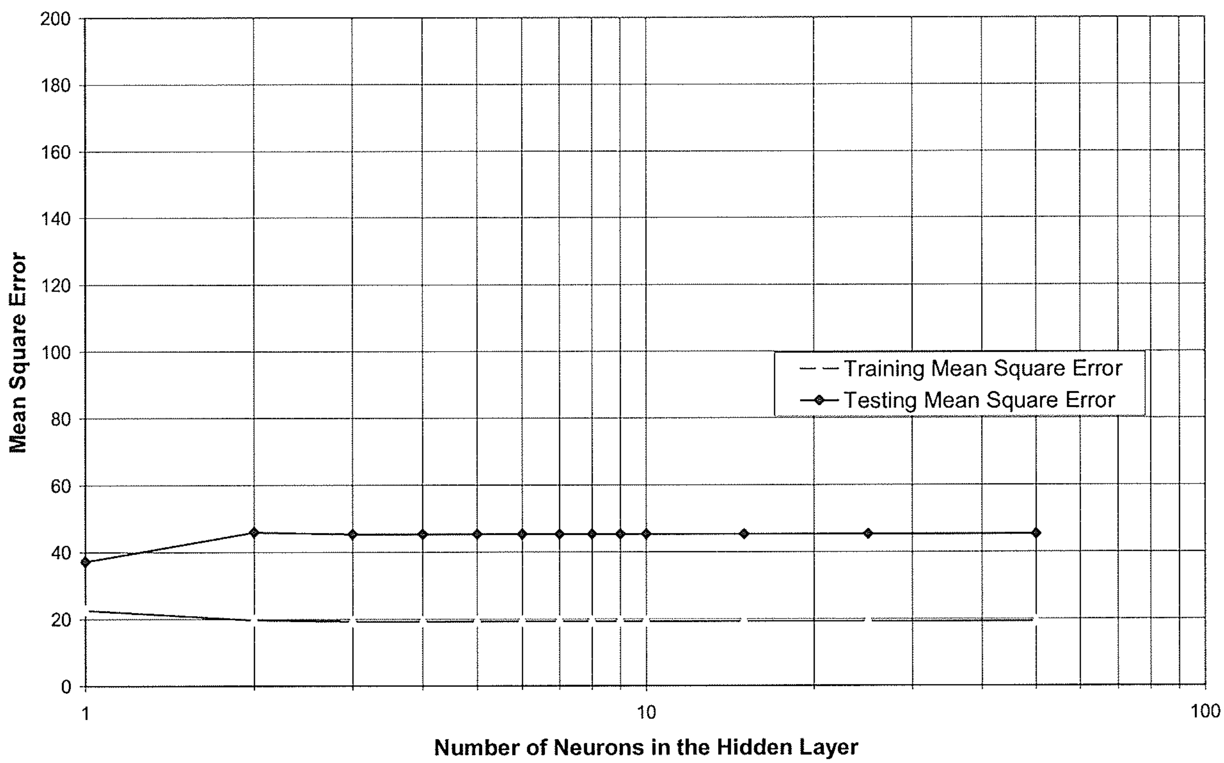


Figure 5.7: Training and Testing Errors from Composite Pavement ANN

Many training runs were conducted on the Composite pavement data to determine what was causing the error values to remain constant. Changing the training algorithms and transfer functions had no appreciable effect on the results; leading to the conclusion the data set was responsible for the results. Although the Composite data set had 167 data points, they are spread over only 6 values on the X- axis (See Figure 5.13). This lack of spread in the data limits the ability of the neural network to learn the relationship between the variables beyond the plateau we see after 3 hidden neurons.

Figures 5.8 & 5.9 contain a graphical representation of the network architectures that were selected based on the training and testing results.

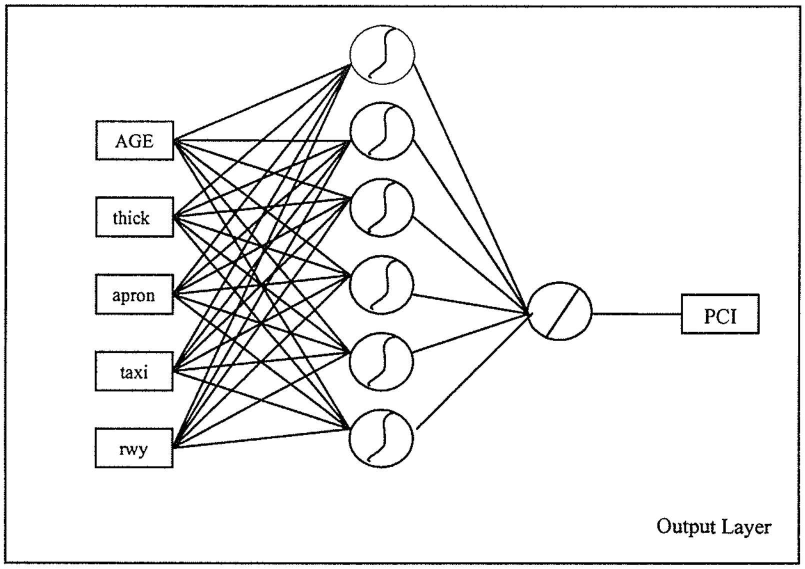


Figure 5.8: PCC Pavement Neural Network Architecture (5 Inputs, 6 Hidden Neurons, 1 Output)

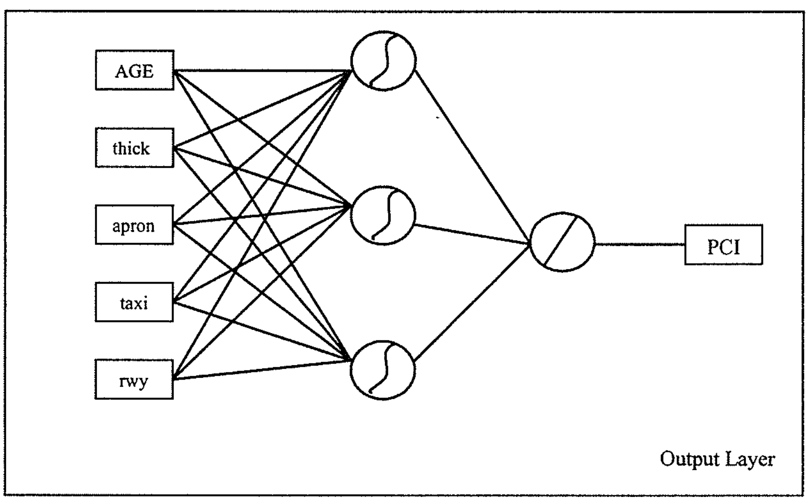


Figure 5.9: Composite Pavement Neural Network Architecture (5 Inputs, 3 Hidden Neurons, 1 Output)

5.2.3 Neural Network Results

Upon completion of the training and testing phases a network simulation was run. This process passes the entire data set through the newly trained neural network. From this simulation two measures of how successful the network was at predicting PCI values, the Mean Squared Error and Coefficient of Correlation (R-value) are obtained. Figures 5.10 and 5.11 contain plots comparing the observed to the predicted PCI values.

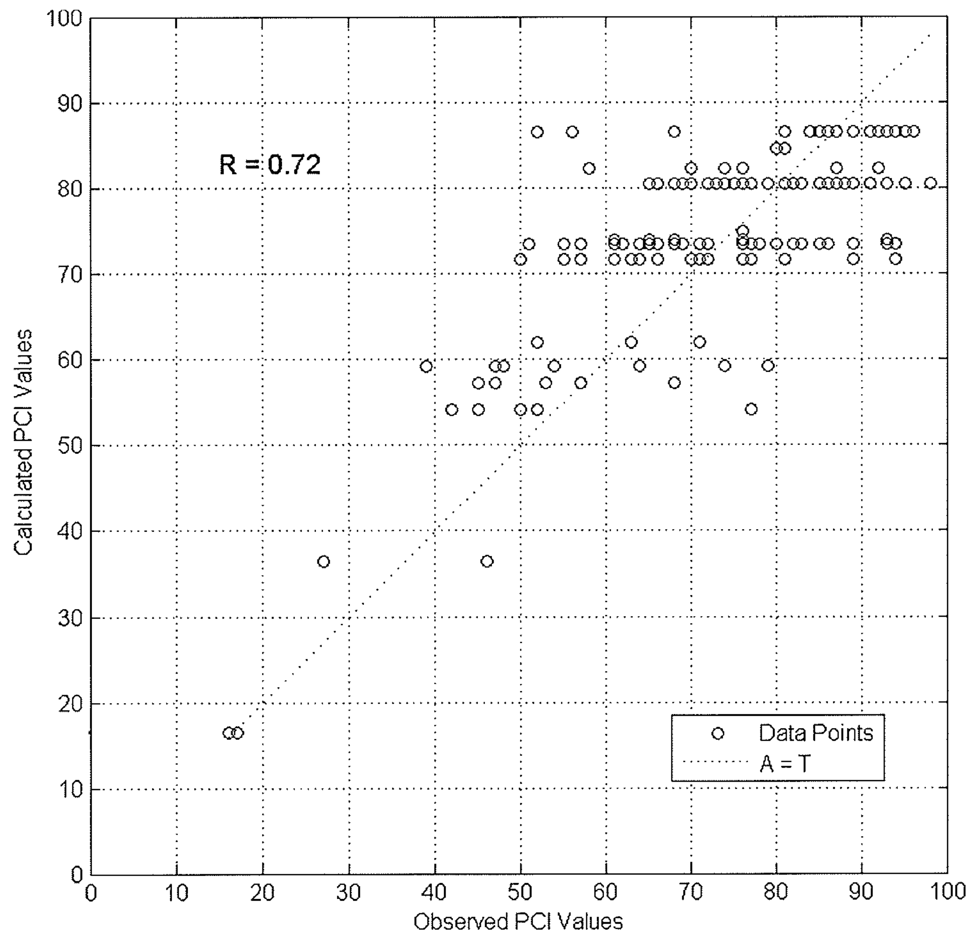


Figure 5.10: Observed vs. Neural Network Calculated PCI Values for PCC Pavement

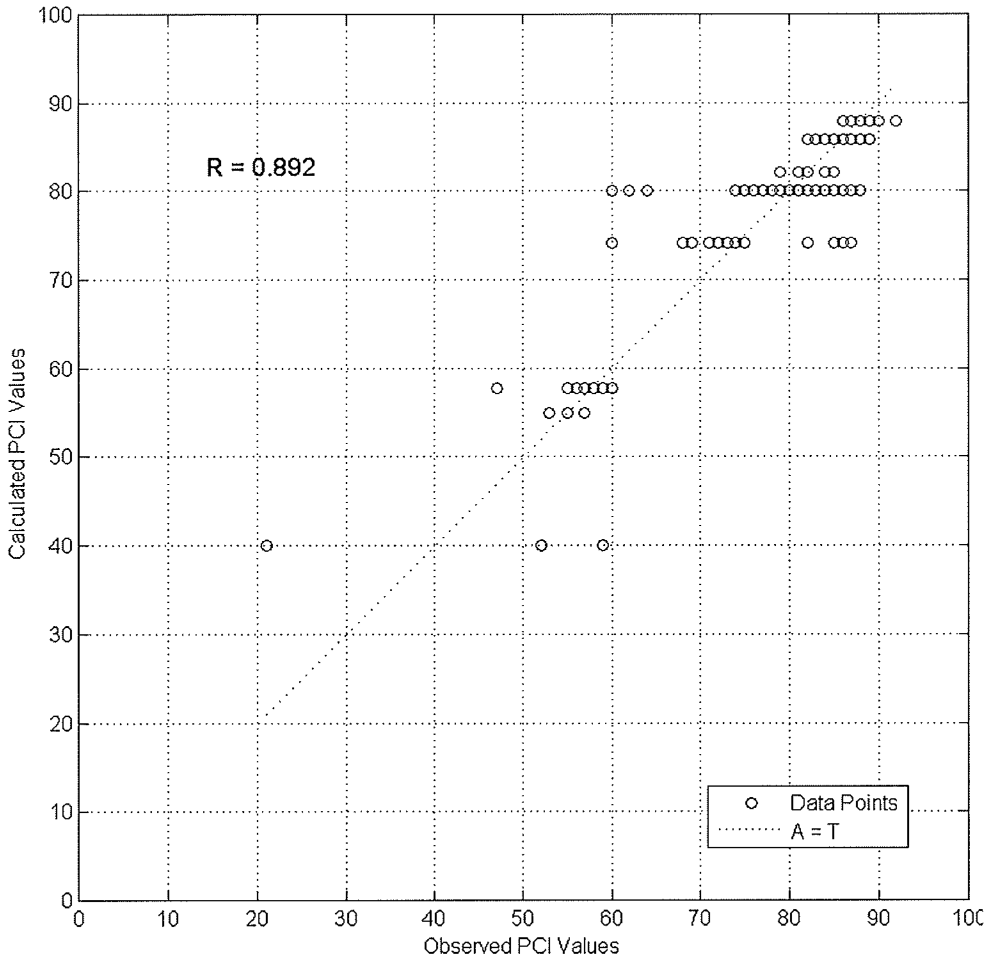


Figure 5.11: Observed vs. Neural Network Calculated PCI Values for Composite Pavement

The closer the data points are to the line of equality (A=T dashed line), the better the model was at predicting the PCI value. A data point exactly on the A=T line represents a predicted value exactly matching the corresponding field observed value. Greater spread can be seen in Figure 5.10 compared to the Figure 5.11. In some instances the spread for a given calculated PCI value can be as much as 40 on the Observed PCI axis. Table 5.1 contains both R-values obtained from the above figures and the MSE values of the models.

TABLE 5.1: Neural Network Modelling Evaluation Results

Model	R-value	R^2 Value	MSE
PCC	0.72	0.5184	123.74
Composite	0.892	0.7957	25.815

Table 5.1, together with Figures 5.10 and 5.11 provide insight into the ability of the neural network models to predict the PCI values for both pavement types. The Composite pavement neural network had both a higher R-value and lower MSE value. A higher R-value indicates the model predicts PCI values closer to the observed PCI ones. An R-value (or R^2 value) of 1 would correspond to a model that had all its data points along the A=T line (line of equality) in Figures 5.10 and 5.11. Mean Square Error (MSE) is the mean of each error valued squared, so taking the square root of this value yields the absolute mean PCI error value. For composite pavements this works out to 5.08 compared to 11.12 for PCC pavements. Indicating the composite neural network was better able to predict PCI values. Since PCI is based on a 100-point scale, we can see that the errors are approximately 5% and 11%, both acceptable error values. These values are acceptable because on the standard PCI rating scale (Table 4.1) the range for each rating is 15

Before the results of the neural network modelling could be compared to Polynomial Least Squares Regression modelling, new regression models had to be developed using the sample unit level PCI data. This was done to allow for comparison between the two types of models. When these new regression models were created, all 145 PCC and 167

Composite data points were included in their respective models. Figures 5.12 & 5.13 contain the new regression models that were created.

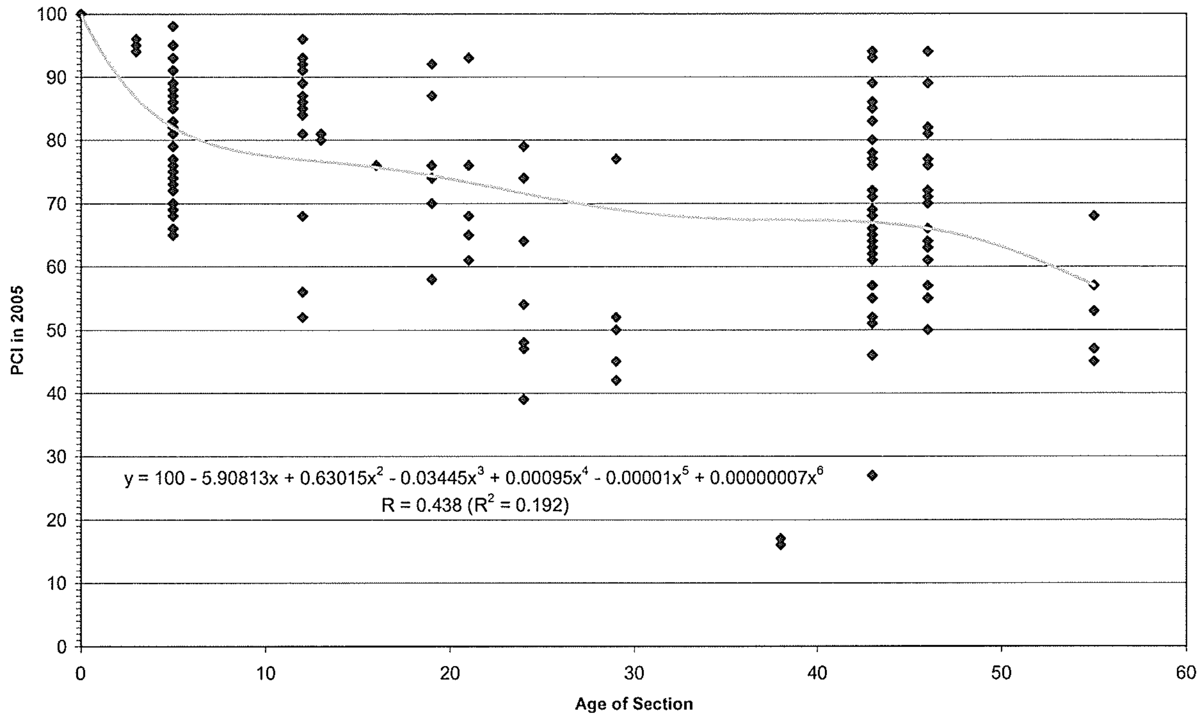


Figure 5.12: Regression Modelling of PCC Pavements based on Sample Unit Data

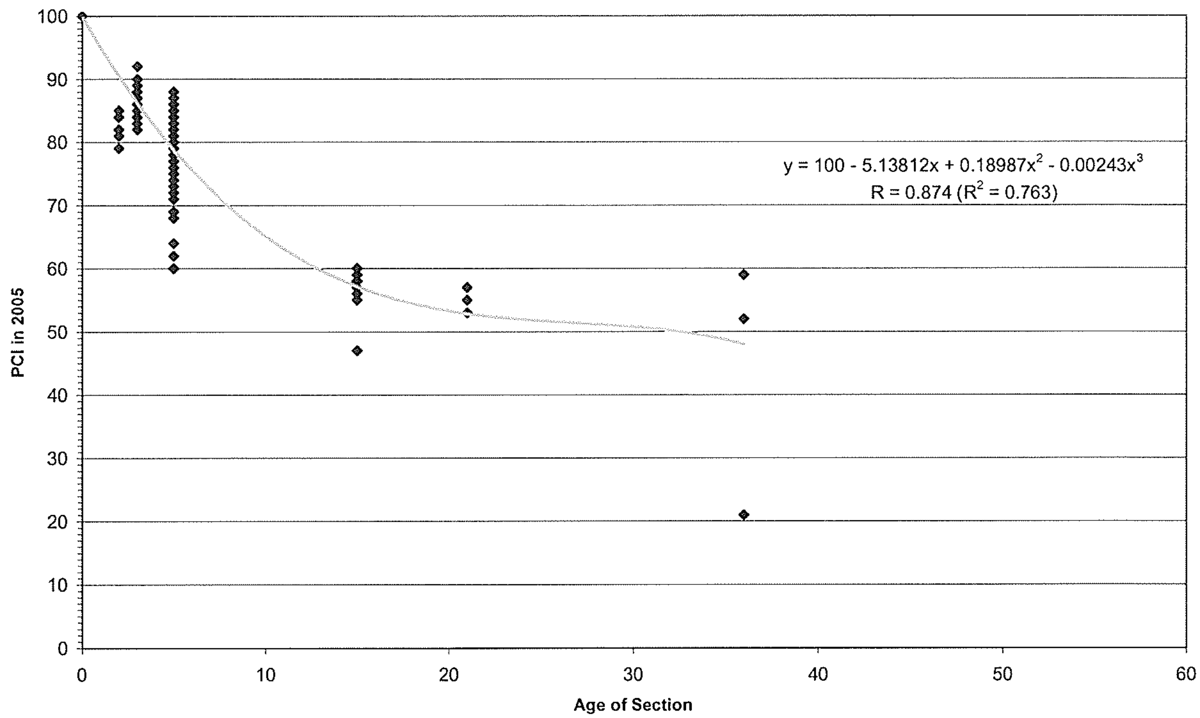


Figure 5.13: Regression Modelling of Composite Pavements based on Sample Unit Data

The output from the NN modelling was a correlation coefficient, or R-value; as such a comparison between the R-values obtained from neural network modelling and the regression modelling is contained in Table 5.2.

Table 5.2: Comparison of R-Values and MSE between Regression and Neural Network Models

	Least Squares Regression R-value	Least Squares Regression MSE	Neural Network R-value	Neural Network MSE
PCC	0.438	126.25	0.72	123.74
Composite	0.874	14.258	0.892	25.815

In both instances, a higher coefficient of correlation (R-Value) was obtained from neural network modelling than from the corresponding Constrained Least Squares Regression models. This finding would seem to support the hypothesis that the neural network models would be more adapt at modelling the nonlinear relationships that exist between the various factors that effect pavement performance. When the MSE was compared, the PCC models showed the same trend. However the composite models produced the opposite results with the Least Squares model producing a lower MSE.

5.3 Evaluation of Deterioration Models from Other Sites using WIA Data

The aim of this section is to examine the applicability of using models created for other facilities in WIA, illustrating why it is necessary to undertake the creation of pavement deterioration models for each new facility that implements a pavement management system. Due to the empirical nature of regression modelling, deterioration models are only applicable for modelling the performance of the pavements in the original data set. This is especially true for the family modelling technique which models pavement performance as a function of only Age. Family modelling works by eliminating certain factors from the equation by grouping similar sections together, something that should not be done across different facilities. Pavements at different airports will be subjected to different loadings, environmental conditions, and maintenance strategies. This explains why there is no universal pavement deterioration model than can be uniformly applied to all airfield pavements.

To illustrate this point, pavement deterioration models contained in a 2002 paper by Suh et al. were compared to the Winnipeg deterioration models and PCI data. The focus of the Suh paper was the development of rigid (PCC) pavement deterioration models for South Korean airfields. Two of the models contained in the paper were chosen for comparison to the Winnipeg data, Model 3: PCC Runway Pavements and Model 4: PCC Taxiway Pavements. Both of these models were created using sample unit level data, so the comparison to the Winnipeg data occurs at this level. To facilitate the comparison, x-values (Age) from the Winnipeg data set were fed into the Korean models. The predicted PCI values from both models were compared to PCI values obtained from the field investigation.

It should be noted that this section focuses on comparing models created using the family modelling technique, as the application of neural network modelling to airfield pavements is a new area that has not been widely researched to this point. The only neural network deterioration models that were discovered during the literature review were for highway pavements, which obviously differ from airfield pavements in terms of design and loadings.

Figures 5.14 and 5.15 contain the results of the comparison that was undertaken between the Winnipeg and Korean models. The Winnipeg data points are presented along with both the model created from this data and results of plugging the x-values from the Winnipeg data into the Korean model. As was expected, the Winnipeg models reported a higher R-value (correlation coefficient) than the Korean models, reaffirming the

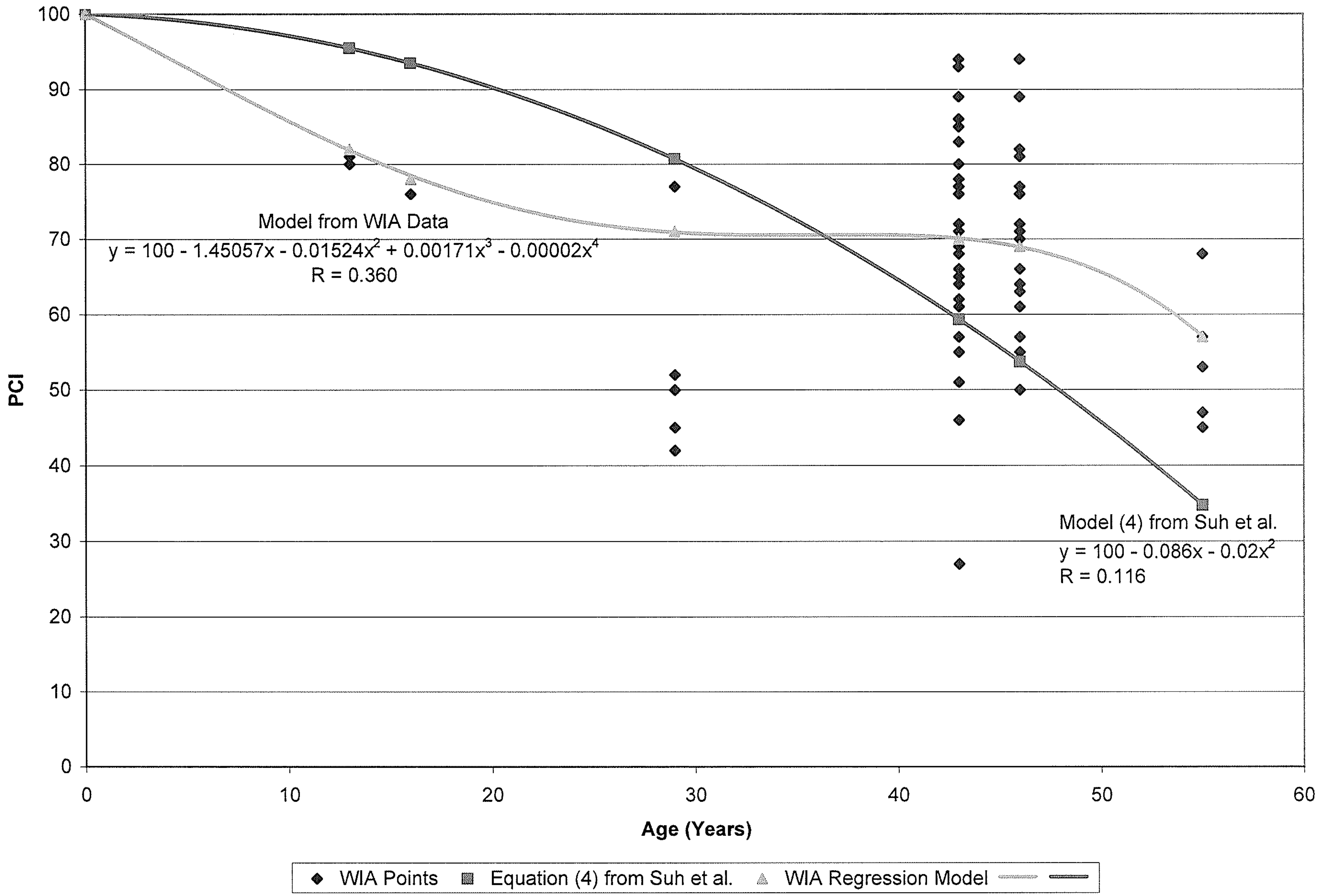


Figure 5.14: Comparison of PCC Taxiway Models

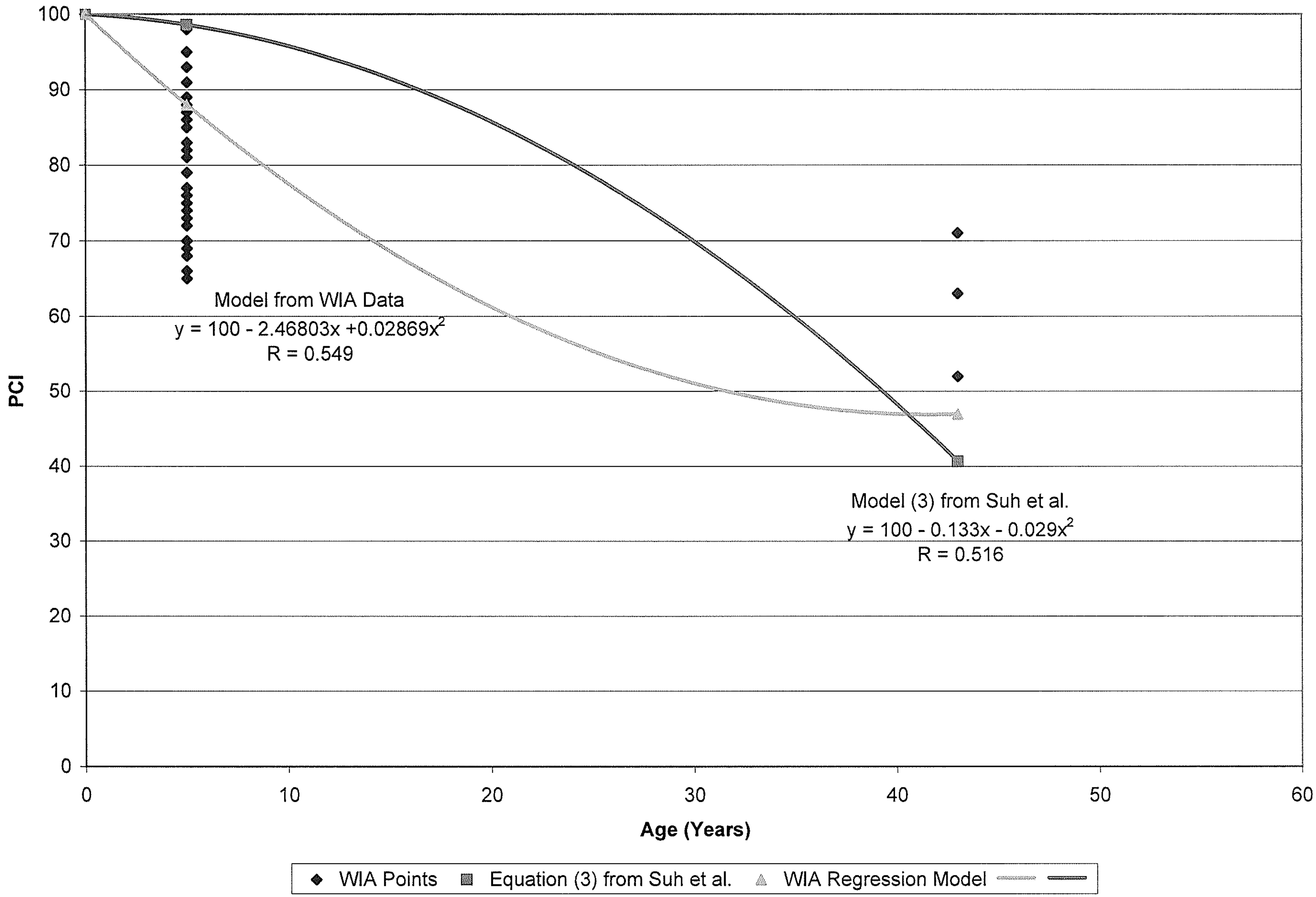


Figure 5.15: Comparison of PCC Runway Models

requirement that site-specific deterioration models be created for each airfield that is to be modelled.

Although pavement deterioration models from one sight cannot be used at other sites, the comparison of the models does still serve a useful purpose. By reviewing deterioration models from other airports, engineers can compare the performance of their pavements to similar pavements at other airfields. This exercise would be especially useful for airports of similar size and in similar climatic zones.

5.4 Summary

Several pavement deterioration models have been developed and reviewed in this chapter. First, the industry accepted standard, family modelling technique was used to create constrained regression models. This method, while widely used and accepted, models the performance of the pavement based on Age. Four of the models created using the WIA inspection data were presented and discussed in this chapter.

Neural network modelling and its suitability for creating pavement deterioration models was also explored. Two networks were created, one for each main pavement type, PCC and Composite, seen at the WIA. NN modelling allows for the inclusion of the many different input variables that contribute to pavement deterioration without requiring prior knowledge of the relationship between the inputs and outputs. While significantly more work is required to create NN deterioration models, the results of this research indicate that they can provide more accurate predictions of pavement performance compared to the standard regression models. One constraint in this research was the lack of available data to model with. Future work should be carried out utilizing additional year's inspection data.

Finally deterioration models developed for other airfields were compared against the Winnipeg ones to emphasise the importance of creating site-specific models. Two regression models created for PCC pavements from Korean airfields were chosen for comparison. The analysis showed that these regression models were not appropriate for modelling the performance of the Winnipeg pavement.

Chapter 6

RESULTS AND DISCUSSIONS

The focus of this research was the development and implementation of an Airfield Pavement Management System that expanded upon the capabilities of traditional systems while reducing the operational aspects of implementation. This chapter contains a discussion of the results of this research, starting with the unique aspects of an Airfield PMSs that created the need for, and spurred the development of this new system. Next, the experiences of developing the system, including an evaluation of the strengths and weaknesses observed during the implementation process are included. Followed by a summary and discussion of the results of the analysis and modelling stages of the thesis. Finally several recommended courses of action for further implementation of the system are presented; these include recommended re-inspection rates, development of a Cost by Condition Table for maintenance and rehabilitation programming and integrating the system within an Asset Management System.

6.1 Unique Characteristics of Airfield Pavement Management Systems

The development of the new PMS for the WIA was driven by the many unique characteristics of Airfield Pavement Management Systems and airfield operations. Geographically airports are unique, that when compared to highway networks they occupy only a small area, eliminating the need to study the effects of climate as a source of differential deterioration between pavement sections. On the other hand, airports are large in terms of the quantity of pavement (in terms of area) that needs to be managed, nearly 1 million square metres at the WIA. It would take over 135000 m of a typical two lane highway cross section (7.4 m wide) to equal the same area of pavement present at the WIA. Moreover, the airfield pavement thickness is twice or more than that of a highway pavement.

Not only do airports have vast quantities of pavement that needs to be managed, they are also held to a higher standard than highway or residential pavement networks and therefore require a greater percentage of the network to be surveyed. During the environmental scan it was discovered that agencies such as the City of Winnipeg utilized a customized pavement distress survey that allows their inspectors to evaluate many kilometres of roads each day. They also complete the survey without measuring distress quantities as the rating is based solely on visual observations. For this project, it was desired to have a minimum pavement inspection rate of 40% for runways and 20% for Taxiways and Aprons. To achieve these survey quantities while employing a detailed distress survey such as the PCI, a fast, repeatable and easily implemented method of recording the survey information needed to be developed. This was another factor that influenced the development of the new system.

Since airports are held to a high standard in terms of pavement condition, certain pavement distresses are often repaired in relatively small units as soon as they appear, such as a slab-by-slab basis in the case of concrete pavements. The reason for the higher standard is both a safety and an operational issue. As described in Chapter 2, pilots rate distresses that have a FOD potential as the highest priority. Many such distresses would not be repaired on a highway pavement, as they would not affect the operational capacity of the road. The standard method of collecting and reporting distress data did not provide the ability to locate and analyze distresses on such a small scale as pavement condition was only presented at the section level, without any information about the geographic location of the distresses. Previous research has identified this issue as a major limitation of the PCI system. The ability to provide geo-referenced distresses location information was identified as another desired feature of the new system.

6.2 Summary and Discussion of Results

In an attempt to address the unique features and limitations discovered in existing systems, this research focused on the creation of a GIS based Airfield Pavement Management System for the Winnipeg International Airport. All the components of this system have been detailed in the various chapters of this thesis. This section will contain a summary and discussion of the results of this thesis.

Data for this project was collected using a mapping grade GPS receiver and the data was stored directly in a GIS map. This new method of conducting a PCI survey greatly reduced the amount of time required to complete a PCI inspection. However, before commencing the analysis stage of the project the collection method needed to be validated. Chapter 3 detailed the verification process that was utilized. The results showed that when compared to measurements made using a total station, the GPS equipment measurements deviated by an average of only 1.6% for length measurements.

Such an error produced little variation in the PCI rating of a given sample unit. The analysis showed that a 15% change in measured distress quantity only produced a 2% change in PCI.

As the validation exercise demonstrated the data collection procedure developed for this project was capable of delivering PCI values with only minor variation from the traditional system, the data collected as part of this project could be analyzed with confidence. The results of the airfield condition survey described in Chapter 4 showed that WIA airfield is in good condition demonstrating their commitment to infrastructure renewal and maintenance has been successful. The average condition rating for runways and aprons was Very Good with taxiways being rated Good.

Chapter 4 also detailed the many new analysis techniques that are possible with the newly acquired geo-referenced distress data. An example of the detailed analysis that is possible was presented in Figures 4.5 - 4.7. By analysing pavement condition data on such a scale the pavement engineer gets a visual representation of the distresses. The density analysis in Figure 4.7 is an example of the use of the spatial analysis tools in the GIS software. This type of analysis is beneficial because it uncovers trends in distress patterns that would go unnoticed in the traditional MicroPAVER system. Figure 4.7 shows locations where Corner Break density is highest on the airfield. It is clear that areas of greatest concern are locations of intersecting, slow moving traffic. In MicroPAVER these areas are all analyzed separately.

Another option available in the new system is the ability to collect additional information at the time of inspection without creating much additional work for the field inspectors. One practical application of this feature, is while collecting standard PCI information pertaining to cracks, the surveyor checks a box on the field computer indicating if the crack is sealed or unsealed (not typically recorded in a traditional PCI survey), allowing for an accurate count of the quantity of unsealed cracks that need repair.

The availability of detailed geo-referenced pavement condition data also creates new options for deterioration modelling. Chapter 5 detailed the creation of both regression models and neural network models created from sample unit level data. Performance was modelled as a function of several variables instead of only age in the neural network models.

Using least squares regression analysis four models were developed in Chapter 5 with varying degrees of success (R^2 vales ranging from 0.301 to 0.971). This type of modelling is referred to as Family Modelling since models are created for several different groups or "families" of similar pavement sections. One noteworthy observation of this modelling was that certain PCC pavement sections at the WIA are performing well above expectations considering their age. Several sections over 40 years of age were removed from the PCC Pavements model to account for the anomaly in performance, the results of which are presented as Figure 5.5.

Conventional pavement deterioration modelling predicts performance as a function of only age. In an effort to expand on the capabilities of the currently used modelling techniques, Chapter 5 also detailed the creation and analysis of neural network deterioration models. Two models were created, one each for PCC and Composite pavements using sample unit level PCI data. The process used to develop the neural network models is detailed in Chapter 5, the end result being networks that contained 6 hidden neurons (PCC Model) and 3 hidden neurons (Composite Model) using input variables such as age, pavement thickness, functional classification (use). The composite neural network produced a higher R^2 (0.79570) and lower MSE (28.815) than the PCC model (R^2 of 0.5184 and MSE of 123.74). In order to compare the neural network results to the least squares regression modelling, new models were created for PCC and composite pavements based of sample unit data. The hypothesis that the neural network models would be better able to model the complex relationships was confirmed except when comparing the MSE of the composite models. This finding needs to be investigated further with additional data from future airfield surveys as currently the composite model contains 167 data points located at only 6 points on the x-axis.

The results of the neural network modelling indicate they are a suitable alternative to least squares regression models due to their ability to model pavement performance as a function of an unlimited number of variables. Since pavement performance is a function of several factors and neural networks are better suited to this type of modelling this area should be researched further.

The final section of Chapter 5 was an attempt to adapt models created from data collected at other facilities to model the WIA pavement performance. The reason for this exercise was to show the importance of creating site-specific models for each facility to ensure pavement performance is modelled accurately. A comparison could only be completed for least squares regression models as the use of neural networks to model airfield pavement is an emerging field with little published information available. The results of the comparison confirmed that the WIA models produce higher correlation coefficients than these models created using other facilities data.

6.3 Observations and Experiences of PMS Implementation

As with any new research development, the proposed system has strengths and weaknesses, which will be the focus of this section. The system has greatly reduced the time required to complete the Pavement Condition Index surveys, made several new forms of data analysis possible, and allowed the use of advanced modelling techniques. The airfield engineer now has many more tools at their disposal to help them better manage their infrastructure network.

Limitations were also observed during the development and implementation process. The main obstacle faced by this new system is that it represents a significant change from current industry practice. Users of traditional PMS systems will be quite accustomed to completing PCI surveys on paper forms and entering the information into the MicroPAVER database, running a standard analysis and printing off a list of section numbers with a corresponding PCI value. The proposed system will require that airport staff receive additional training on the expanded capabilities and features. Field surveyors will still follow the standard inspection technique; they will simply have to learn the GPS/GIS interface used for this project. The airfield engineer using the PMS in the office to plan future work will have to become familiar with GIS software and its many capabilities.

Another apparent drawback of the proposed system is that it requires the purchase of additional equipment and software not required in a traditional system. However, the additional expense associated with this equipment will be recovered through reduced survey times and expanded distress analysis tools. Overall this will lead to a cost savings for users switching from traditional PMSs.

6.4 Recommendations for Continued Implementation of the WIA PMS

The development and initial implementation of the WIA APMS have been completed. There are many possibilities for future uses and expansions of this new system. Infrastructure management is an ongoing process that requires continual updating and work. Additional inspection information will keep the pavement deterioration models current and accurate. Many agencies inspect their airfield on a rotating basis, inspecting a given section every 2 to 4 years. However, since the newly developed system has minimized the time required to complete a PCI inspection (average of 5 to 10 minutes per sample unit), and the sample units to be re-inspected can be relocated easily with the GPS receiver and GIS map, the entire Winnipeg airfield could be surveyed each year with much less effort than a traditional system.

6.4.1 Development of Budget Forecast and M&R Plan

The scope of this research was limited to the development and implementation of a new style PMS for the WIA that addressed many of the limitations of existing systems. With this system now developed and implemented, the most obvious next stage would be to incorporate cost data and perform a budget analysis, creating an M&R plan for the airfield. Over time the PMS could also be used to assess the cost effectiveness of various repair techniques by tracking the PCI score or individual distress severity in the GIS map to observe which method produces the best result.

The budget analysis and M&R planning was outside the scope of this project. However to give an indication of the usefulness of this undertaking a sample cost by condition table has been developed using some limited construction cost information obtained from recent WIA projects and is presented here as Table 6.1. This table is used in MicroPAVER along with the deterioration models developed in Chapter 5 to give an indication of when and where money is best spent. From this table it can be clearly seen that repairing a pavement with a higher PCI (better condition) is more cost effective than a pavement with a low PCI. While this may seem intuitive, due to factors such as limited budgets and political pressure many agencies simply repair the worst sections first, not spending any additional M&R funds until the section is in a failed state. Once the budget analysis and planning stage is completed in MicroPAVER, the most optimal spending can be determined that will either keep the network average PCI constant or increasing.

Table 6.1: Example Cost by Condition Table

AC	PCI	0	10	20	30	40	50	60	70	80	90	100
Runway	per m^2	$46.82	$46.82	$44.48	$39.80	$33.36	$26.75	$20.13	$13.58	$7.55	$2.52	$0.00
Taxi/Apron	per m^2	$46.82	$46.82	$44.48	$37.11	$29.26	$21.30	$13.58	$7.20	$2.87	$0.94	$0.00
Local Preventative	per m^2	$17.56	$13.11	$9.19	$5.97	$3.39	$1.40	$0.47	$0.35	$0.23	$0.12	$0.00
Stop Gap M&R	per m^2	$13.46	$9.77	$6.67	$4.04	$1.99	$0.53	$0.18	$0.09	$0.04	$0.00	$0.00
Concrete	**PCI**	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
M&R airfields	per m^2	$87.79	$87.79	$72.11	$20.37	$10.07	$6.56	$5.62	$4.97	$4.45	$2.75	$0.00
Local Preventative	per m^2	$47.99	$29.62	$20.84	$8.55	$3.51	$1.46	$1.05	$0.76	$0.53	$0.26	$0.00
Stop Gap M&R	per m^2	$47.99	$29.26	$16.39	$7.26	$2.22	$0.76	$0.53	$0.35	$0.18	$0.05	$0.00

A more detailed cost analysis is possible in the WIA APMS. Using individual distress information, along with the cost for repairing that type of distress, an analysis could be run that would estimate with a high level of certainty the cost of repairing that distress in a given sample unit, across the entire section or even across the entire airfield.

At this stage, the WIA should also consider if it would be better suited using a custom PCI distress scale as opposed to the 7 classifications in the standard (Table 4.1). A scale that accurately reflects the airports maintenance and repair strategy should be implemented. For example, using the scale presented in Table 6.2 would simplify the M&R planning and better reflect how the facility manages the airfield.

Table 6.2: Simplified PCI Rating Scale

PCI	Rating
71 - 100	Good
56 - 70	Fair
40 - 55	Poor
0 - 40	Failed

6.4.2 Future Expansions of WIA System

With additional time and effort, new features could be added to the WIA APMS. Due to the flexibility of the GIS portion of the system, additional information regarding any of the pavement sections could be added with ease.

The incorporation of the Aircraft Classification Number (ACN) and Pavement Classification Numbers (PCN) into the database would be a useful expansion. The ACN and PCN are ratings used throughout the world to classify the strength of a pavement and the potential damage an aircraft could do. As long as the ACN for an aircraft is lower than the PCN for a pavement section the aircraft can operate without restriction. Within the GIS database, the PCN for each pavement section could be appended to the existing records. This would allow for queries to be run comparing the ACN for a given aircraft to the GIS map, having problem areas being automatically highlighted. This system is much easier and more reliable than the traditional paper maps full of PCN codes that are currently in use by many agencies.

Another possibility for the future of this system would be to incorporate the existing database into a larger Asset Management System (AMS). Such a system should include the management of such things as lighting systems, airfield signs, pavement markings, and manholes, all geo-referenced and stored directly on the same GIS map currently used. This would allow facilities to optimize the management of their entire infrastructure network using consistent criteria.

Several possible expansions and further implementation steps have been presented in this chapter, all of which will enhance the functionality of the WIA PMS. Only setting the re-inspection schedule and conducting the budgeting analysis using the custom distress scale presented are recommended for completion in the immediate future. The addition of the ACN/PCN system would be more beneficial to an organization like the Canadian Air Force, which routinely uses the international standard to determine if aircraft from foreign countries will constitute an overload operation at their facilities. The incorporation of the PMS into a larger Asset Management System for the entire facility, while a worthwhile undertaking, will take considerable time to implement, as it will involve the coordination of several disciplines and should include groundside infrastructure and facilities.

Chapter 7

CONCLUSIONS AND RECOMMENDATIONS

The focus of this thesis has been the development and implementation of a network level Airfield Pavement Management System for the Winnipeg International Airport. Chapter 7 will summarize the thesis and the outcomes of the research as they relate to the original research objectives as well as recommend future research opportunities based on the work commenced in this project.

7.1 Summary

This thesis has documented the development of a PMS for the Winnipeg International Airport. The system expands the capabilities of existing systems by incorporating new data collection and analysis techniques. A thorough literature review was completed to examine past research in the area of airfield pavement management systems. A survey was also conducted to assess the state of PMS implementation at Canadian airports.

The classification of airfield network was completed and a Pavement Condition Index inspection of the airfield was conducted. A total of 312 individual PCI inspections were completed across the airfield during the summer of 2005. The PCI inspections were conducted using a GPS receiver to record the location and quantity of the distresses observed. The geo-referenced distress information was stored in a GIS map, allowing several new data analysis methods to be completed.

Pavement deterioration models were created from the pavement condition to forecast the future condition of the pavement. Models were created using both the traditional least squares regression technique and with neural networks. The neural network models were studied due to their ability to model pavement performance as a function of several interdependent variables. Finally pavement deterioration models from other airports were analyzed using the Winnipeg data to illustrate the need for creating new models for every airport.

7.2 Research Objectives Accomplished

All six research objectives presented in Chapter 1 have been accomplished through the development and implementation of the WIA PMS. Developing new methods of data collection allowed for all airfield condition surveys to be completed without impacting airport operations. All 312 PCI inspections were conducted during the day, with no interruptions to scheduled airport operations. This was only possible because the time required to collect pavement distress data was minimized through the use of a GPS receiver to log observed distresses. On occasion while surveying a sample unit, the runway or taxiway would have to be cleared to allow for aircraft movements. The WIA system allowed for the PCI survey to be continued exactly where it was left off, without error, because a graphical display of distresses logged is provided.

Another objective met was the integration of the historical pavement construction records into the newly developed system. Extensive use of GIS software along with geo-referenced distress information allowed new data analysis techniques to be explored making more efficient use of the newly recorded pavement condition data and historical construction records.

The WIA PMS also addressed limitations and concerns raised by previous researchers regarding the use of the Pavement Condition Index procedure. Collecting geo-referenced distress information allows for PCI calculation as well as advanced analysis. As demonstrated in this thesis it is now possible to analyze the geo-referenced distress data to detect problem areas that would have remained undetected simply using the assigned PCI value, to be detected and repaired. Another advantage is that collected distress information can be used to accurately calculate repair quantities on a useable scale.

The final research objective accomplished was the development of deterioration models for the WIA pavement. Models were developed using both family modelling and Neural Network modelling. The use of neural networks to model the performance of airfield pavement shows great promise. While significantly more work is required to create neural network models, the results of this research indicate that they can provide more accurate predictions of pavement performance compared to the standard regression models.

7.3 Recommended Future Research and Development

Research completed as part of this project has expanded upon the findings of previous projects. Similarly, further research into the outcomes of this project is required. One such example would be the development of a system capable of conducting automated PCI inspections using a vehicle-mounted system. The end result of such a system would be geo-referenced distress maps that look the same as the maps created for this project, the main difference being the required survey time. With an automated distress capture system the time to survey the airfield would be minimal, drastically minimizing the operational impacts of implementation.

Another area for potential development is the integration of several of the different software packages and technologies used as part of this research. The creation of such a program would increase the usability of the WIA system.

Much work also needs to be done in the area of advanced pavement deterioration modelling. The traditional modelling approach has sufficed in the past, but modern computing technology has made several advanced modelling techniques possible. Neural networks have shown promise as they are not constrained by limited numbers of regression parameters and can account for the interactions between the parameters and nonlinear relationships. It is recommended that the work be expanded once additional year's inspection data are available. The additional data should increase the accuracy of the models and allow the neural networks to better predict future pavement performance.

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Appendix A

SUMMARY OF RESPONSES TO PAVEMENT MANAGEMENT SURVEY FROM CANADIAN AIRPORTS

Facility	Date of Imp.	Airside / Groundside	in-house / consultant	Software	Distress Index	Inspection Frequency	GIS Capabilities	GPS Capabilities	Additional Info Collected	Use in Planning	Part of Larger AMS
YYC	1998	initially both, subsequent inspections only airside	consultant completed surveys	MicroPAVER	PCI	Rwys: 3-4yrs Taxi: 3-4yrs Apron: 3 yrs Grndside: Once	ARCview used for mapping and presenting data	None	Structural data collected by FWD/HWD	"we use the system to develop our 5-year capital plan for all pavement restoration programs and schedule maintenance around the major construction projects. We also incoporate joint sealing and patching work history into the database"	No
YVR	1998	Airside	Consultant	Custom Application	TC system (AK-68-32-000 or TP1849)	Annually	"Largely"	None	additional info collection and kept on file wehre applicable	"Large"	No
YOW	10+ years	Both	Consultant	custom application	PCI	Bi-Annually	Beginning implementation	Beginning Implementation	"All of the Above"	"100%"	"Presently creating a GIS database and this will be growing into an Asset Management System"
YYZ	2002	Both	JEGEL (airside) and ERES (Groundside)	Customized MicroPAVER	PCI	5 year cycle / Roads on 3 year cycle	Geomedia Transporation Module (70%) Orthoimagery (15%) Others (15%)	None	Incoporate roughness, rutting, and HWD separately in PMS	"PMS is part o fthe AMMS and Facilities Asset Management System (FAMS) and a report is issued each year covering 5 year schedule"	Yes
Yukon Airports	1997	Both	PWGSC	custom application	PCI	Annually	None	None	None	"considerable"	No
Quebec Region TC Airports	In developmen t	Both	Transport Canada	Undecided	TC system (AK-68-32-000 or TP1849)	Bi-Annually	None	None	Mainly surface, some cases friction and roughness	"Main input for capital program"	No
Port Hardy BC	(date unknown)	Both	TC and consultant	unknown	TC system (AK-68-32-000 or TP1849)	Annually	None	None	"All other info collected as well"	"It is the sole basis for planned repairs.overlays/HIP or maintenance"	Yes
NWT Airports	1999	Airside	Consultant	customized commercial app	PCI	Bi-Annually	None	None	None	"The APMS is used to predict and prioritize all major maintenance, rehabilitation and reconstruction project requirements, based on an annual system analysis of current inspection data. A 20-Year Construction Program is generated annually from the analysis"	"In a manner of speaking yes, since certain information in the APMS is used in the Department's Tangible Capital Asset Management Database (which is Excel bsaed)"
Dryden	No										

Appendix B

GPS DATA COLLECTION VALIDATION EXERCISE RESULTS

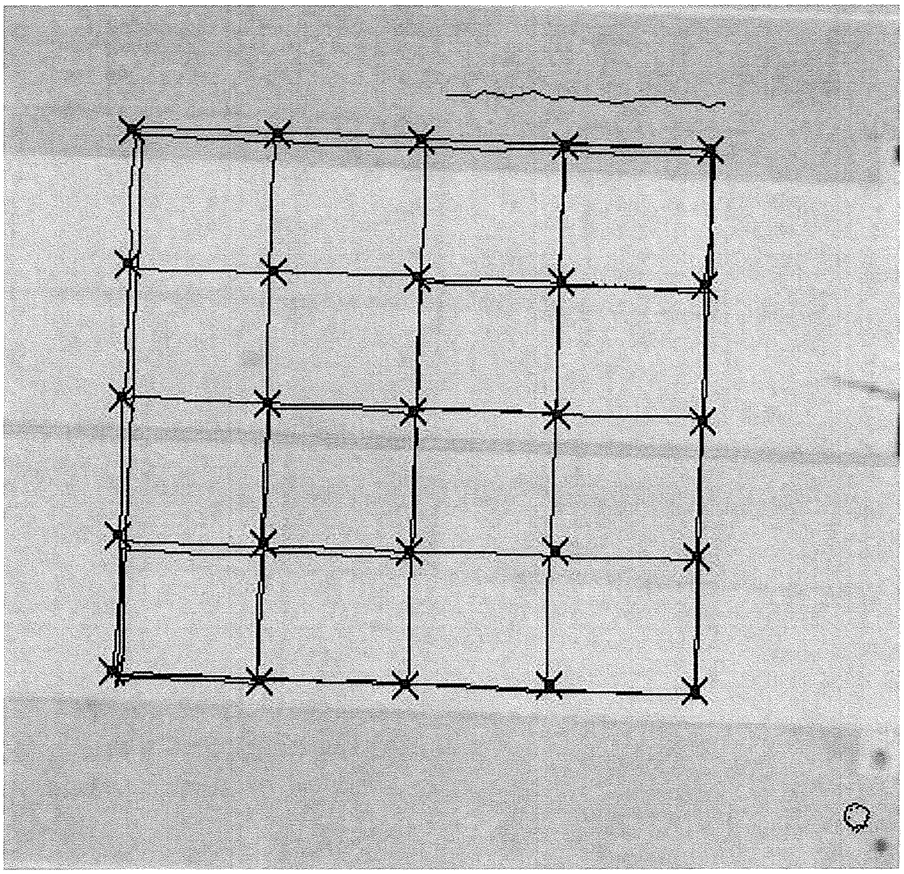

Figure B1: Validation Data Captured with GPS Equipment

Table B2: Effect of Varying Distress Quantities on PCI Values

		-15%	-10%	-5%	Baseline	5%	10%	15%
Distress	Severity	0.85	0.9	0.95	1	1.05	1.1	1.15
Joint Reflection Cracking	Low	62.9	66.6	70.3	74	77.7	81.4	85.1
Long - Trans Cracking	Low	48.45	51.3	54.15	57	59.85	62.7	65.55
Weather/Raveling	Medium	21.25	22.5	23.75	25	26.25	27.5	28.75
PCI		**76**	**76**	**75**	**75**	**75**	**74**	**74**

Appendix C

PCI SUMMARY TABLE FROM MicroPAVER SECTION LEVEL DATA

Branch ID	Section ID	Last Const. Date	Surface	Use	Area	Inspection Date	Age	PCI
Apr1 (Apron 1)	Apr1-01	07/01/1985	PCC	APRON	8,748	06/21/2005	20	70
Apr1 (Apron 1)	Apr1-02	07/01/1985	PCC	APRON	7,868	06/21/2005	20	82
Apr1 (Apron 1)	Apr1-03	07/01/2004	APC	APRON	18,062	07/29/2005	1	82
Apr1 (Apron 1)	Apr1-05	07/01/1987	PCC	APRON	25,012	06/21/2005	18	76
Apr1 (Apron 1)	Apr1-06	07/01/1994	PCC	APRON	18,802	06/22/2005	11	84
Apr1 (Apron 1)	Apr1-09	07/01/1982	PCC	APRON	24,585	06/17/2005	23	58
Apr2 (Aprons 2 &3)	Apr2-01	07/01/1985	AC	APRON	17,749	08/22/2005	20	44
Apr4 (Apron 4)	Apr4-01	07/01/1994	PCC	APRON	12,272	06/15/2005	11	83
Apr5 (Apron 5)	Apr5-01	07/01/1994	PCC	APRON	11,104	06/16/2005	11	79
Apr7 (Apron 7)	Apr7-01	07/01/1968	PCC	APRON	6,448	06/24/2005	37	17
Apr7A (Apron 7A)	Apr7A-01	07/01/2003	PCC	APRON	19,728	06/24/2005	2	95
R1331 (Runway 13-31)	R1331-01	07/01/2001	APC	RUNWAY	14,678	07/26/2005	4	78
R1331 (Runway 13-31)	R1331-02	07/01/2001	APC	RUNWAY	15,594	08/22/2005	4	75
R1331 (Runway 13-31)	R1331-03	07/01/2001	APC	RUNWAY	12,882	07/27/2005	4	81
R1331 (Runway 13-31)	R1331-04	07/01/2001	APC	RUNWAY	1,403	07/26/2005	4	75
R1331 (Runway 13-31)	R1331-05	07/01/2001	APC	RUNWAY	1,380	07/26/2005	4	80
R1331 (Runway 13-31)	R1331-06	07/01/2001	APC	RUNWAY	1,376	07/26/2005	4	75
R1331 (Runway 13-31)	R1331-07	07/01/2001	PCC	RUNWAY	5,641	08/22/2005	4	71
R1331 (Runway 13-31)	R1331-08	07/01/2001	PCC	RUNWAY	4,166	08/22/2005	4	82
R1331 (Runway 13-31)	R1331-09	07/01/2001	PCC	RUNWAY	4,169	08/22/2005	4	86
R1331 (Runway 13-31)	R1331-10	07/01/2001	PCC	RUNWAY	7,020	07/26/2005	4	67
R1331 (Runway 13-31)	R1331-11	07/01/2001	APC	RUNWAY	6,461	07/26/2005	4	73
R1331 (Runway 13-31)	R1331-12	07/01/2001	APC	RUNWAY	7,278	07/26/2005	4	76
R1331 (Runway 13-31)	R1331-14	07/01/2001	PCC	RUNWAY	6,875	07/28/2005	4	90
R1331 (Runway 13-31)	R1331-15	07/01/2001	APC	RUNWAY	20,837	07/29/2005	4	80
R1331 (Runway 13-31)	R1331-16	07/01/2001	PCC	RUNWAY	23,163	08/22/2005	4	83
R1331 (Runway 13-31)	R1331-17	07/01/2001	APC	RUNWAY	17,872	07/28/2005	4	83
R1331 (Runway 13-31)	R1331-18	07/01/1963	PCC	RUNWAY	5,560	07/27/2005	42	61
R1836 (Runway 18-36)	R1836-01	07/01/2003	APC	RUNWAY	26,757	08/22/2005	2	85
R1836 (Runway 18-36)	R1836-02	07/01/2003	APC	RUNWAY	32,243	08/25/2005	2	88
R1836 (Runway 18-36)	R1836-03	07/01/2003	APC	RUNWAY	26,116	08/22/2005	2	87
TaxiA (Taxiway A)	TaxiA-02	07/01/1951	PCC	TAXIWAY	11,962	06/28/2005	54	54
TaxiA (Taxiway A)	TaxiA-03	07/01/1970	APC	TAXIWAY	5,647	07/18/2005	35	50
TaxiC (Taxiway C)	TaxiC-01	07/01/1991	APC	TAXIWAY	27,860	07/25/2005	14	57
TaxiC (Taxiway C)	TaxiC-02	07/01/1985	APC	TAXIWAY	6,784	07/25/2005	20	55
TaxiE (Taxiway E)	TaxiE-01	07/01/1960	PCC	TAXIWAY	4,456	08/05/2005	45	73
TaxiE (Taxiway E)	TaxiE-02	07/01/1960	PCC	TAXIWAY	25,172	08/05/2005	45	83
TaxiF (Taxiway F)	TaxiF-01	07/01/1960	PCC	TAXIWAY	3,174	08/04/2005	45	64
TaxiF (Taxiway F)	TaxiF-04	07/01/1960	PCC	TAXIWAY	13,608	08/04/2005	45	75
TaxiG (Taxiway G)	TaxiG-01	07/01/1977	PCC	TAXIWAY	23,316	07/18/2005	28	53
TaxiH (Taxiway H)	TaxiH-02	07/01/1960	PCC	TAXIWAY	22,789	08/02/2005	45	65
TaxiN (Taxiway N)	TaxiN-01	07/01/1963	PCC	TAXIWAY	7,126	08/05/2005	42	36
TaxiP (Taxiway P)	TaxiP-01	07/01/1963	PCC	TAXIWAY	12,788	07/28/2005	42	81
TaxiP (Taxiway P)	TaxiP-02	07/01/1963	PCC	TAXIWAY	17,756	08/22/2005	42	69
TaxiQ (Taxiway Q)	TaxiQ-01	07/01/1963	PCC	TAXIWAY	9,753	08/04/2005	42	67
TaxiS (Taxiway S)	TaxiS-01	01/07/1993	PCC	TAXIWAY	7,079	08/05/2005	12	80
TaxiT (Taxiway T)	TaxiT-01	07/01/1963	PCC	TAXIWAY	33,957	08/03/2005	42	80
TaxiT (Taxiway T)	TaxiT-02	07/01/1963	PCC	TAXIWAY	17,551	08/03/2005	42	68
TaxiV (Taxiway V)	TaxiV-01	07/01/1963	PCC	TAXIWAY	9,044	08/05/2005	42	61
TaxiV (Taxiway V)	TaxiV-02	07/01/1990	PCC	TAXIWAY	3,179	08/05/2005	15	76

Appendix D

TAXIWAY C TRADITIONAL ANALYSIS

Re-inspection Report

erated Date: 29/10/200(

WIA Name: Winnipeg International Airport

TaxiC Name: Use: TAXIWAY Area: 34,644.00SqM

TaxiC-02 of 2 From: R1331 To: Taxi H Last Const.: 01/07/198
APC Family: APC Zone: Category: Rank: B
,784.00SqM Length: 295.00M Width: 23.00M
Street Type: Grade: 0.00 Lanes: 0
ents:

)ate25/07/2005 Total Samples: 14 Surveyed: 3
PCI:55.00 |

nber: 4 Type: R Area: 400.00SqM PCI = 55

ERING/RAVELING	L	400.00	SqM
TUDINAL/TRANSVERSE CRACKING	M	3.91	M
TUDINAL/TRANSVERSE CRACKING	M	3.17	M
TUDINAL/TRANSVERSE CRACKING	L	1.73	M
TUDINAL/TRANSVERSE CRACKING	L	14.04	M
ERING/RAVELING	M	6.01	SqM
ERING/RAVELING	M	5.97	SqM
ERING/RAVELING	M	23.62	SqM
ERING/RAVELING	M	14.10	SqM
ERING/RAVELING	M	4.92	SqM
ERING/RAVELING	M	24.04	SqM
PILLAGE	N	0.14	SqM

ıber: 8 Type: R Area: 503.00SqM PCI = 57

ING	L	79.04	SqM
ERING/RAVELING	L	423.96	SqM
TUDINAL/TRANSVERSE CRACKING	M	5.09	M
TUDINAL/TRANSVERSE CRACKING	L	5.91	M
TUDINAL/TRANSVERSE CRACKING	L	11.76	M
TUDINAL/TRANSVERSE CRACKING	M	4.68	M
TUDINAL/TRANSVERSE CRACKING	L	1.83	M
TUDINAL/TRANSVERSE CRACKING	M	21.14	M
TUDINAL/TRANSVERSE CRACKING	M	19.88	M
TUDINAL/TRANSVERSE CRACKING	L	9.53	M
TUDINAL/TRANSVERSE CRACKING	M	4.53	M
TUDINAL/TRANSVERSE CRACKING	M	7.71	M

ıber: 12 Type: R Area: 506.00SqM PCI = 53

ING	L	66.73	SqM
ERING/RAVELING	L	423.30	SqM
TUDINAL/TRANSVERSE CRACKING	L	3.09	M
TUDINAL/TRANSVERSE CRACKING	M	0.50	M
TUDINAL/TRANSVERSE CRACKING	L	0.92	M
TUDINAL/TRANSVERSE CRACKING	L	2.27	M
TUDINAL/TRANSVERSE CRACKING	M	2.93	M
TUDINAL/TRANSVERSE CRACKING	M	19.80	M
TUDINAL/TRANSVERSE CRACKING	M	16.67	M
TUDINAL/TRANSVERSE CRACKING	M	0.58	M
TUDINAL/TRANSVERSE CRACKING	M	5.82	M
TUDINAL/TRANSVERSE CRACKING	L	1.84	M
TUDINAL/TRANSVERSE CRACKING	M	2.12	M
TUDINAL/TRANSVERSE CRACKING	M	7.13	M
ING	L	1.07	SqM
TUDINAL/TRANSVERSE CRACKING	L	19.72	M
TUDINAL/TRANSVERSE CRACKING	M	11.41	M
TUDINAL/TRANSVERSE CRACKING	M	4.65	M
TUDINAL/TRANSVERSE CRACKING	L	7.43	M
TUDINAL/TRANSVERSE CRACKING	M	3.56	M

Re-inspection Report

erated Date: 29/10/200(

TUDINAL/TRANSVERSE CRACKING	M	4.68 M
TUDINAL/TRANSVERSE CRACKING	M	3.25 M
TUDINAL/TRANSVERSE CRACKING	M	0.88 M
TUDINAL/TRANSVERSE CRACKING	L	12.59 M
TUDINAL/TRANSVERSE CRACKING	M	0.55 M
TUDINAL/TRANSVERSE CRACKING	M	1.87 M
TUDINAL/TRANSVERSE CRACKING	M	0.99 M
TUDINAL/TRANSVERSE CRACKING	M	3.46 M
TUDINAL/TRANSVERSE CRACKING	M	5.34 M
PILLAGE	N	0.28 SqM

Appendix E

PCC RUNWAY AND COMPOSITE RUNWAY DETEROIRATION MODELS

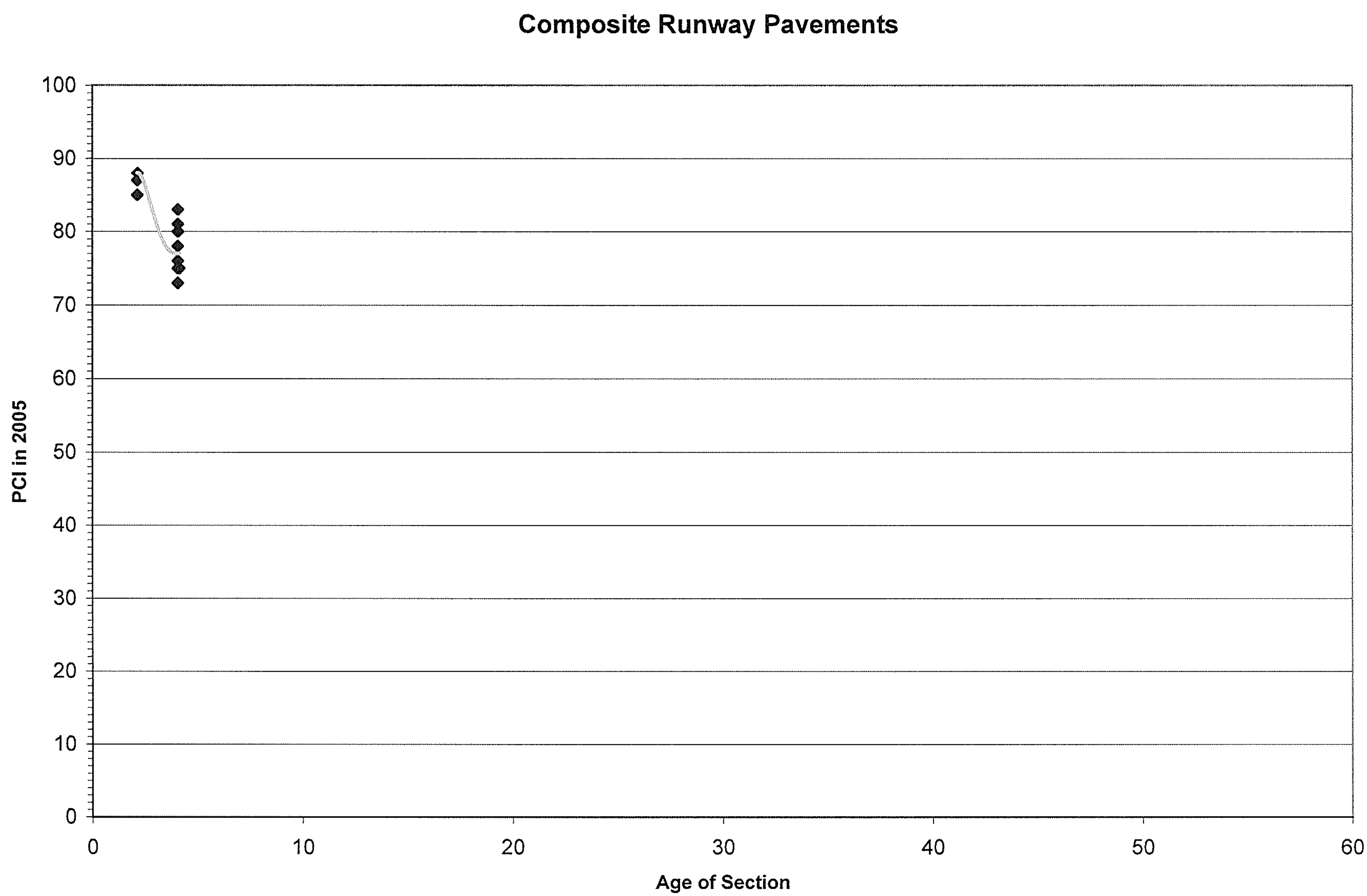

Figure E1: Composite Runway Pavements Deterioration Curve

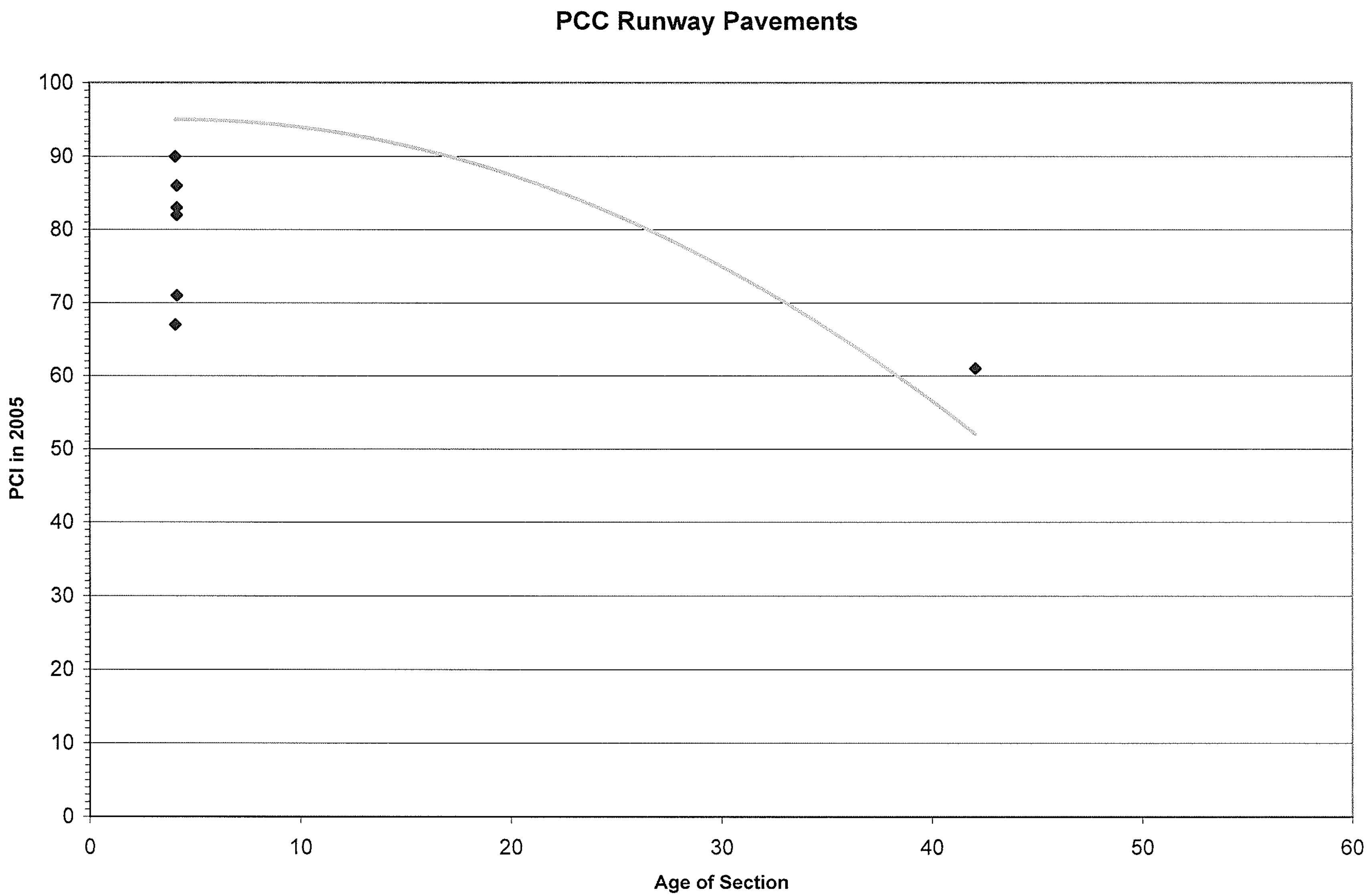

Figure E2: PCC Runway Pavements Deterioration Curve

Appendix F

MATLAB CODE USED FOR PCC NEURAL NETWORK

```
echo on
clc

load nnet.mat

pn = p;
tn=t;
[R,Q] = size(pn);
iitst = 2:4:Q;
iitr = [1:4:Q 3:4:Q 4:4:Q];
testing.P = pn(:,iitst);
testing.T = tn(:,iitst);
ptr = pn(:,iitr);
ttr = tn(:,iitr);

net = newff(minmax(ptr),[6 1],{'tansig' 'purelin'},'trainlm');

        %    TRAINING THE NETWORK
        net.trainParam.show = 500;
        net.trainParam.epochs = 500;
        net.trainParam.mu = 1;
        net.trainParam.mu_dec = 0.8;
        net.trainParam.mu_inc = 1.2;
        net.trainParam.lr = 0.5;

        [net,tr]=train(net,ptr,ttr);

        inputweights=net.iw{1,1};

        for i=1:2
               networkbias{i} = net.b{i};
        end
        for i=2:2
                layerweight{i-1}=net.lw{i,1};
        end

        y=sim(net,ptr);
        e = ttr-y;
        perf = mse(e)
        perfarray(1,1)=1;
        perfarray(1,2)=perf;

        for i = 1:100
            i
            net = newff(minmax(ptr),[6 1],{'tansig'
'purelin'},'trainlm');
            net.trainParam.show = 500;
            net.trainParam.epochs = 500;
            net.trainParam.mu = 1;
            net.trainParam.mu_dec = 0.8;
            net.trainParam.mu_inc = 1.2;
            net.trainParam.lr = 0.5;

            [net,tr]=train(net,ptr,ttr);
```

```
            y=sim(net,ptr);
            e = ttr-y;
            tempperf = mse(e)
            if tempperf < perf
                inputweights=net.iw{1,1};
                    for j=1:2
                       networkbias{j} = net.b{j};
                    end
                    for j=2:2
                       layerweight{j-1}=net.lw{j,1};
                    end
             perf=tempperf;
             perfarray(i+1,1)= i+1;
             perfarray(i+1,2)=perf;
            end
            perfarray2(i+1)=tempperf;
        end

        net.iw{1,1}=inputweights;
        for i=1:2
                net.b{i}=networkbias{i};
        end
        for i=2:2
                net.LW{i,1}=layerweight{i-1};
        end

y=sim(net,ptr);
e=ttr-y;
perf = mse(e)

b=sim(net,testing.P);
e2 = testing.T-b;
perf2 = mse(e2)

% % Simulate the trained network.
a = sim(net,pn);
e3 = tn-a;
perf3 = mse(e3)

% %    DISPLAY RESULTS
 for i=1:1
     figure(1)
     [m(i),b(i),r(i)] = postreg(a(i,:),tn(i,:));
 end

 echo off
% disp('End of NNSAMPLE')
```