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Justin C. Meihaus

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UNDERSTANDING THE EFFECTS OF CLIMATE ON AIRFIELD PAVEMENT DETERIORATION RATES

THESIS

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AFIT-ENV-13-M-16

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

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THESIS

Presented to the Faculty

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Captain, USAF

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AFIT-ENV-13-M-16

Abstract

Over the past two decades, pavement engineers at the Air Force Civil Engineer Center have noticed the majority of identified distresses from PCI airfield surveys are climate related. To verify these trends, a comprehensive analysis of the current airfield pavement distress database was accomplished based on a climate region perspective. A four-zone regional climatic model was created for the United States using geospatial interpolation techniques and climate data acquired from WeatherBank Inc. Once the climatic regional model was developed, the climate information for each installation was imported into the Air Force pavement distress database within PAVER^{TM}. Utilizing the pavement condition prediction modeling function in PAVER^{TM}, pavement deterioration models were created for every pavement family at each base in each climatic zone. This was done to generate a list of bases that may have multiple pavement families with rates of deterioration that are better or worse than the regional rates of deterioration. The average regional rates of deterioration for each pavement family were found to be within the parameters of conventional wisdom observed in Asphalt Concrete (AC) and Portland Cement Concrete (PCC). The results of the pairwise comparisons using the Student's T-test determined the Freeze-Dry climate region deterioration rates for the PCC pavement family were statistically different than the other three regions. No significant statistical differences were observed in the AC pavement comparisons. This analysis established a foundation to investigate and identify variables causing the rates of deterioration at specific installations to differ from the regional rates of deterioration.

I would like to dedicate this thesis to my wife and my daughter. Without their love, support, and encouragement I would not be where I am today. From the bottom of my heart, thank you.

Acknowledgments

I would like to express my deepest gratitude to my wife. You truly are my best friend in the journey of marriage. I will never forget the early morning coffee runs and the amazing breakfasts to jump-start my day. I am so thankful for your love and dedication. I cannot say thank you enough for your unending support over the past 18 months. I would, also, like to thank my research advisor, for his advice, guidance and support throughout this endeavor. You guided and challenged me every step of the way, which ensured that I developed a solid foundation of knowledge and know how for solving complex problems. For that I am truly grateful. This research effort would not have been possible without the unending support and expertise of my thesis committee. I am truly indebted to you both for your valuable insight and expertise that you provided throughout this effort. I am truly grateful for the time you spent explaining the intricate details of pavement management, pavement management and distresses, and PAVER$^{\text{TM}}$.

Justin C. Meihaus

Table of Contents

Page

List of Figures

Page

List of Tables

Page

UNDERSTANDING THE EFFECTS ON CLIMATE ON AIRFIELD PAVEMENT DETERIORATION RATES

1.0 Introduction

1.1 Background

The United States government, Department of Defense (DoD), and Air Force are facing a pivotal point in their history due to massive reductions to the overall government budget. The DoD is on the cusp of a reduction of $478 billion dollars over 10 years. The Air Force is not exempt from these cuts and will have to overcome a reduction of approximately $12 billion in their operating budget over the next 10 years while still maintaining the ability to execute its mission. Large portions of the cuts will affect the maintenance and repair budgets used to maintain the Air Force's aging infrastructure. As a result, Air Force engineers are exploring and developing new innovative processes and procedures for accomplishing a strategic approach to managing facility and infrastructure assets.

Asset management, often referred to as Facility Management (FM), consists of tools developed over the past 20 years in the public and private sectors to effectively manage facility and infrastructure assets. The International Infrastructure Management Manual (IIMM) describes asset management as "the combination of management, financial, economic, engineering and other practices applied to physical assets with the objective of providing the required level of services in the most cost effective manner" (American Association of State Highway and Transportation Officials, 2011). FM embraces these concepts in an attempt to provide and maintain adequate facilities and infrastructure to the built environment, which could be a large city or military installation. However, accomplishing FM is a monumental challenge when dealing with unrelenting budgets cuts and massive reductions in workforces (Cotts, Roper, & Payant, 2010). To address this challenge within the Air Force, new principles and practices must be identified and created to facilitate a new era of asset and infrastructure management. The Civil Engineer (CE) community has responded and is in the process of implementing asset management as the foundation of CE operations in "Building Sustainable Installations," which is one of three goals identified in the 2011 U.S. Air Force Civil Engineer Strategic Plan. One aspect of this plan involves the maintenance and management of airfield pavements to enable the safe and efficient movement of air and space craft. Critical to this effort is the use of pavement deterioration models as a management tool to enable installation engineers to meet the required level of service in the most cost effective manner.

Pavement deterioration models can enhance the capabilities of a pavement management system, thereby producing an effective tool for pavement engineers. These models allow pavement engineers to predict the timing for maintenance and rehabilitation activities and to estimate the long-range funding requirements for preserving the airfield pavement system (Sadek, Freeman, & Demetsky, 1996). Performance prediction models are crucial to the management of pavements at both the network and project levels. At the network level, these models are used for the selection of optimal Maintenance & Rehabilitation (M&R) strategies, condition forecasting, budget planning, scheduling inspections, and working planning (Shahin, 2005). Prediction models are used at the project level to assist with design and life-cycle costs analyses (Gendreau & Soriano, 1998). Network level prediction models can also be used to identify and select rehabilitation alternatives to meet expected traffic and climate conditions (Shahin, 2005).

Deterioration models predict the deterioration rate of a pavement section over time to enable managers to predict M&R activities well into the future. In contrast, functional performance models predict the present serviceability index, often called the Pavement Condition Index (PCI). Starting in 1968, the U.S. Army Construction Engineering Research Laboratory (USACERL) began developing an objective and repeatable rating system to be used to provide an index of a pavement's structural integrity and surface operational condition (Shahin, 2005). Their research led to the development of the PCI. PCI is a numerical index that measures pavement condition on a scale from 0 to 100, with 0 being a failed pavement section and 100 being a perfect/newly installed pavement section (Shahin, 2005). The PCI is based on the results of a visual condition survey in which distress type, severity, and quantity are identified (Shahin, 2005). PCI condition surveys provide pavement engineers insight into whether load-related factors or climate-related factors led to the cause of distresses (Shahin, 2005). The PCI is the distress condition rating system that the Air Force currently uses for pavement management activities. The surface distress data used to calculate PCIs, for Air Force airfields, are collected through the extensive airfield evaluation program managed by pavement engineers located at the Air Force Civil Engineer Center-East.

Airfield pavements must be able to function all over the world in a wide array of environmental conditions supporting multiple types of aircraft. Haas (2001) identifies five key factors affecting pavement performance, as shown in Figure 1. Each one of these identified factors can affect pavement performance with varying degrees of magnitude. Environmental, or climate, conditions can have significant impacts on the pavement and sub-grade materials, which can radically affect the performance lifespan of a pavement. Notable environmental factors that affect pavement performance are temperature, precipitation, subsurface-moisture, and freeze-thaw cycles (Li, Mills, & McNeil, 2011). Typically, pavements are designed to minimize extreme damage due to temperature. For example, eliminating frost susceptible materials frost heave effects can be minimized. Using properly designed asphalt binders that perform well in cold temperatures can minimize thermal cracking in flexible pavements. However pavements will deteriorate over time due to environmental factors even with the correct design. In essence, environmental factors can affect both the structural and functional capacities of airfield pavements.

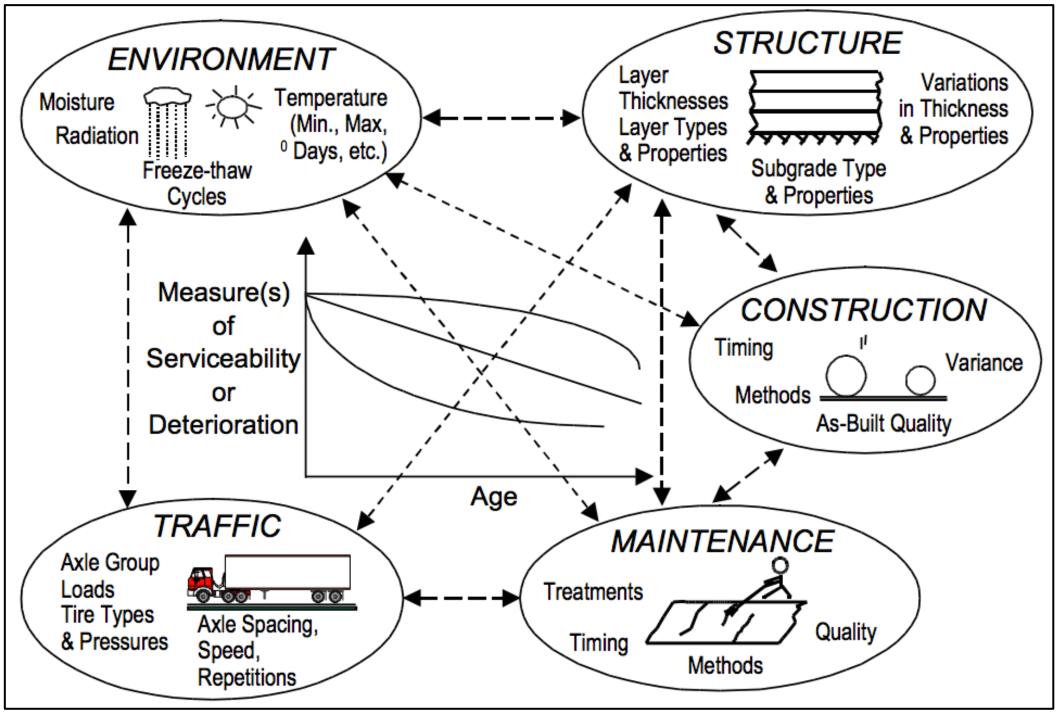

Figure 1. Factors Affecting Pavement Performance (Haas, 2001)

The current Air Force predictive models are developed using PAVER^{TM}, a pavement management software program. PAVER^{TM} uses surface distress data collected from an airfield survey to calculate PCI values for each type of pavement family. Shahin (2005) defines a pavement family as a group of pavement sections with similar deterioration characteristics. In turn, the PCI values are used to create a performance predictive model for a specific pavement family. Developing a regional climatic pavement deterioration model would allow pavement engineers to identify bases with rates of deterioration that are greater than or less than the regional model. This will help pavement engineers identify and investigate factors affecting the rate of deterioration. Future research could then be conducted to identify an individual base's M&R and design strategies that are could be contributing to the degradation of the pavement performance or are extending the lifespan of the pavement network.

1.2 Problem Statement

The Air Force has over 1.6 billion square feet of concrete and asphalt pavements in its current infrastructure inventory. Over the past two decades, pavement engineers at AFCEC-East have noticed the majority of the identified distresses from the PCI airfield surveys are climate related. To verify these trends, a comprehensive analysis of the current airfield pavement distress database must be accomplished based on a climate region perspective. There are a number of climatic models that exist however; the models data were outdated and not suitable for the analysis of pavement deterioration. Therefore, a regional climatic model must be created to conduct this type of analysis. Generating a regional climate model will allow an in-depth analysis of how the average rates of deterioration of bases compare to that of a climatic regional rate of deterioration. Furthermore, this analysis will establish a baseline that will allow pavement engineers to investigate and identify, through future research, which variables are causing average rates of deterioration to differ from the regional rates of deterioration.

1.3 Research Objectives

The objective of this research was to answer the question: How can climate regions, within the United States, be used to understand and quantify the effects of climatic conditions on the deterioration rates of airfield pavements? To effectively answer this question, the following investigative questions were addressed.

1. What climatic/environmental variables should be used to develop a regional climate model for pavement deterioration modeling?
2. How do the regional climate-based average rates of deterioration for each family of pavements compare to the individual base average rates of deterioration for each family of pavements within the same region?
3. Are the climate based regional average rates of deterioration statistically different from one another?

These research objectives revolve around establishing an understanding of how environmental factors affect pavement deterioration rates and developing a conceptual process to evaluate the effects of environmental factors on pavement deterioration rates.

1.4 Methodology

The methodology used to accomplish the main goal of this research effort had three major parts. The first part created four regional climate zones for the continental United States, Hawaii, and Alaska and classifies each Air Force base with an operational airfield into one of the four zones. The second part used the climate zones and the PCI survey data to create a regional pavement deterioration models for each base and for each family of pavements defined in Figure 2. The third phase was to conduct a statistical examination of the individual, regional, and overall average rate of deterioration for each of the family of pavements.

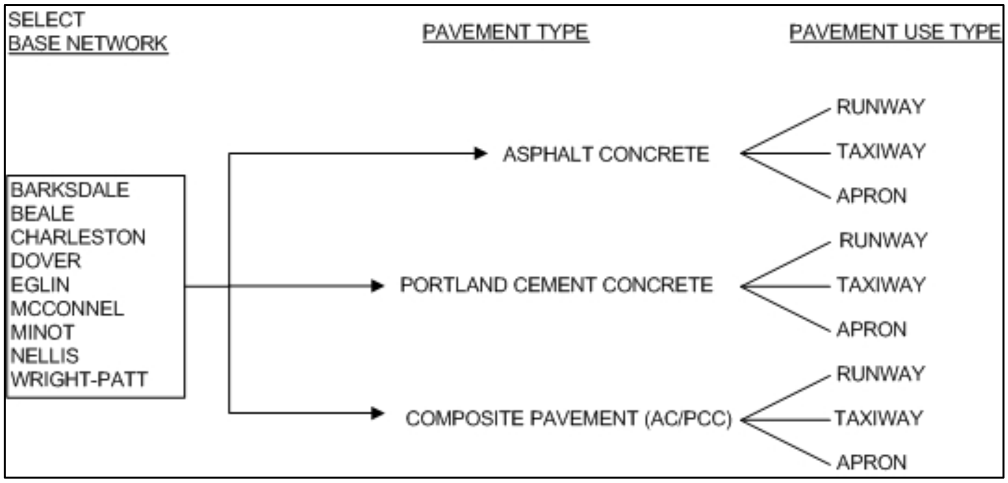

Figure 2. Family Definition Tree (Shahin, 2005)

Initial efforts to find a suitable climate model for the research were not successful. The Federal Highway Administration (FHWA) was contacted to acquire information regarding their climate zone model, but was informed that the model was developed in the early 1990s and was out of date and had not been updated. Therefore, research was conducted to find environment/climate variables that effect pavement deterioration within the relevant literature. Four variables, temperature, precipitation, subsurface moisture, and freeze-thaw cycles, were identified as having the most significant impact on pavement deterioration. Precipitation and Freezing-Degree-Day (FDD) data was acquired from WeatherBank Inc. located in Edmond, Oklahoma, to build the climate model for this research effort. WeatherBank continuously collects data from approximately 1,700 National Oceanic and Atmospheric Administration (NOAA), National Weather Service (NWS), and Federal Aviation Administration (FAA) stations scattered across the United States, including Alaska and Hawaii. The data provided was collected from 1982 through 2011. A 30-year average value for precipitation and FDD was provided for each of the 1,700 stations. To create a climate model, ArcGIS's geostatistical interpolation capabilities and the WeatherBank data was used to create four climate zones: Freeze-Dry, Freeze-Wet, No Freeze-Dry, and No Freeze-Wet. The specific thresholds that defined each of the zones were established through the guidance of engineers at the U.S. Army Cold Regions Research and Engineering Laboratory.

Once the climatic regional models were developed, the climate information was imported into the Air Force pavement distress database within PAVER^{TM}. To generate regional pavement deterioration models, the PAVER^{TM} database was first organized into pavement family types, i.e., Portland Cement Concrete (PCC), Asphalt Concrete (AC), and composite pavements (AC/PCC combination), and then by pavement usage categories, i.e., runways, taxiways, and aprons. Figure 2 is an example of a family definition tree using the pavement factors: use, type, and rank. This figure is a representation of how the data was organized to enable PAVER^{TM} to develop the pavement deterioration models.

Utilizing the pavement condition prediction modeling function in PAVER^{TM}, pavement deterioration models were created for every pavement family at each base in each climatic zone. The final phase of this study was a statistical examination of the individual, regional, and overall average rate of deterioration for each family of pavements. This will assist with identifying bases that have average rates of deterioration above and below 1 standard deviation from the regional rate of deterioration. The final part of the statistical analysis was to conduct an analysis of variance (ANOVA) to test the hypothesis that the climate region rates of deterioration for each family of pavements are statistically different from one another and different from the Air Force overall rate of deterioration for each pavement family.

1.5 Overview

This chapter established the background and objectives for this research effort. Chapter 2 examines existing literature relating to pavement management systems, pavement conditions surveys, pavement deterioration, and pavement condition prediction models. Chapter 3 discusses the methodology used for the three phases of developing the new climatic pavement prediction deterioration models. Chapter 4 discusses the results from generating a climate model with four zones and the statistical analysis of the regional average rates of deterioration. Finally, Chapter 5 provides a discussion of the findings and conclusions of the research effort along with recommendations for future research on this topic.

2.0 Literature Review

This chapter discusses the current practices and body of knowledge for pavement management principles, techniques, and systems. It also discusses how pavement management systems utilize predictive performance models to enhance a decision-maker's capabilities of creating and implementing maintenance and rehabilitation strategies. Furthermore, this chapter discusses the effects of certain environmental factors on pavement deterioration and performance.

2.1 Asset Management

The United States government, Department of Defense (DoD), and Air Force are facing fiscal uncertainty for the foreseeable future. The political volatility in Washington, D.C., is triggering a wave of budget cuts and constraints across the entire federal government. In 2013, the DoD will operate with a reduced budget and the threat of looming sequestration cuts. The FY 2013 budget has reduced defense spending $5.2 billion from 2012 and will reduce planned spending by $487 billion over the next 10 years (Chief Financial Officer, 2012). The American Taxpayer Relief Act of 2012 deferred proposed sequestration budget cuts, from the Budget Control Act, until March 1, 2013. The proposed sequestration will cut the DoD by $500 billion, on top of the $478 billion in cuts already proposed over the next 10 years (Garamone, 2012). DoD officials have warned top political officials that these sequestration cuts will "blow the bottom out of the defense strategic guidance released in early 2012" (Garamone, 2012). Efforts are currently underway, on all fronts, to reduce federal spending across the full spectrum of the federal government in an attempt to reduce the federal deficit, which in turn has significant impacts on the DoD and the Air Force. Memorandums released by the Deputy Secretary of Defense and the Under Secretary of the Air Force in early 2013 paved the path to “implement immediate prudent actions to mitigate probable budget reductions” (Carter, 2013).

Large portions of the cuts will affect the maintenance and repair budgets used to maintain the Air Force’s aging infrastructure, including airfield pavements. Aging infrastructure, both on and off of military installations, are deteriorating at a rapid rate due to the lack of adequate funds designated for maintenance and repair in most annual operating budgets. The Air Force is not exempt from the challenges of managing old and outdated infrastructure while striving to maintain the ability to support the mission directives of the DoD. In 2011, Gen. Norton Schwartz, Air Force Chief of Staff, stated the Air Force “will play a role in the solution not by retrenching or continuing business as usual on a reduced scale…” but by making “difficult choices to balance near-term operational readiness with longer term needs and fit all of that into a more affordable package” (Air Force Civil Engineer, 2011, p. 2). As a result, Air Force engineers are exploring and developing new innovative processes and procedures for accomplishing a strategic approach to managing facility and infrastructure assets.

The Air Force Civil Engineer mission is to “provide, operate, maintain, and protect sustainable installations as weapon-systems platforms through engineering and emergency response services across the full mission spectrum” (Air Force Civil Engineer, 2011). To accomplish this mission, the Civil Engineer (CE) community has developed the following three main strategic goals to meet the challenges facing the Air Force in near future: Build ready engineers, Build great leaders, and Build sustainable installations. To address these challenges within the Air Force, new principles and practices must be identified and created to facilitate a new era of asset and infrastructure management. The CE community has responded and is in the process of implementing asset management as the foundation of CE operations in "Building Sustainable Installations," which is the third goal identified in the 2011 U.S. Air Force Civil Engineer Strategic Plan.

Asset management, often referred to as facility management (FM), consists of tools developed over the past 20 years in the public and private sectors to effectively manage facility and infrastructure assets. The International Infrastructure Management Manual describes asset management as "the combination of management, financial, economic, engineering and other practices applied to physical assets with the objective of providing the required level of services in the most cost effective manner" (AASHTO, 2011, p. 1-11). FM embraces these concepts in an attempt to provide and maintain adequate facilities and infrastructure in the built environment, which could be a large city's roadway network or military installation's airfield network. However, accomplishing FM is a monumental challenge when dealing with unrelenting budgets cuts and massive reductions in workforces (Cotts, Roper, & Payant, 2010). Airfield pavements represent a major asset in the Air Force's infrastructure inventory. Preservation of this asset is of the upmost importance, which requires solid design and construction techniques and standards, quality management practices, robust inspection programs, innovative technology, and adequate financing.

In the public sector, Transportation Asset Management (TAM) is a branch of Asset Management that has gained strength over the past decade. The American Public Works Association Asset Management Task Force defines TAM as "…a methodology needed by those who are responsible for efficiently allocating generally insufficient funds amongst valid and competing needs" (Office of Asset Management, 1999). This quote sheds light on the new fiscal environment that Civil Engineers face for the foreseeable future due to the current fiscal situation in the federal government. Asset Management and Transportation Asset Management are holistic concepts that help managers and decision-makers organize, plan, and implement goals and objectives. Asset managers most accomplish these tasks while maintaining their responsibility to optimize expenditures and to maximize the value of the assets over its life-cycle. The International Infrastructure Management Manual (IIMM) describes the purpose of TAM as "to meet a required level of service, in the most cost effective manner, through the management of assets for present and future conditions" (AASHTO, 2011, p. 1-12). In essence, the main goal of TAM is to build, maintain, and operate facilities in the most cost-effective manner while providing the best value to the stakeholder or customer. TAM can touch nearly every aspect of a transportation agency's business, to include everything from planning, engineering, construction, and maintenance. TAM or AM is a way of doing business that brings a particular perspective to how a public agency or federal entity should conduct daily business.

The benefits of implementing a comprehensive asset management plan can be seen in a variety of ways. Asset management plans provide a long-term view for organizations. This puts an emphasis on managing assets throughout the duration of their life-cycle, which could be 40 years or longer (AASHTO, 2011). This provides a level of comfort to the stakeholders by knowing that the assets are being managed for their expected lifespan. A properly executed TAM plan will have its principles and practices integrated into every level of the organization. A strategic TAM plan will deliver the desired level of service to the customer or stakeholder, through sound financial planning coupled with solid management plans and concise reporting tools (AASHTO, 2011). Furthermore, transportation assets such as airfields are costly to build, maintain, operate and use. Therefore, stressing the importance of life-cycle analysis, the AASHTO Transportation Asset Management Guide states, "TAM helps to ensure that the benefits delivered by the network are maximized while the cost of providing, maintaining, and using it are minimized" (AASHTO, 2011, p. 1-13). A well designed asset management plan and process can provide an organization a comprehensive picture of asset performance. Air Force engineers use a variety of asset management tools to develop a comprehensive picture of the wide range of facility and infrastructure assets that exist on an installation. In the pavement arena, engineers use the pavement management systems approach to accomplish the strategic goals of asset management.

2.2 Pavement Management Systems

Airfield managers and engineers go to great lengths to ensure that the pavement associated with an airfield are safe for flying operations every day of the year. In the Air Force, this enormous responsibility is accomplished through teams of expert engineers at the Air Force Civil Engineer Center (AFCEC), at the respective Air Force Major Commands (MAJCOM), and local engineers at the respective installations. To effectively manage the 1.6 billion square feet of concrete and asphalt pavements, Air Force engineers have implemented a Pavement Management (PM) system. A PM system is a systematic tool that enables effective and economical management of an entire pavement network. Shahin (2005, p. 1) describes a PM system as “a systematic, consistent method for selecting Maintenance and Rehabilitation (M&R) needs and determining priorities and the optimal time of repair by predicting future pavement condition.” PM systems are designed to assist decision-makers in finding strategies for funding and maintaining pavements to a specified condition over time in the most economically feasible plan. According to Shahin and Walther (1990), 80% of the repair costs can be avoided if M&R is performed before the rate of deterioration of the pavement increases sharply, as shown in Figure 3. Neglecting the importance of routine pavement inspections to identify distresses that are in need of repair in a pavement network has negative financial consequences.

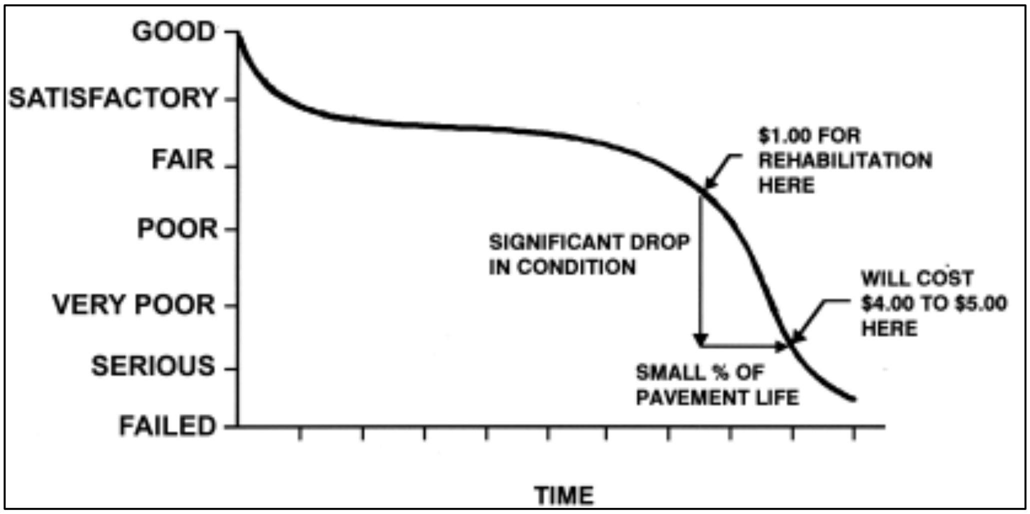

Figure 3. Conceptual Illustration of a Pavement Condition Life-cycle (Shahin, 2005)

As the backbone of the installation weapon-system, airfields require constant investment and attention to maintain an adequate pavement network for flying operations. The Air Force does have installations that have pavements that were originally constructed in the 1940s and 1950s that still exist. The fact that these pavements are still serviceable is due to the active maintenance programs on these installations, which allows for a high operations tempo. However, the current fiscal climate does not warrant the ability to replace full runways and/or aprons. Therefore, the maintenance program must be proactive to extend the service life of existing pavements. Managing aging pavement networks is a rather difficult task due to the complexity of pavement behavior in the variety of climate regions across the United States. Through multiple years of research, PM systems have been created and developed to provide a structured and inclusive approach to pavement management.

A PM system can incorporate a variety of processes and tools to accomplish the strategic goals of the pavement management organization. Pavement management is conducted at two levels: at the network level and project level. Network-level management is used for budgeting, planning, scheduling, and selecting of potential M&R projects for an entire pavement network, such as an Air Force installation (Shahin & Walther, 1990). To accurately select potential projects at this level, the future condition of each section must be accurately predicted. Projecting the future condition of the section enables two tasks to be performed. The first task is to schedule future inspections for sections that have been flagged for having a high rate of deterioration. The second task is to identify sections of pavement that will require major M&R in future years for budget estimating (Shahin & Walther, 1990). Typically, these sections are flagged for major M&R projects because their condition has reached a predetermined level. As seen in Figure 3, this is the point at which the curve begins the sharp decline in condition and major M&R projects should be executed. Therefore, network-level management requires managers to consider the organization's current and future budget needs, consider the current and future network pavement condition, and identify and prioritize a list of projects to be considered at the project level (Shahin & Walther, 1990). At the project level, projects identified from the network-level analysis undergo an in-depth evaluation to develop alternatives based on specific site conditions (Shahin & Walther, 1990). The analysis done at this level will produce a list with the most cost-effective M&R projects within existing management or organization constraints (Shahin & Walther, 1990). Pavement management engineers need a systematic approach to pavement management to deliver the most strategic plans that deliver the best return on investment (Shahin, 2005).

The PM approach consists of six main steps: Inventory Definition, Pavement Inspection, Condition Assessment, Condition Prediction, Condition Analysis, and Work Planning. The first four steps will be discussed in detail over the next sections in this chapter. This approach has evolved over 30 years of research and development of the PAVER^{TM} pavement management system (Shahin, 2005). Air Force, Army and Navy pavement managers use this computer software pavement to automate the analysis and storage of the data associated with a PM system. PAVER^{TM} was initially developed in the late 1970s to help the Department of Defense manage maintenance and repair activities for its enormous pavement inventory (Colorado State University, 2012). The development of this program was orchestrated under the backing of the U.S. Army Corps of Engineers with funding from both the Air Force and the Army (Shahin & Walther, 1990). The program continues to be updated by the U.S. Army Corp of Engineers with funding provided by the Air Force, Army, Navy, Federal Aviation Administration, and the Federal Highway Administration. There are numerous other software programs similar to PAVER^{TM}; however, this program is used exclusively by the whole DoD to analyze and summarize data collected from airfield inspections.

2.2.1 Inventory Definition

Inventory Definition breaks the pavement inventory into networks, branches, and sections. A network is a logical grouping of pavements for M&R management. For example, a military installation could have two networks, one for the base roadways and one for all of the airfield pavements. Shahin (2005, p.2) defines a branch as "an easily identifiable entity with one use, for example a runway, a taxiway, or a parking apron." A branch can be further subdivided into sections based on construction condition of pavement and/or traffic. A section is the smallest pavement area and must consist of the same pavement type, i.e., concrete or asphalt. A section is also the smallest management unit in the PAVER^{TM} PM systems, where M&R treatments are selected and applied. Pavement managers must take into account factors such as pavement structure, construction history, traffic, and pavement rank when determining how to break branches into sections (Shahin, 2005). The next phase in the process is to conduct a pavement inspection.

2.2.2 Pavement Inspection

Airfield inspections conducted on Air Force installations provide full spectrum structural, surface distress, and friction airfield evaluations. This program provides critical data to Air Force engineers to efficiently manage and effectively control airfield pavements. According to AFI 32-1041, *Airfield Evaluation Program*, engineers use the pavement strength, condition, and performance data to accomplish the following (Department of the Air Force, 1994).

- Determine the size, type, gear configuration, and weight of aircraft that can safely operate from an airfield without damaging the pavement or the aircraft.
- Develop operations usage patterns for a particular aircraft pavement system (for example, parking, apron use patterns, and taxiway routing).
- Project or identify major maintenance or repair requirements for an airfield pavement system to support present or proposed aircraft missions. Evaluations provide engineering data to help in designing projects.
- Help airbase mission and contingency planning functions by developing airfield layout and physical property data.
- Develop and confirm design criteria.
- Help justify major pavement projects.
- Ensure flying safety by providing pavement surface data which quantify traction and roughness characteristics.

Initially, all pavement evaluation testing was destructive in nature, which caused significant airfield closures and severely impacted airfield operations (Davit, Brown, & Green, 2002). These tests were labor intensive and took as long as 8 hours to complete, including time for repairs. Plate bearing tests were performed on rigid pavements and California Bearing Ratio tests were performed on flexible pavements (Davit, Brown, &

Green, 2002). In the 1970s, non-destructive testing methods were introduced to reduce the conflicts caused by closing the airfields for extended periods of time. Between 1985 and 1990, multiple new technologies were incorporated to minimize disruptions to airfield operations, enhance ability to respond to contingencies, and reduce analysis and reporting times (Davit, Brown, & Green, 2002).

There are three main types of evaluations that are performed during the course of a pavement evaluation: airfield pavement structural evaluation, runway friction characteristics, and airfield pavement condition index (PCI) surveys. Active airfields are structurally evaluated on an 8-10 year cycle along with PCI surveys conducted every 3 or 5 years. The data collected from the surveys help base and command personal determine the operational condition of pavements, prioritize repair and construction projects, and determine whether an airfield structural pavement evaluation is needed (Department of the Air Force, 1994). PCI surveys will be discussed in the Pavement Condition section of this chapter.

2.2.2.1 Structural Evaluations

Airfield pavement structural evaluations determine a pavement‘s load-carrying capacity by testing the physical properties of the pavement in its current condition (Department of the Air Force, 1994). Typical equipment includes Heavy Weight Deflect (HWD) meters, automated and manual dynamic cone penetrometers (DCPs), and pavement core drills. The HWD test is one of the most widely used tests when assessing the structural integrity of airfield pavements (Gopalakrishnan, 2008). This test is conducted by dropping a large mass onto a circular metal plate, on which seven deflection measurement sensors are attached to record the resultant forces and deflections (Davit, Brown, & Green, 2002). This piece of equipment has the ability to impart a load to the pavement with weights ranging from 6,500 pounds to 54,000 pounds (Davit, Brown, & Green, 2002). The system uses an on-board computer to record the deflection data and provides the operator with instantaneous deflection information that is stored for further analysis (Davit, Brown, & Green, 2002). The ultimate goal of the HWD is to replicate the force history and deflection magnitudes of a moving aircraft tire (Gopalakrishnan, 2008).

The second tool often used for structural evaluation is the Dynamic Cone Penetrometer (DCP) and the Automated DCP (ADCP). Results from the test can be used to determine the soil type and California Bearing Ratio (CBR); it can also be used to interpret soil layer thickness in underlying pavement layers (Davit, Brown, & Green, 2002). These tests consist of dropping a hammer with a known weight and drop height, manually or mechanically, against an anvil that drives a cone into the soil. The number of hammer blows is quantified in terms of a DCP index, which is a ratio of the depth of penetration to the number of blows of the hammer (Davit, Brown, & Green, 2002). The DCP index is then correlated to CBR.

The final structural evaluation that is conducted is core drills of rigid and flexible pavements. The core drill is used to take pavement samples and gain access to the base, subbabse, and subgrade so DCP and ADCP testing can be conducted and take soil samples to characterize the soil type, layer thickness and calculate in-situ soil strength. The cores are extracted from asphalt concrete and PCC pavements by a six-inch diameter diamond-tipped coring barrel (Davit, Brown, & Green, 2002). At least one core sample from each airfield feature is taken by HQ AFCEC Airfield Pavement Evaluation tea for laboratory testing. These structural tests are used to get adequate data about the existing airfield pavements to ensure that airfields are fully capable of supporting the flying mission.

2.2.2.2 Friction Characteristic Evaluation

The second type of pavement evaluation conducted on Air Force airfields is a friction characteristics evaluation. According to Air Force Instruction 32-1041, runway friction characteristics evaluations assess a runway's tractive qualities and hydroplaning potential since they contribute to aircraft braking response. This evaluation has three primary objectives: determine certain runway surface characteristics (such as slope and texture), conduct measurements of the runway surface coefficient of friction, and assess the capability of the runway to drain excess water and recover its friction properties (AFCESA, 1994). Pavement surface transverse and longitudinal slopes are measured every 500 feet along the entire length of the runway. Transverse slopes are measured at distances of 5 and 15 feet on both sides of the runway centerline. The surface texture measurement is conducted by a flow meter. The final test is completed through the use of continuous friction measuring equipment. This equipment uses internal systems to simulate rain-wetted pavement surface conditions during which friction measurements are taken while the system is traveling at speeds between 40 and 60 miles per hour. This test helps identify areas of the runway pavement that are smooth due to poor macro or microtexture, excessive wear due to heavy traffic, aggregate polishing, heavy rubber build-up, and/or oil/fuel spills (AFCESA, 1994).

2.2.3 Condition Assessment

One of the most important features of a solid PM system is the ability to determine the current condition of a pavement network in order to predict a future condition (Shahin, 2005). Starting in 1968, the U.S. Army Construction Engineering Research Laboratory (USACERL) began developing an objective and repeatable rating system to be used to provide an index of a pavement's structural integrity and surface operational condition (Shahin, 2005). Their research led to the development of the Pavement Condition Index (PCI).

The PCI is a numerical index that measures pavement condition on a scale from 0 to 100, with 0 being the worst and 100 being perfect (Shahin, 2005). The PCI rating system provides commanders a visual trigger regarding the level of maintenance and/or repair activities that should be performed (Davit, Brown, & Green, 2002). Figure 4, is an example of a PCI rating scale.

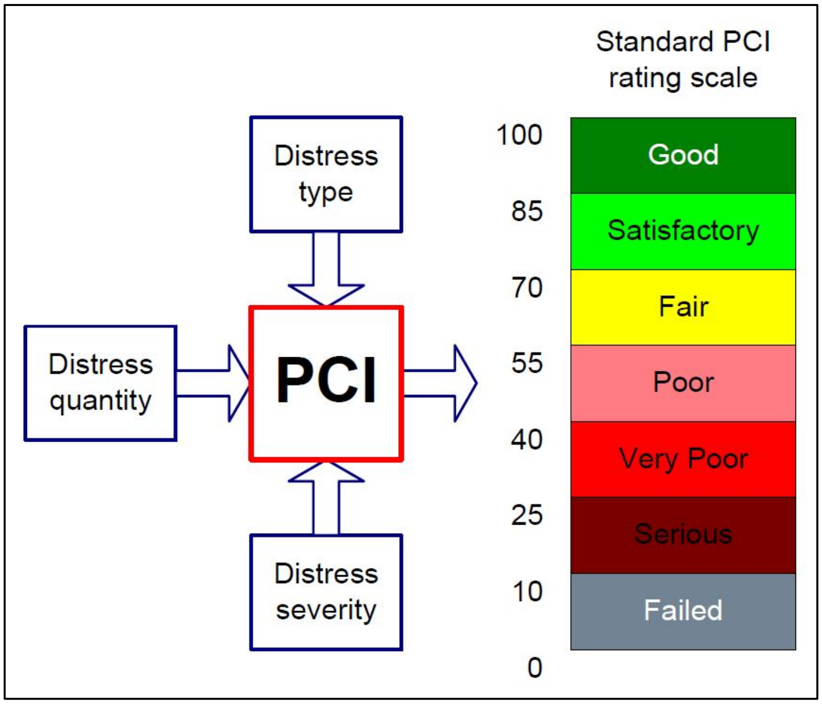

Figure 4. Pavement Condition Index (PCI) Rating Scale (Colorado State University, 2012)

The PCI is calculated based on the results of a visual survey in which distress type, severity, and quantity are identified for a predetermined number of sample units. (Shahin, 2005). The PCI survey is conducted by trained individuals to identify and document pavement distresses caused by aircraft loading and environmental conditions. The distresses used to calculate the PCI for both roadways and airfield pavements can be found in the American Society for Testing and Materials D6433-11 and D5340-11, respectively. The distress information collected during a pavement condition inspection provides pavement managers insight into whether the distress is caused by repetitive loading or overloading, climactic factors, or other factors such as construction-related issues (Shahin, 2005). Shahin (2005, p. 17) states, “The degree of pavement deterioration is a function of distress type, distress severity, and distress density.” However, developing an index that accounted for all factors proved to be extremely difficult. Therefore, “deduct values” are used as weighting factor’s to accurately account for the effect that each combination of distress type, severity level, and distress density has on pavement condition (Shahin, 2005). The PCI can either be calculated by hand or the inspection data can be entered PAVER^{TM} to help automate the calculations and analysis.

2.2.4 Condition Prediction

Predicting future pavement performance is a critical tool for pavement managers and engineers. Pavement prediction modeling is an absolutely essential element of any complete PM system. The accuracy of the prediction model can heavily influence many strategic management decisions, especially when it comes to M&R strategies for a particular agency. Accurate and reliable performance prediction models are needed now more than ever due to the drastic budget cuts that the DOD will have to deal with in the near future.

Condition prediction models are used at both the network and project levels to analyze the condition of the pavement and to determine the required maintenance and repair activities (Shahin, 2005). Shahin (2005, p. 141) points out that uses of prediction models include “condition forecasting, budget planning, inspection scheduling, and work planning.” Likewise, Gendreau and Soriano (1998, p. 202) state, “that at the network level, they (performance prediction models) serve first and foremost in the selection of optimal M&R strategies and in short- and long-term budget optimizations.” At the project level, the use of prediction modeling is used for detailed analysis when selecting M&R

alternatives, or for designing pavements, as well as providing input when performing life-cycle cost analyses (Shahin, 2005).

Many techniques exist for developing a pavement deterioration model, such as straight-line extrapolation, regression (empirical), mechanistic-empirical, polynomial constrained least square, and others (Shahin, 2005). However, the PAVER^{TM} software uses the Family Method that was created in a research program conducted at the U.S. Army Engineering Research and Development Center-Construction Engineering Research Laboratory (Shahin, 2005). A "family" modeling approach is used by many pavement management systems to generate performance models. This approach groups pavement sections with similar characteristics and uses regression modeling to determine the rate of deterioration for the specified family of pavement. This method consists of five major steps to develop the pavement deterioration model for a pavement section: (1) Define the pavement family, (2) Filter the data, (3) Conduct data outlier analysis, (4) Develop the family model, and (5) Predict the pavement section condition (Shahin, 2005).

The first step in the process is to define the pavement family. A pavement family is defined as a group of pavement sections with similar deterioration characteristics (Shahin, 2005). The individual user or installation can define a family based on numerous factors, including pavement use category, surface type, pavement rank, construction date, and PCI. Figure 2, in Chapter 1, is an example family definition using three factors: use, type, and rank.

Many techniques exist for developing a pavement deterioration model, such as straight-line extrapolation, regression (empirical), mechanistic-empirical, polynomial constrained least square, and others (Shahin, 2005). However, the PAVER^{TM} software uses the Family Method that was created in an extensive research program conducted at the U.S. Army Engineering Research and Development Center-Construction Engineering Research Laboratory (Shahin, 2005). This approach groups pavement sections with similar characteristics and uses constrained least square modeling to determine the rate of deterioration for the specified family of pavement. This method consists of five major steps to develop the pavement deterioration model for a pavement section: (1) Define the pavement family, (2) Filter the data, (3) Conduct data outlier analysis, (4) Develop the family model, and (5) Predict the pavement section condition (Shahin, 2005).

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The next step in the "family" method is to filter the data. PAVER^{TM} allows the users to filter or remove suspicious data points. The PAVER^{TM} program conducts internal checks to find data that potentially contain errors. It moves inspection data to the "errors file" if PCI values are different for the same section and age. If the same section is listed twice with the same PCI and age, only one point is retained for that section and age. By defining the boundaries of the minimum and maximum life span of the pavement section, the user can further identify pavement sections that may contain errors.

The main goal of this step is to remove obvious errors from the data set before continuing with the development of the pavement prediction models.

The third step takes data filtering to the next level by examining the data for statistical removal of extreme points. This step is vital because in the event there is a pavement section that has unusual performance it needs to be identified. Pavements with unusual performance can have considerable effects on the family performance model. PAVER calculates the prediction residuals, which are the differences between the observed and predicted PCI values, using a fourth-degree polynomial least-error curve (Shahin, 2005). In the initial development of this model, the residuals were found to have a normal frequency distribution which allowed for confidence intervals to be set (Shahin, 2005). If pavement sections are found to be outside of the confidence interval, they are placed in the outlier error file.

The fourth step of the process is to create the family deterioration model. The fitted polynomial is constrained in such a way that the model PCI can't increase with age without the intervention of M&R activities. An unconstrained option is also available. The final step is to predict the pavement section condition. The predictive curve for a particular pavement family depicts the representative behavior of all of the pavement sections for the family of pavements (Shahin, 2005). The deterioration of all the pavement sections in a given family are similar and are a function of only their present condition, regardless of age (Shahin, 2005). Figure 5 shows that a section predictive curve, drawn through the latest PCI/age point, is parallel to the family prediction curve.

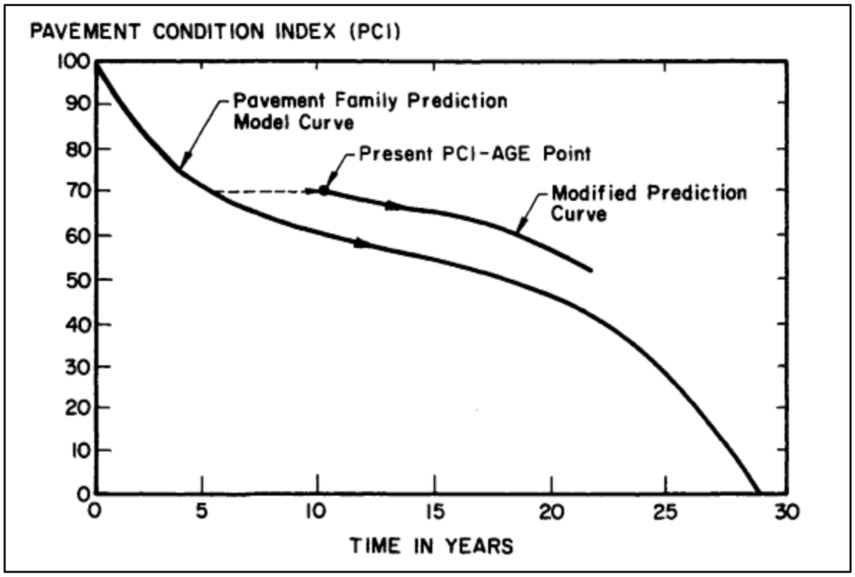


Figure 5. Pavement Section Prediction in Relation to the Family Model (Shahin, 2005)

The effects of maintenance, traffic, drainage, and other factors that affect pavement performance can be seen in the section-to-family comparison (Shahin, 2005). One can learn a great deal by comparing the section curve to the family deterioration curve.

2.4 Environmental Factors Affecting Pavement Deterioration

Airfield pavements must be able to function in a wide array of environmental conditions supporting multiple types of aircraft all over the world. Environmental, or climate, conditions can have significant impacts on pavement and sub-grade materials, which can radically affect the performance and lifespan of a pavement surface. Environmental conditions can affect the strength and load-bearing capacity of the pavement (Li, Mills, & McNeil, 2011). The effects of climate factors can be exacerbated when combined with factors such as traffic loads, construction methods, materials, and

M&R strategies (Li, Mills, & McNeil, 2011). The most notable environmental factors that affect pavement performance are temperature, precipitation, subsurface-moisture, and freeze-thaw cycles; these factors all have a major impact on long-term pavement performance (Haas, 2001; Johanneck & Khazanovich, 2010; Li, Mills, & McNeil, 2011; Loizos, Roberts, & Crank, 2002; Mfinanga, Ochiai, Yasufuku, & Yokota, 1996; Mills & Andrey, 2002). Pavements are susceptible to deterioration and deformation in situations where they are exposed to weather or climate conditions overtime. Accounting for these effects will help pavement engineers design and manage more suitable pavements for current climatic conditions.

2.4.1 Temperature

Temperature variations can cause damage in both flexible and rigid airfield pavements. However, the temperature effects produce different distresses in PCC versus AC pavements, which lead to different rates of pavement deterioration. In flexible pavements, high and low temperatures can affect the stiffness properties of the bituminous layers. For example, at low or freezing temperatures, asphalt becomes hard and brittle, which can cause thermal cracking (Hironaka, Cline, & Schiavino, 2004). In essence, the asphalt layers shrink and harden, which causes cracks to propagate through the asphalt layers. The most common form of thermal cracking is transverse cracking. The asphalt binder grade, age of the asphalt pavement and pavement temperature are the primary factors affecting transverse cracking in AC pavements (Moses, Husley, & Connor, 2009). However, most pavement engineers develop mix designs and appropriate binders for the climate that the pavement will be constructed in.

Unlike asphalt pavements, Portland Cement Concretes (PCC) does not experience the same type of distresses with high or low temperatures. Variations in temperature can cause damage due to expansion, contraction, and slab curling. Typically, when PCC experiences wide temperature gradients, stress and strains are introduced into the concrete layers and result in distortions in the shape of the slab. For example, curling is the deflection of a PCC slab due to a temperature differential through the depth of the PC slab (ASCE). In upward curling, the edges of the slab curl upward. This is a result of the slab surface being cooler than the slab bottom (ACSE). Repetitive trafficking of curled slabs can cause corner cracking.

2.4.2 Precipitation and Subsurface Moisture

Precipitation and subsurface moisture is the root of many problems that affect pavement deterioration. Moisture becomes a problem in both PCC and AC when distress open cracks in the pavement surface allowing moisture to infiltrate the pavement and the underlying layers potentially reducing the strength of the subgrade, base, and subbase. A combination of moisture, heavy traffic loads, and freezing temperature can have negative effects on the material properties, overall performance, and rate of deterioration of a pavement network (Boudreau, Christopher, & Schwartz, 2006). High and low temperatures can cause surfaces distress that allow water to seep into the various pavement and subbase layers. Joints, cracks, shoulder edges, and other surface defects provide easy access for water to penetrate into the subsurface pavement layers. Over time, as the pavement continues to deteriorate, cracks become wider and more abundant. This results in more moisture being allowed to penetrate into the pavement structure, which leads to an accelerated deterioration rate and an increased number of moisture-related distresses (Boudreau, Christopher, & Schwartz, 2006). Tables 1 and 2 outline specific distresses that are caused by excessive moisture within flexible and rigid pavements. The detrimental effects of water that has infiltrated a pavement structure are outlined by AASHTO (1993) as:

- Reduced strength of unbounded granular materials,
- Reduced strength of subgrade soils,
- Pumping of concrete pavement with subsequent failing, cracking, and general shoulder deterioration, and
- Pumping of fines in aggregate base under flexible pavements with resulting loss of support.

Once moisture has infiltrated a pavement structure, the capabilities, performance, and design life will be drastically reduced. This is why moisture is one of the main environmental factors that have significant effects on pavement deterioration.

2.4.3 Freeze/thaw weakening

Cold regions cover approximately one-third of the United States. Pavements are subjected to freezing in the winter months and thawing in the spring. During the winter months the load carrying capacity of the pavement increases because the pavement structure is frozen (Janoo & Berg, 1991) In the spring months, the pavement structure below the PCC or AC pavements thaw and can become saturated with water from the melting ice lenses and infiltration of surface water. The saturation of the underlying layers could reduce the strength of the base, subbase, and subgrade which, could led to an overall reduction of bearing capacity of the entire pavement structure (Janoo & Berg, 1998). Freeze/thaw cycles can potentially cause spalling, scaling, and durability cracking PCC pavements and intensify fatigue (alligator) and transverse cracking in AC pavements. In essence, typical loading may severely damage a pavement during the spring thaw seasons in areas prone to freeze/thaw cycles every year.

Weather and climate factors directly affect pavement performance and the rate at which the pavement deteriorates. These factors also affect the planning, design, construction, and maintenance and repair strategies of pavement infrastructure, both roadways and airfields. Pavement managers must be cognizant of the climate factors that affect their area to enable better M&R strategies for preventive maintenance of the pavement network.

Table 1. Moisture Related Distresses in Flexible (AC) pavements (Boudreau, Christopher, & Schwartz, 2006)

Type	Distress Manifestation	Moisture Problem	Climatic Problem	Material Problem	Load Associated Distress	Structural Defect Begins in		
						AC	Base	Subgrade
Surface Deformations	Bump or Distortion	Excess Moisture	Frost Heave	Volume Increase	No	No	No	Yes
	Corrugation or Rippling	Slight	Moisture and Temperature	Unstable Mix	Yes	Yes	Yes	No
	Stripping	Yes	Moisture	Loss of Bond	No	Yes	No	No
	Rutting	Excess in Granular Layers or Subgrade	Moisture	Plastic Deformation, Stripping	Yes	Yes	Yes	Yes
	Depression	Excess Moisture	Suction & Materials	Settlement, Fill Material	No	No	No	Yes
	Potholes	Excess Moisture	Moisture, Temperature	< Strength, > Moisture	Yes	Yes	Yes	Yes
Cracking	Longitudinal	No; Accelerates	No	Construction	No	Faulty Construction	No	No
	Alligator (fatigue)	Yes; Accelerates	Spring - Thaw, Strength loss	Thickness	Yes	Yes, Mix	Yes	No
	Transverse	No; Accelerates	Low Temp. Freeze - Thaw Cycles	Thermal Properties	No	Yes, Temp. Susceptible	No	No
	Slippage	Yes	No	Loss of Bond	Yes	Yes, Bond	No	No

Table 2. Moisture Related Distress in rigid (PCC) pavements (Boudreau, Christopher, & Schwartz, 2006)

Type	**Distress Manifestation**	**Moisture Problem**	**Climatic Problem**	**Material Problem**	**Load Associated Distress**	**Structural Defect Begins in**		
						AC	**Base**	**Subgrade**
Surface Defects	Spalling	Possible	Freeze / Thaw Cycles	Mortar	No	Yes	No	No
	Scaling	Yes	Freeze / Thaw Cycles	Chemical Influence	No	Yes; Finishing	No	No
	D-Cracking	Yes	Freeze / Thaw Cycles	Aggregate Expansion	No	Yes	No	No
	Crazing	No	No	Rich Mortar	No	Yes; Weak Surface	No	No
Surface Deformation	Blow-up	No	Temperature	Thermal Properties	No	Yes	No	No
	Pumping and Erosion	Yes	Moisture	Inadequate Strength	Yes	No	Yes	Yes
	Faulting	Yes	Moisture - Suction	Erosion - Settlement	Yes	No	Yes	Yes
	Curling / Warping	Yes	Moisture & Temperature	Moisture and Temperature Differentials	No	Yes	No	No
Cracking	Corner	Yes	Moisture	Cracking Follows Erosion	Yes	No	Yes	Yes
	Diagonal Transverse Longitudinal	Yes	Moisture	Follows Erosion	Yes	No	Yes	Yes
	Punchout (CRCP)	Yes	Moisture	Deformation Follows Cracking	Yes	No	Yes	Yes

2.5 Regional Climate Model

The last section of this chapter outlines the background information that was used to develop a regional climate model for this research effort. The first section explains the environmental factors that were used as well as the supporting information for the data. The second section provides information pertaining to the Geospatial techniques and tools used to create the climate model.

2.5.1 Environmental Factors for Climate Model

Relevant to the current research effort, the following two environmental factors are explored in more detail in this section: precipitation and freezing degree-day (FDD). The National Oceanic and Atmospheric Administration defines precipitation as "the process where water vapor condenses in the atmosphere to form water droplets that fall to the Earth as rain, sleet, snow, hail, etc" (NOAA, 2009). Precipitation has detrimental effects on pavement, especially when precipitation infiltrates the lower pavement layers, subbase, and subgrade. The second environmental factor chosen for this analysis was freeze/thaw cycles in the form of FDD data. The Unified Facilities Criteria (UFC) 3-130-01, *General Provisions-Artic and Subartic Construction,* defines FDD as "the degree-days for any one day equal to the difference between the average daily air temperature and 32°F." FDD is calculated as,

$$FDD = (32 - T_a)$$

where T_a is the average daily air temperature in degrees Fahrenheit (White, 2004). An FDD is considered positive when temperatures are below freezing and negative when temperatures are above freezing (White, 2004). Freezing degree-days is an expression of a freezing index, which is used to calculate the depth of frost penetration in pavements and the subbase. AASHTO (1993, p. 1-25) defines the frost index as “the cumulative effect of intensity and duration of subfreezing air temperature.”

Freezing degree-day models or temperature indices have been used successfully to relate temperature data to frost penetration in pavement soil structures, heating requirements for building, ice-dynamic modeling, flood forecasting, hydraulic modeling, and snow melt modeling (Hock, 2003). According to Hock (2003, p. 104-105), temperature index models are extremely versatile due to four reasons: “(1) general wide availability of air temperature data, (2) relatively easy interpolation and forecasting possibility of air temperature, (3) generally good model performance despite their simplicity, and (4) conceptual simplicity.”

The depth of frost penetration is a vital piece of information that engineers must know or calculate to effectively design roadway or airfield pavements in seasonal frost regions, which experience winter temperatures that cause the ground to freeze and then thaw during the springtime (Cortez, Kestler, & Berg, 2000). In the 1950s, the United States Army Corps of Engineers (USACE) studied ground freezing and thawing cycles and how these cycles affect soil properties (Bianchini & Gonzalez, 2012). These research efforts resulted in the development of the modified Berggren (ModBerg) equation. Cortez, Kestler, and Berg (2000, p.92) describe this equation as, “A mathematical model that represents a one-dimensional heat flow across a moving freezing front beneath a paved or unpaved ground surface.” However, due to the complexity of the calculations required when using this equation, CRRL developed a tool within the Pavement-Transportation Computer Assisted Structural Engineering (PCASE) program to compute the frost penetration depth. Due to the large freeze susceptible area within in the U.S. and the detrimental effects that freeze/thaw cycles have on pavement performance and deterioration, FDD will be used as a primary variable for building the regional climate zones.

2.5.2 Quantitative Spatial Analysis

Spatial analysis is a form of quantitative study that encompasses a set of procedures to develop an inferential model that considers the spatial relationship present in geographic data. Geospatial analysis has the ability to provide a "distinct perspective on the world, a unique lens through which to examine events, patterns, and processes that operate on or near the surface of our planet" (de Smith, Goodchild, & Longley, 2007). Spatial interpolation is a spatial analysis tool that enables a user to make an estimate of a value of a continuous field at locations where measurements have not actually been taken (Longley, Goodchild, Maguire, & Rhind, 2011). At its core, spatial interpolation is founded on the Tobler Law. The Tobler law states, "nearby things are more related than distant things" (Longley, Goodchild, Maguire, & Rhind, 2011). In essence, the best way to estimate the value for a point is to use the values from the closest observation points.

Spatial interpolation can be accomplished with the help of geographic information system (GIS) applications to generate a continuous surface of a property (i.e., precipitation or temperature). Environmental Systems Research Institute's (ERSI) ArcInfo offers a suite of interpolation methods such as inverse distance weight (IDW) and kriging. Longley et al (2011) describe IDW as "employing the Tobler Law by estimating unknown measurements as weighted averages over the known measurements at nearby points, giving the greatest weight to the nearest point." In essence, IDW provides a simple way of estimating values at locations where measurements cannot be taken. The advantages of IDW are the simplicity of the core principles and programming, as well as providing quick and reasonable results (Hu, 1995). The primary disadvantage of IDW is that ambiguity may be introduced based on the choice of the weighing factor, especially when the underlying surface characteristics are not known and the interpolation can be effected by an uneven distribution of observed data points (Hu, 1995).

Kriging is one of the most common spatial interpolation techniques that depends on mathematical and statistical models. To generate a spatial interpolation surface, kriging uses a weighted moving average method (Hu, 1995). Kriging methods rely on the notion of autocorrelation to generate a predictive surface. Autocorrelation is a function of distance, which is a defining feature of geostatistic techniques (ESRI, 2012). Geostatistic techniques create a prediction surface, as well as the error or uncertainty surfaces, associated with the predictive surface. The error provides an indication of how good or bad the predictions are for the predictive surface.

Kriging has two distinct tasks: quantifying the spatial structure of the data and generating a smooth predictive surface. Quantifying the surface fits a spatial-dependent model to the observed data points. Embedded in this step, empirical semivariograms are calculated and interpreted to explore the relationship that the Tobler Law represents. In essence, pairs of data points that are close in distance should have a smaller difference compared to data points that are far away from one another (ESRI, 2012). Semivariograms measure the degree of spatial correlation between the observed data points based on a function of distance and direction (Hu, 1995). The software generates the spatial-dependent model by using the weighted least squares fit process. Kriging uses the spatial-dependent model, the spatial data configuration, and the values of the observed points to make a prediction for an unknown value for a specific location (ESRI, 2012).

The kriging method has its share of disadvantages. One of the main weaknesses is that the original observation points are seldom honored, which is one of the common problems with grid-based spatial interpolation methods (Hu, 1995). Because kriging is a smooth interpolation technique, situations where the surface appears to be on the wrong side of the observed data point may be observed in the generated surface. Kriging also has potential issues with the estimation of the semivariogram. Hu (1995) states, “it is not always easy to ascertain whether a particular estimate of the semivariogram is in fact a true estimator of the spatial correlation in an area.”

2.6 Literature Review Summary

This chapter examined the relevant literature related to pavement management and the associated tools and processes used to assist with the management responsibilities. This chapter also discussed the predominant environmental factors that can significantly affect pavement deterioration rates and pavement lifespan. Finally, this chapter discussed the tools and techniques to develop a regional climate model for the United States.

3.0 Methodology

The purpose of this chapter is to present the processes and analysis methods used for this research effort. The methodology is a three-phased approach. The first phase developed a four-zone regional climate model for the United States with weather data from WeatherBank Inc. The second phase developed average rates of deterioration models for each family pavement type that can be found on the 61 Air Force airfields located in the United States (U.S.). The final phase of the study was a statistical examination of the individual, regional, and overall average rate of deterioration for each of the family of pavements.

3.1 Developing Climate Zones

Based on the literature review, precipitation, temperature, subsurface-moisture, and freeze-thaw cycles were considered the predominant environmental factors that significantly affect pavement deterioration and lifespan. Therefore, precipitation and freezing degree-day (FDD) data were the two environment factors used to create the four climate zone regions in the United States. WeatherBank Inc., a meteorological consulting company, provided the environmental data for the research effort. WeatherBank provides weather data and products for businesses, government agencies, and the general public (WeatherBank, 2012). WeatherBank collects data from approximately 1,700 National Oceanic and Atmospheric Administration (NOAA), National Weather Service (NWS), and Federal Aviation Administration (FAA) weather observation sites scattered across the U.S., Alaska, and Hawaii. Figure 6 shows the locations of the weather stations.

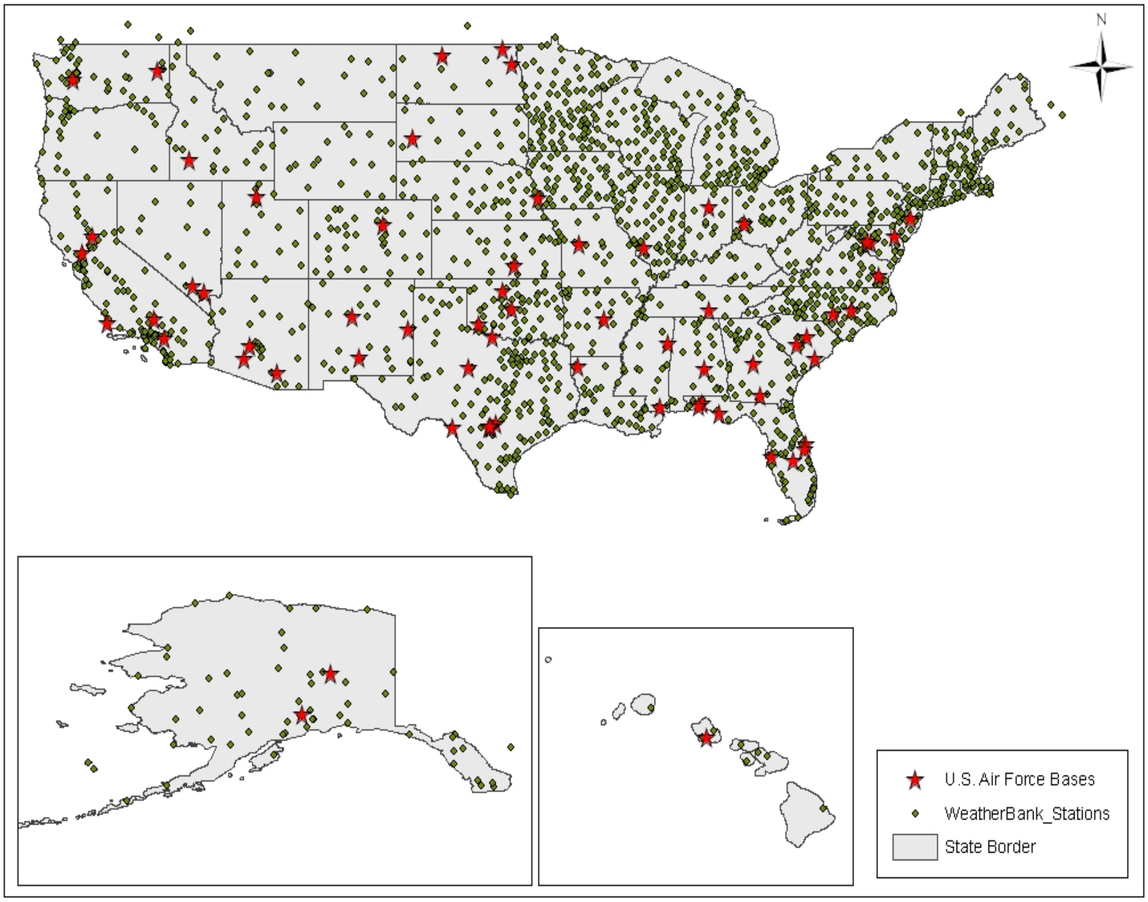


Figure 6. WeatherBank U.S. Weather Station Locations

WeatherBank possesses the ability to collect hourly data for 20 different weather parameters such as temperature, humidity, wind speed, and precipitation (WeatherBank, 2012). For this analysis, WeatherBank provided 30-year normalized precipitation and freezing degree-day data for each of the 1,700 weather observation sites located in the United States. WeatherBank calculates normalized data using raw weather data from 1982 through 2011. NOAA defines a "normal" of a weather variable as "the 30-year average" (National Climatic Data Center, 2011). WeatherBank uses a mathematical process to calculate the 30-year normals from daily observations from each of the weather observations sites. The precipitation data is the total 30-year normal annual amount of precipitation for each station in inches. Likewise, the FDD data is the FDD calculated as a 30-year normal for each station.

To quantify the weather data to establish the four climate regions, thresholds for the environmental factors had to be established for both precipitation and freezing degree-days. The thresholds were established from engineering judgment and insight from individuals at the USACE Cold Regions Laboratory and the Air Force Civil Engineer Center. The following equation defines the wet categories:

$$Wet > 25'' \; in \; precipitation/year$$

The following equation defines the freezing categories:

$$Freeze > 750 \; FDD$$

The precipitation and freezing degree-day data were imported into ESRI's ArcGIS to utilize the geospatial analysis tools to create the regional climate model.

The subsequent geospatial analysis involved combining and analyzing the environmental geospatial data from WeatherBank. The precipitation and freezing degree-day data were geospatially related to the location of the individual weather stations. As stated in the previous chapter, ArcGIS has a suite of spatial analyst tools that have the ability to create an interpolated surface from geospatially related data. Spatial interpolation is applicable in many applications such as estimating environmental variables (precipitation, temperature, or wind) at locations where weather stations are not available; estimating elevation of a surface between measured locations; and estimating where a contour line belongs in between two measured points (Longley, Goodchild, Maguire, & Rhind, 2011).

To generate the climate zone model, the weather station geospatial data was imported into ArcGIS. With the data imported, predictive surfaces were created using the Inverse Distance Weight (IDW) and kriging geospatial interpolation techniques. Each interpolation technique produced two surfaces, one for precipitation and one for freezing degree-days. Using the statistical comparison feature within ArcGIS, it was determined that the kriging method produced the most accurate interpolation surfaces for both precipitation and freezing degree-days. To create the final climate region map, the interpolated surfaces for precipitation and freezing degree-days were combined. This process was executed through the "union" function in ArcMap. The "union" function computes a geometric intersection between multiple inputs. Using this method produced a climate model consisting of the following zones: No Freeze-Wet, No Freeze-Dry, Freeze-Wet, and Freeze-Dry.

3.2 Developing Pavement Deterioration Rates

The Air Force Civil Engineer Center Pavements division provided the full Air Force PAVER^{TM} database for this effort. This database contained PCI inspection data from the majority of the U.S. Air Force bases with an active airfield. The database contained PCI inspection data for 61 bases scattered throughout the United States. However, some of the more recent inspections for the bases were not yet included in the database.

The database was imported into the PAVER^{TM} program to calculate the average linear rate of deterioration for each pavement family. All of the pavement sections included in the PAVER^{TM} database were categorized with the use of the family definition tree (see Figure 2 in Chapter 1). Using the family model to categorize the pavement sections, the average rate of deterioration for each separate type of pavement family was produced using the prediction modeling function within the PAVER^{TM} system. As previously stated in Chapter 2, PAVER^{TM} uses the "Family Method" to predict the rate of deterioration of pavement sections. This method produces a predictive pavement deterioration model (trend) for a family of pavements, which represents the average behavior for the entire pavement sections associated with that particular family (Shahin, 2005). In essence, PAVER^{TM} uses mathematical techniques to develop a best-fit curve that produces the smallest amount of error with the constraints that (1) at age zero the PCI is 100 and (2) the PCI can only decrease with increasing age. PAVER^{TM} automatically calculates the number of coefficients that produces the best-fit curve for the data set. To get the average linear rate of deterioration for a family of pavements, the number of coefficients must be set to two. Therefore, the slope of the line is the average rate of deterioration for the family of pavements. This procedure was executed for every combination of pavement from Figure 2 for each of the 61 bases in the Air Force PAVER^{TM} database.

3.3 Statistical Analysis

This phase of the research used Excel and the software JMP v10.0. The first goal of this portion was to identify bases with average rates of deterioration within the following sampling distribution areas: (1) plus or minus one standard deviation from the average regional rate of deterioration, (2) more than one standard deviation greater than the average regional rate of deterioration, and (3) more than one standard deviation less than the average regional rate of deterioration. The second goal was to conduct an ANOVA to determine if the climate regional average rates of deterioration for each family of pavement are statistically different from one another.

By specifically identifying the family of pavements at individual bases with average rates of deterioration more than one standard deviation from the regional rate of deterioration, future research can be conducted to identify factors significantly influencing the rate of deterioration. As discussed in Chapter 2, these factors may be load or environmental related or may be due to the individual's base M&R strategies. Figure 7 shows the distribution and the associated upper and lower bounds for the regions described above. Due to the small sample size of each family of pavements within in each climate zone, a t-distribution was used to establish the upper and lower bounds to help identify the distribution region for each individual bases average rate of deterioration.

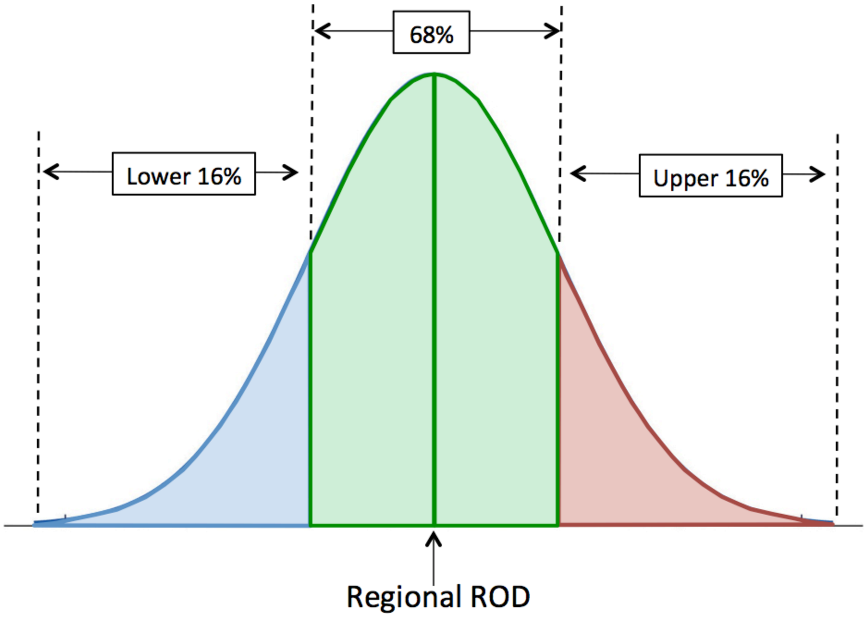


Figure 7. Distribution Areas

The t-distribution is a family of theoretical continuous probability distributions similar to a normal distribution (Benson, McClave, & Sincich, 2011). The primary difference between a normal distribution and a t-distribution is the variability, which in the case of the t-distribution is dependent on the sample size *n* (Benson, McClave, & Sincich, 2011). Using the t-distribution, a t-test statistic can be calculated to determine the upper and lower bounds based off the degrees of freedom and the standard deviation for each family of pavements.

The final step in the statistical analysis was to conduct an ANOVA to test the hypothesis that the climate region rates of deterioration for each family of pavements are statistically different from one another and different from the Air Force overall rate of deterioration for each family of pavements. ANOVA is a statistical tool used to test for a significant difference between two means. The validity of the ANOVA procedure is based on the assumption that the population of data is normally distributed. The main goal of the ANOVA is to determine whether or not the difference between two means can be attributed to normal variance or to a statistical difference between the two populations (Benson, McClave, & Sincich, 2011). Two types of variances are addressed with an ANOVA: the "within-group variance" and the "between-group variance." The "within-group" variance is between the observations sampled from the same population, which is assumed to be equal for each population. The "between-group variance" is the variance between the means of each population being used in the comparison. Typically, the "between-group" variance will be greater than the "within-group" variance.

Before the Student's t-test can be executed, each family of pavements distribution of measurements must be tested for normalcy via the Shapiro-Wilk Test. In 1965, S.S. Shapiro and M.B. Wilk created the Shapiro-Wilk test to determine if a small random sample comes from a normal distribution (NIST/SEMATECH, 2012). For this analysis, the null hypothesis (H_o) states that the sample data is from a normal distribution. The alternative hypothesis (H_a), states that the sample did not come from a normal distribution. In this test, a W-statistic is calculated, which in the case of the JMP software is a p-value. For example if a significance level or alpha level is set at 95% (α=0.05) then the null hypothesis is rejected if the p-value is less than 0.05. However, if the p-value is greater than 0.05 the null hypothesis has not been rejected, which means the sample data came from a normal distribution. If the Shapiro-Wilk test verifies the null hypothesis, then the Student's t-test can be used for the pairwise comparison of the regional rates of deterioration.

The JMP software executes a one-way analysis when analyzing the means from two or more groups. To identify which pairs of means are statistically different, individual pairwise comparisons are conducted using Student's t-test. For the pairwise Student t-test, the null hypothesis (H_o) states that there is no difference between a pairwise group. The alternative hypothesis (H_a) states that the difference between pairwise groups is statistically different. For all tests, a 95% confidence interval (α=0.05) was applied. The Student's t-test will generate a probability value for the t-test. If the corresponding p-value for the Student's t-test is less than 0.05, the null hypothesis (H_o) is rejected. The conclusion can then be made that there is a statistical difference between the two average rates of deteriorations being compared.

3.4 Methodology Summary

This research effort utilized a three-phased approach. The first phase focused on constructing a regional climate model based on the predominant environmental factors that affect pavement performance and deterioration. The second phase discussed the process of generating the average rates of deterioration for each pavement family at each of the bases in the PAVER^{TM} database. The final phase discussed the statistical analysis that was conducted at the climate region level, as well as the ANOVA that was conducted to evaluate if a statistical difference between the climate regions exists.

4.0 Results and Analysis

The purpose of this chapter is to present the results of this research effort. The chapter is organized into three main sections: Regional Climate Zone Model, Rates of Deterioration, and Statistical Analysis. The first section discusses the results from generating the regional climate zone models. The second section discusses the results from calculating the average rates of deterioration for every pavement combination outlined in Chapter 1. Finally, the results of the statistical analysis are divided into five main subsections that discuss each climate zone and the analysis of variance (ANOVA) results separately. To gain better insight into the results, Subject Matter Experts (SME) at the Air Force Civil Engineer Center (AFCEC) were consulted.

4.1 Regional Climate Zone Model

The first phase of the research effort was centered on the construction of a four-zone climate region model. The climate model consisted of the following four zones: No Freeze-Wet, No Freeze-Dry, Freeze-Wet, and Freeze-Dry. Precipitation and freeze/thaw cycles were the two environmental factors that were chosen for the creation of the climate model. Using the Kriging geospatial interpolation technique, two predictive surfaces were created from the precipitation and freezing degree-day data; Figure 8 shows the respective interpolated surfaces.

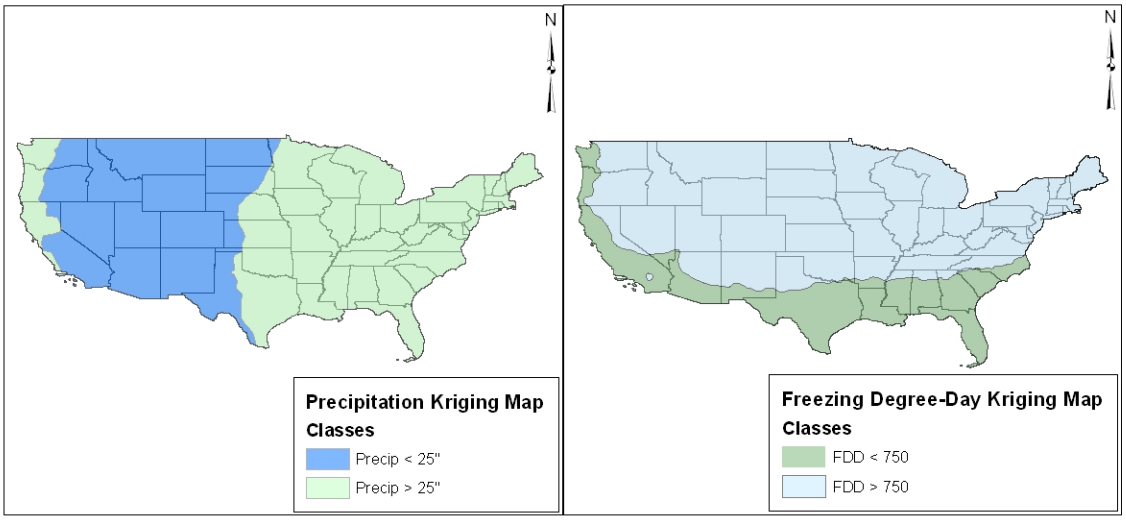


Figure 8. Kriging Maps for Precipitation and Freezing Degree-Days

As stated in Chapter 3, the precipitation and freezing degree-day surfaces were combined to develop the final climate region map. Shown in Figure 9, the final map consisted of four zones defined by the following criteria:

- No Freeze-Wet: Precipitation > 25” and FDD < 750
- No Freeze-Dry: Precipitation < 25” and FDD < 750
- Freeze-Wet: Precipitation > 25” and FDD > 750
- Freeze-Dry: Precipitation < 25” and FDD > 750

Table 3 shows the number of bases in each of the zones. This table shows that the numbers of bases are relatively distributed across the four zones, with a significant number of stations in each category.

Table 3. Distribution of Air Force Bases for each Climate Zone

No Freeze-Wet	No Freeze-Dry	Freeze-Wet	Freeze-Dry
24	10	16	11

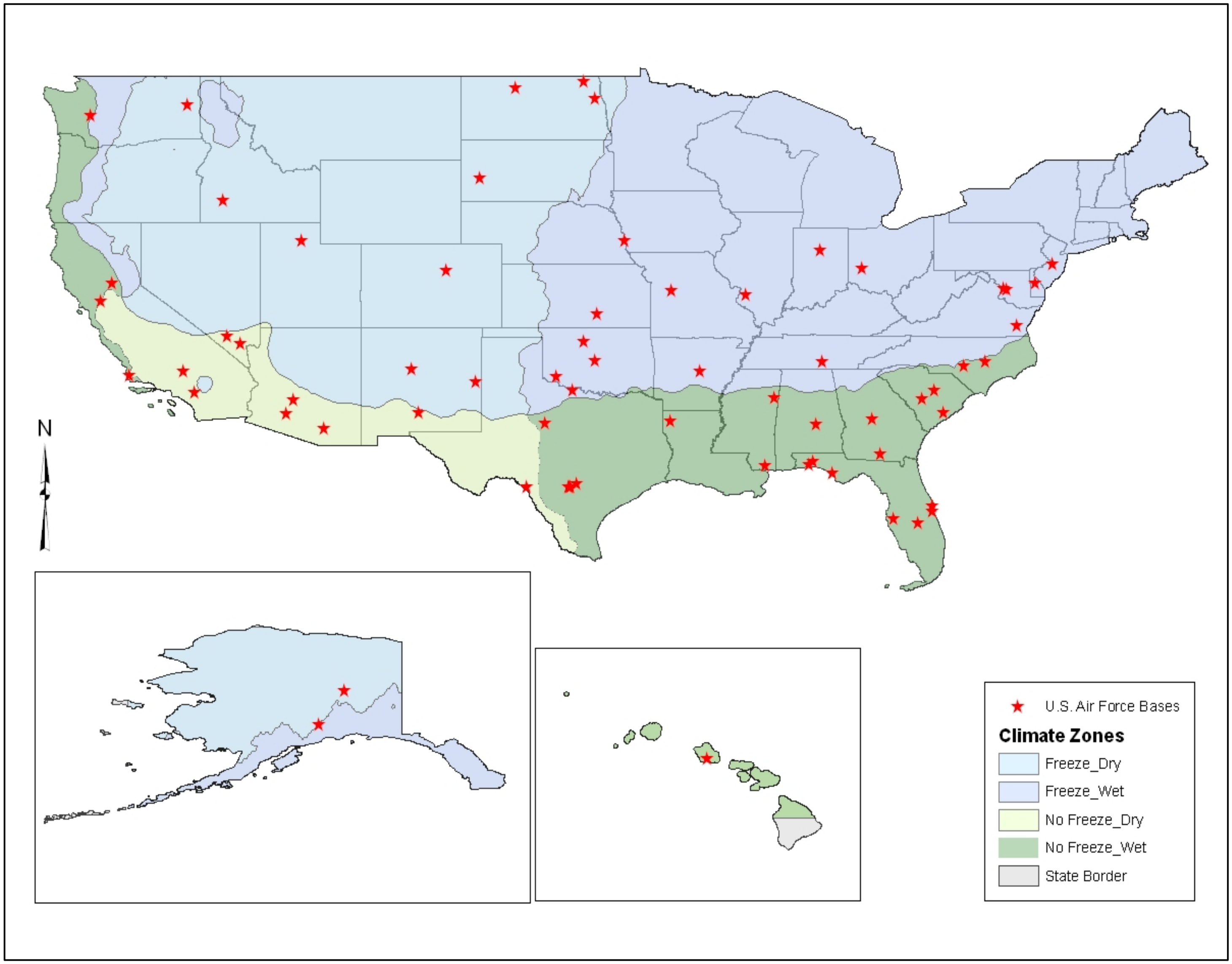
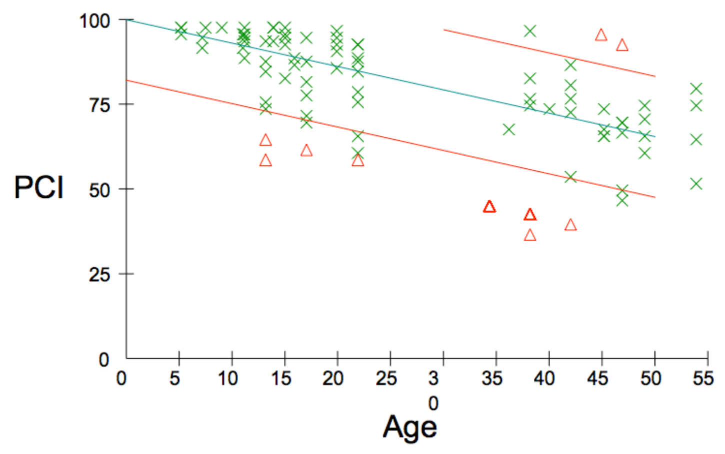


Figure 9. Climate Zone Map for the United States

4.2 Rates of Deterioration

This section of the results discusses the average rates of deteriorations calculated for each of the 61 bases in the database. As stated in Chapter 3, PAVER's^{TM} prediction modeling function produces a best-fit curve for a particular data set. However, to generate the average rate of deterioration for each family of pavements, the number of coefficients was set to two to allow the prediction modeling function to generate a straight-line trend model. Figure 10 shows an example output of the prediction modeling function. In the figure, 0.69034 is the average rate of deterioration, which is defined as the number of PCI points per year a particular family of pavement will deteriorate.



Y= 100-0.69034X

Coeff of correlation = 0.744

Approximate R^2 = 0.554

Standard deviation of error = 9.096

Figure 10. PAVER^{TM} Prediction Modeling Output

Originally, the pavement family tree (see Figure 2 in Chapter 1) defined nine separate families of pavements for each airfield. However, the current database did not contain enough information to generate a model for each combination of pavements. Sections of composite pavements (asphalt overlays of PCC pavements) are not as widely used on Air Force airfields as AC or PCC pavements, which is why the database contained minimal composite pavement sections. Therefore, the composite pavement family did not have enough data to warrant generating deterioration models for further analysis. Not every airfield network in the Air Force inventory contained pavement sections from every possible combination of pavement family defined in Figure 2 in Chapter 1. The average rates of deterioration for each region and base can be found in Appendix B.

4.3. Statistical Analysis

This section presents the results from the statistical analysis of each of the four climate zones as well as the comparison of the regional average rates of deterioration for each family of pavements. As one would expect, individual airfield design varies based on soil condition and mission aircraft as well as availability/cost effectiveness of construction materials in different regions. Because of this fact, the number of bases with data for each of the pavement families differs from region to region. Therefore, not every base in a given region has data for each of the respective family of pavements associated with the research. This will be evident in the respective rate of deterioration distribution tables for each individual climate zones. If the average deterioration rate for a particular pavement family at a given base, is in the upper 16% of the distribution based on the regional average rate of deterioration, this indicates the pavements in that family at that base are deteriorating at a higher rate than other similar pavements within the climate region. On the contrary, if the average rate of deterioration for a particular family of pavements is in the lower 16% of the distribution based on the regional average rate of deterioration, then the pavements are deteriorating at a much slower pace than other similar pavements within the region.

4.3.1 No Freeze-Wet Climate Region

The No Freeze-Wet Climate region consisted of 24 bases predominantly located in the southeastern part of the United States and also the coastal areas in the states of Washington, Oregon, and California. Table 4 shows the average rate of deterioration for each family of pavements in this climate region. Through the use of JMP, it was determined that all of the family of pavement distributions for this zone passed the Shapiro-Wilk tests, i.e. the rate of deterioration of the bases within each family came from a normally distributed population. See Appendix A for distribution graphs for each family of pavements. Overall, the values for the average rates of deterioration are within the expected range for pavement deterioration. Approximately 68% of the bases had pavements from every family with an average rate of deterioration within 1 standard deviation from the regional average except the PCC runway family (60%). Additionally, the table indicates that AC runways are deteriorating 4 times faster than PCC for runways. AC taxiways and aprons are deteriorating approximately 2.5-3 times faster than the PCC pavements for taxiways and aprons. Typically, the bases place a greater emphasis on M&R on the runway pavements. Therefore, one would expect that the average rate of deterioration for these pavements would be relatively low. For PCC runway pavements, this theory holds true. However, the AC runway pavements experience the highest average rate of deterioration as compared to AC taxiways and aprons.

Table 4. No Freeze-Wet Rate of Deterioration Summary Table

	No Freeze-Wet Zone (24 Bases)					
	Runway		**Taxiway**		**Apron**	
Units for ROD (PCI pts/year)	PCC	AC/AAC	PCC	AC/AAC	PCC	AC/AAC
# of Bases w/ROD data	20	12	22	12	21	7
Regional Average ROD	**0.5121**	**2.1342**	**0.5799**	**1.7229**	**0.7069**	**1.8735**
Standard Deviation	0.2442	0.6773	0.2555	0.4420	0.2140	0.7460
# of Bases within +/- 34% of the regional ROD	12	8	15	9	15	5
Lower 16% of Dist based on Regional ROD	5	2	2	1	3	1
Upper 16% of Dist based on Regional ROD	3	2	5	2	3	1

Tables 5 and 6 show the bases that are in the top and bottom 16%, respectively, of the distribution in terms of the rate of deterioration for each family of pavements. As shown in Table 5, Charleston, Dyess and Moody have rates of deterioration more than 1 standard deviation greater than the regional rate of deterioration for two of the three PCC categories. This trend could possibly mean that these PCC pavements are experiencing major load and environmental distresses that are different than any other base within in the region. This climate region receives well over 25 inches of precipitation a year, which could provide for an explanation for these bases having a higher rate of deterioration than the regional average. Corner, diagonal transverse longitudinal cracking, curling, warping, and pumping are all PCC distresses that potentially lead to higher than average rates of deterioration. AC distresses such as corrugation and rutting could be causing a higher than average rate of deterioration. Typically, corrugation and rutting are distresses caused by loading effects, but both are a result of an unstable subbase, which could be a direct result of increase moisture in the soil beneath the pavement. Again, future research needs to be conducted to isolate the factors that are leading to the high rate of deterioration.

Table 5. No Freeze-Wet List of Bases Above 1 Standard Deviation

	No Freeze-Wet Zone					
	Runway		Taxiway		Apron	
	PCC	AC/AAC	PCC	AC/AAC	PCC	AC/AAC
Upper 16% of Dist based on Regional ROD	Dyess	Columbus	Charleston	Charleston	Charleston	Pope
	Hurlburt	Tyndall	Dyess	Hickam	Moody	
	McChord		Moody		Shaw	
			Randolph			
			Seymour Johnson			

Table 6. No Freeze-Wet List of Bases Below 1 Standard Deviation

	No Freeze-Wet Zone					
	Runway		Taxiway		Apron	
	PCC	AC/AAC	PCC	AC/AAC	PCC	AC/AAC
Lower 16% of Dist based on Regional ROD	Beale	North Aux	Cape Canaveral	Randolph	Cape Canaveral	Randolph
	Eglin	Seymour Johnson	Hickam		McChord	
	Moody				Robins	
	Randolph					
	Shaw					

From Table 6, Cape Canaveral was the only base that had an average rate of deterioration that is in the lower 16% of the distribution based on rate of deterioration for two PCC pavement use categories. However, this Air Force station does not have an active flying mission and experiences very limited aircraft traffic on a regular basis, which could be a possible explanation for the low rates of deterioration. Randolph AC taxiway and apron pavements also show low rates of deterioration based on the analysis. Further analysis into these bases could yield significant findings on whether or not the local M&R strategies are influencing the low rate of deterioration, which then could be applied to other bases within the region.

4.3.2 No Freeze-Dry Climate Region

The No Freeze-Dry climate region consisted of 10 bases primarily located in the southwest part of the United States including, the southern parts of Arizona, California, Nevada, New Mexico, and parts of Texas. Table 7 shows the average rate of deterioration for each family of pavements in this climate region. Through the use of JMP, it was determined that all of the family of pavement distributions for this zone passed the Shapiro-Wilk tests. See Appendix A for distribution graphs for each family of pavements. Overall, the values for the average rates of deterioration are within the expected range for pavement deterioration. At least 62% of the bases had the runway AC, taxiway PCC, and apron AC pavement families within 1 standard deviation from the regional average. 77% of the bases had the runway PCC, taxiway AC and apron PCC pavement families within 1 standard deviation from the regional mean. The region had at least one or two bases that were identified as having average rates of deterioration that categorized that particular pavement family into the top or bottom 16% of the distribution based on average rate of deterioration. Additionally, the table indicates that runway and taxiway AC pavements are deteriorating 4 times faster than PCC pavements for runways and taxiways and 3 times faster than the PCC apron pavements.

Table 7. No Freeze-Dry Rate of Deterioration Summary Table

	No Freeze-Dry Zone (10 Bases)					
	Runway		**Taxiway**		**Apron**	
Units for ROD (PCI pts/year)	PCC	AC/AAC	PCC	AC/AAC	PCC	AC/AAC
# of Bases w/ROD data	9	8	9	6	9	6
Regional Average ROD	**0.6004**	**2.4213**	**0.4599**	**1.8043**	**0.6434**	**1.9540**
Standard Deviation	0.3047	1.3342	0.1929	0.5558	0.2138	0.6078
# of Bases within +/- 34% of the regional ROD	7	5	6	5	7	4
Lower 16% of Dist based on Regional ROD	1	2	1	0	1	1
Upper 16% of Dist based on Regional ROD	1	1	2	1	1	1

Tables 8 and 9 show the list of bases that are in the top and bottom 16% of the distribution in terms of rate of deterioration in each family of pavements. From Table 8, Nellis Air Force Base (AFB) pavements can be identified as having a rate of deterioration in the top 16% of the distribution according to rate of deterioration for runway and taxiway pavements. Davis-Monthan AC runway and taxiway pavement families also show rates of deterioration well above the regional average rate of deterioration for the same family of pavements.

Table 8. No Freeze-Dry List of Bases above 1 Standard Deviation

	No Freeze-Dry Zone					
	Runway		**Taxiway**		**Apron**	
Upper 16% of Dist based on Regional ROD	PCC	AC/AAC	PCC	AC/AAC	PCC	AC/AAC
	Nellis	Davis-Mon	Edwards	Davis-Mon	Laughlin	Nellis
			Nellis			

Table 9. No Freeze-Dry List of Bases below 1 Standard Deviation

	No Freeze-Dry Zone					
	Runway		**Taxiway**		**Apron**	
Lower 16% of Dist based on Regional ROD	PCC	AC/AAC	PCC	AC/AAC	PCC	AC/AAC
	Vandenburg	Holloman	Laughlin		Vandenburg	March
		March				

Because of the climate region that Nellis and Davis-Monthan AFB are located in, environmental distresses can lead to an increased rate of deterioration for airfield pavements. This climate region experiences a wide range of temperatures, depending on the time of year, and very low amounts of precipitation. During the summer months, ambient air temperatures can climb to well over 100°F for sustained periods of time. During the fall and winter months, temperatures can range from an average of 70°F during the day and drop to below freezing during the night. The large temperature range of the daily temperature cycle, especially during the winter months, can lead to significant L/T cracking and block cracking in asphalts. The high solar radiation at these two bases also contributes to the hardening of the asphalt pavements potentially causing higher weathering of the asphalt binder and raveling of the aggregate in the asphalt mix. All the above factors can lead to higher rates of asphalt pavement deterioration. Hot temperatures can cause blowups in concrete pavements especially at joints. However, blowups occur relatively infrequently on Air Force airfields. These are possible explanations for the observed high rates of deteriorations from the analysis. However, these explanations were outside the scope of the research and were not verified through the analysis.

From Table 9, Vandenberg AFB shows low average rates of deterioration for runway and apron PCC pavement usage categories, and March AFB shows low rates of deterioration for AC runway and apron pavements. This trend potentially shows that theses base have better airfield maintenance programs are working, which are driving the low rate of deterioration. Another possible explanation could be the level of traffic for the airfield is low as well. These observations need to be investigated. Keeping the rate of deterioration low prolongs the life of the pavements, which reduces the life-cycle costs of the pavement. Further research, must be conducted to establish exactly what trends and factors are influencing the rates of deteriorations at the bases.

4.3.3 Freeze-Wet Climate Region

The Freeze-Wet climate region consisted of 16 bases located in states located primary in the Midwest to the Northeast part of the United States, such as Indiana, Maryland, Missouri, Ohio, Oklahoma, Tennessee, and Virginia. Through the JMP analysis, 3 families of pavements did not pass the Shapiro-Wilk Test, due to statistical outliers. See Appendix A for distribution graphs for each family of pavements. In the PCC taxiway pavement family, the Shapiro-Wilk Test p-value (0.0255) was less than 0.05. This was mainly due to the calculated rate of deterioration for PCC taxiways at Wright Patterson and Grissom AFBs. These outliers were identified from the box plot from the histogram output from JMP. Figure 11 shows the histogram distribution for this region as well as the outlier, which is represented by the small yellow square. These two bases also showed high standard deviations (Grissom = 21.55 and Wright-Patterson = 16.989) from generating the average rate of deterioration trend model in PAVER^{TM} indicating considerable variation with the data for each of these bases. Once the bases were removed, the PCC taxiway pavement family passed the Shapiro-Wilk test.

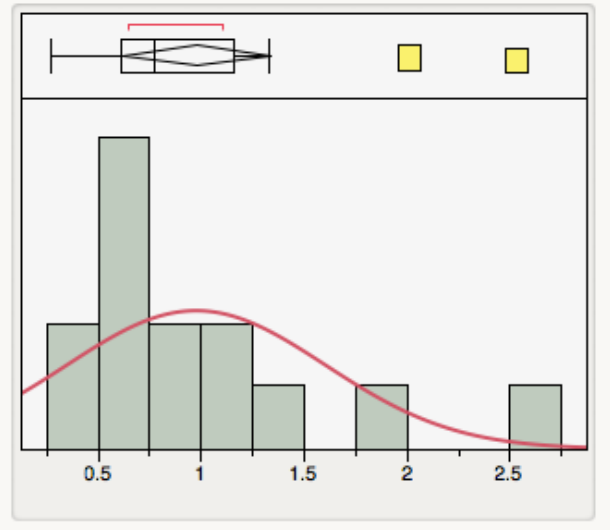


Figure 11. Freeze-Wet Taxiway-Concrete Distribution

Similar situations were observed in the AC Runway and PCC Apron pavement families for this region. The AC runway pavements at Altus AFB and the PCC Apron pavements at Grissom were flagged as statistical outliers. Altus's AC taxiway average rate of deterioration was 6.99 PCI points per year, which is 3 times as a high as the next highest average rate of deterioration within this pavement family. Clearly, this rate of deterioration is well beyond 2 standard deviations from regional mean, which means that this rate of deterioration is heavily influencing the sample distribution. Grissom's rate of deterioration showed a high relatively standard deviation (Grissom = 15.457) from generating the average rate of deterioration trend model in PAVER^{TM} indicating considerable variation with the data for each of these bases. Both of the distributions for these pavement families did pass the Shapiro-Wilk test once the outliers were removed.

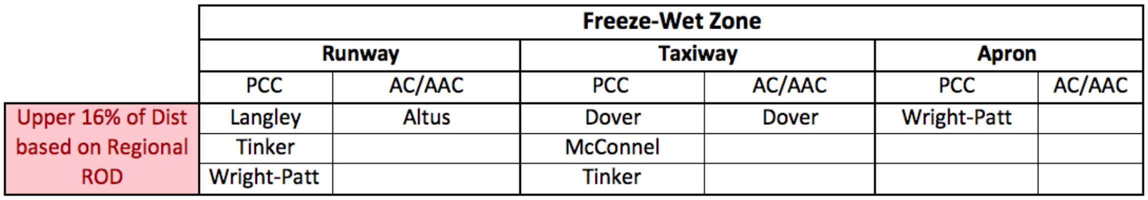
Table 10 shows the average rate of deterioration for each family of pavements in this climate region. Overall, the region did have at least one or two bases that were identified as having average rates of deterioration that fell in to the top or bottom 16% of the distribution based on average rate of deterioration for each of the respective pavement families. 70% of the bases had four out of the six pavement families within 1 standard deviation from the regional average rate of deterioration. 60% of the bases contained the PCC runway and taxiway pavement families within 1 standard deviation of the regional average rate of deterioration. Additionally, the table indicates that runway AC pavements are deteriorating 3.25 times faster than PCC pavements for runways and 2.5 times faster than the PCC pavements for taxiways and aprons. The AC runway rate of deterioration standard deviation among the bases was relatively higher than the rest of the pavement categories. In the AC runway pavement family, Altus's AC runway average rate of deterioration was 4.79 PCI points per year, which is approximately 1.65 times higher than the next highest rate of deterioration within this family of pavement.

Table 10. Freeze-Wet Rate of Deterioration Summary Table

	Freeze-Wet Zone (16 Bases)					
	Runway		**Taxiway**		**Apron**	
Units for ROD (PCI pts/year)	PCC	AC/AAC	PCC	AC/AAC	PCC	AC/AAC
# of Bases w/ROD data	15	8	12	6	14	2
Regional Average ROD	**0.7347**	**2.4110**	**0.7635**	**1.8843**	**0.7695**	**2.0391**
Standard Deviation	0.4569	1.1091	0.3114	0.2568	0.3017	N/A
# of Bases within +/- 34% of the regional ROD	9	7	7	5	11	0
Lower 16% of Dist based on Regional ROD	3	0	2	0	2	0
Upper 16% of Dist based on Regional ROD	3	1	3	1	1	0

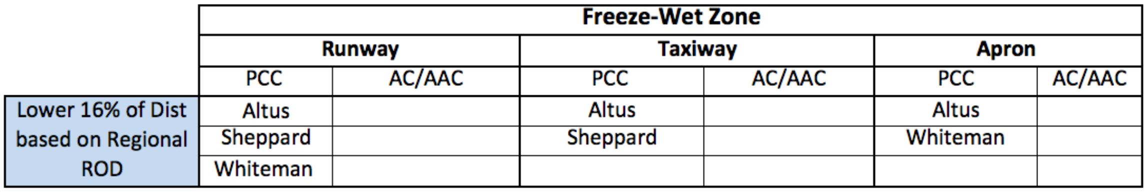
Tables 11 and 12 show the list of bases that are in the top and bottom 16% of the distribution in terms of rate of deterioration in each family of pavements. The bases in this climate region are subjected to annual freeze/thaw cycles that play a substantial role in pavement performance and could significantly influence the average rate of deterioration. Freeze/thaw cycles can potentially cause spalling, scaling, and durability cracking in PCC pavements and exacerbate fatigue (alligator) and transverse cracking in AC pavements. The root cause of fatigue cracking is typically load related however, once cracks have formed the subsequent freeze/thaw cycles can make the pavement deteriorate at a more rapid rate. From Table 11, Wright Patterson and Tinker had two of the three pavement usage categories fall into the top 16% of the distribution in terms of rate of deterioration. Altus and Dover were the only bases in the AC pavement surface categories to have rates of deterioration in the top 16% of the distribution in terms of rate of deterioration. These airfield pavements may be experiencing load and environmental distresses that may be different than any other base within in the region causing the rate of deterioration to be much higher than the rest of the bases within in the region. It is interesting to point out that the AC runway pavement at Altus were in the top 16% of the distribution in terms of rate of deterioration. Whereas the rate of deterioration for the PCC pavements at Altus were in the bottom 16% of the distribution in terms of rate of deterioration. This observation raises the question of whether or not there is a potential issue with the design or construction of the AC pavements at this location.

Table 11. Freeze-Wet List of Bases Above 1 Standard Deviation



	Freeze-Wet Zone					
	Runway		Taxiway		Apron	
	PCC	AC/AAC	PCC	AC/AAC	PCC	AC/AAC
Upper 16% of Dist based on Regional ROD	Langley	Altus	Dover	Dover	Wright-Patt	
	Tinker		McConnel			
	Wright-Patt		Tinker			

Table 12. Freeze-Wet List of Bases Below 1 Standard Deviation



	Freeze-Wet Zone					
	Runway		Taxiway		Apron	
	PCC	AC/AAC	PCC	AC/AAC	PCC	AC/AAC
Lower 16% of Dist based on Regional ROD	Altus		Altus		Altus	
	Sheppard		Sheppard		Whiteman	
	Whiteman					

From Table 12, all three of the PCC pavement usage categories for Altus AFB fell into the bottom 16% of the distribution based on average rate of deterioration. Sheppard's PCC runway and taxiway pavement family had a deterioration rate that is below the regional rate of deterioration. Additionally, Whiteman's PCC runway and apron pavement family had a deterioration rate that is below the regional rate of deterioration. A potential explanation of this could be the level of airfield maintenance programs keeping the rate of deterioration at a low level. Keeping the rate of deterioration low prolongs the life of the pavements, which reduces the cost associated with maintain the airfield pavement network. Again, these types of observations have not been confirmed through this research effort.

4.3.4 Freeze-Dry Climate Region

The Freeze-Dry climate region consisted of 11 bases located in the Midwest portion of the United States including the states of Alaska, North and South Dakota, Montana, Colorado, Utah, and Wyoming. Through the use of JMP, it was determined that all of the family of pavement distributions for this zone passed the Shapiro-Wilk tests. Table 13 shows the average rate of deterioration for each of the pavement families in this climate region. Overall, the data for this region was distributed fairly well. At least 70% of the bases contained five out the six pavement families with rates of deterioration within 1 standard deviation of the regional average rate of deterioration. 66% of the bases contained the PCC apron pavement family with rates of deterioration within 1 standard deviation of the regional average. As to be expected, there are a number of bases with average deteriorations rate that fall into the top and bottom 16% of distribution in terms of rate of deterioration. The AC pavements deteriorated approximately 2.5 times faster than the PCC pavements for all three pavement usage types in this region.

Table 13. Freeze-Dry Rate of Deterioration Summary Table

	Freeze-Dry Zone (11 Bases)					
	Runway		**Taxiway**		**Apron**	
Units for ROD (PCI pts/year)	PCC	AC/AAC	PCC	AC/AAC	PCC	AC/AAC
# of Bases w/ROD data	7	6	8	8	9	4
Regional Average ROD	**0.9851**	**2.4170**	**0.8515**	**2.1053**	**1.0048**	**2.3775**
Standard Deviation	0.6482	1.5132	0.3072	0.6157	0.1797	0.6406
# of Bases within +/- 34% of the regional ROD	5	5	6	6	6	3
Lower 16% of Dist based on Regional ROD	1	0	1	1	1	1
Upper 16% of Dist based on Regional ROD	1	1	1	1	2	0

Tables 14 and 15 show the list of bases that are in the top and bottom 16% of the distribution in terms of rate of deterioration in each family of pavements. Kirtland AFB PCC taxiway and apron pavement families have been identified as having higher rates of deterioration than the regional average. This climate region is another region that has annual freeze/thaw cycles. As was stated for the Freeze-Wet region, the freeze/thaw cycles can have a significant effect of the rate of deterioration for both AC and PCC pavement families. The Elmendorf PCC Taxiway and Apron pavement families had produced average rates of deterioration that were well below the average rate of deterioration for those particular pavement families. These airfield networks have clearly been identified as bases that require future research to pinpoint exactly what factors are causing the high and low average rates of deterioration.

Table 14. Freeze-Dry List of Bases Above 1 Standard Deviation

	Freeze-Dry Zone					
	Runway		**Taxiway**		**Apron**	
Upper 16% of Dist based on Regional ROD	PCC	AC/AAC	PCC	AC/AAC	PCC	AC/AAC
	Elmendorf	Minot	Kirtland	Hill	Eielson	
					Kirtland	

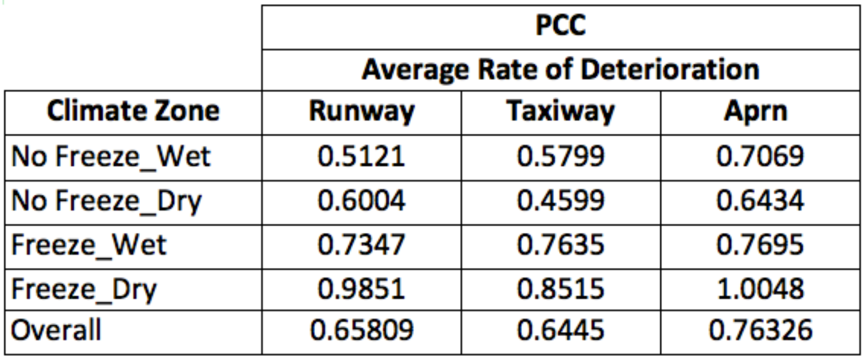
Table 15. Freeze-Dry List of Bases Below 1 Standard Deviation

	Freeze-Dry Zone					
	Runway		**Taxiway**		**Apron**	
Lower 16% of Dist based on Regional ROD	PCC	AC/AAC	PCC	AC/AAC	PCC	AC/AAC
	Cannon		Elmendorf	Mountain Home	Elmendorf	Eielson

4.3.5 Overall Observations

Tables 16 and 17 summarize the average rates of deterioration for each climate region. When comparing the deterioration rates of the pavement families of an individual pavement network the apron pavements typically deteriorate at a more rapid rate than taxiways and taxiways have deterioration rates higher than those of runways. The higher deteriorations in aprons may be attributed to the lower load frequency (slow rolling loads) and static loading of parked aircraft. Bases also typically place more emphasis on M&R for runways and taxiways, which may lead to higher apron deterioration rates. AFCEC SME's has often observed this situation on large expanses of aprons that are not used and not maintained. Finally, the fluids from the aircraft can cause an increased rate of deterioration particularly when combined with heat from the Aircraft Power Units (APU) such as the case with the B-1 bomber. This trend is clearly observed from the values for the overall rates of deterioration. Another observation that these two tables point out is the fact that AC pavements have a much higher rate of deterioration than PCC pavements for the same pavement usage type. Based on the analysis AC pavements have a deterioration rate 2.5 to 4 times higher than PCC pavements.

Table 16. Overall Climate Zone Average Rates of Deterioration-PCC



	PCC		
	Average Rate of Deterioration		
Climate Zone	**Runway**	**Taxiway**	**Aprn**
No Freeze_Wet	0.5121	0.5799	0.7069
No Freeze_Dry	0.6004	0.4599	0.6434
Freeze_Wet	0.7347	0.7635	0.7695
Freeze_Dry	0.9851	0.8515	1.0048
Overall	0.65809	0.6445	0.76326

Table 17. Overall Climate Zone Average Rates of Deterioration-AC

	AC/AAC (AC AGE RESTRICTED)		
	Average Rate of Deterioration		
Climate Zone	**Runway**	**Taxiway**	**Aprn**
No Freeze_Wet	2.1342	1.7229	1.8735
No Freeze_Dry	2.4213	1.8043	1.9540
Freeze_Wet	2.4110	1.8843	N/A
Freeze_Dry	2.4170	2.1053	2.3775
Overall	2.31677	1.864	2.0205

Overall, the vast majority of the PCC had regional average deterioration rates were under 0.80 PCI points per year, which at that rate it would take approximately 37 years for the pavement to reach a PCI of 70 assuming the pavement has an initial PCI of 100. The rates of deterioration for PCC pavements fall slightly below the parameters of the conventional wisdom of having approximately a 1-2 PCI point/ year deterioration rate. The average rate of deterioration for AC pavement families observed from this analysis were as low as 1.7 PCI points per year to as high as 2.4 PCI points per year. Again, these rates of deterioration fall within the parameters of conventional wisdom for average rate of deterioration for AC pavements, which is typically 2 to 3 PCI points per year. Based on the average rates of deterioration, the Freeze-Dry and Freeze-Wet climate zones do have higher rates of deterioration than the No Freeze-Dry and No Freeze-Wet zones. A potential explanation for this observation could be that the bases in the Freeze prone regions are exposed to the annual freeze/thaw cycles and other climate conditions, which causes an increase in the rate of deterioration. For example, in the Freeze-Dry areas like Colorado, the daily temperature cycle and the solar radiation are relatively high causing higher climate caused pavement stresses especially in the surface layers. In the

Freeze-Wet areas like Ohio, the combination of freezing and wet conditions is likely to stress the pavement structure, which increases the rate of deterioration.

Through the rate of deterioration generation portion of the research it was discovered that the PCI data associated with AC pavements at certain bases may have issues with the accuracy of the age of the inspected pavement sections. In these instances, pavement sections were observed as having ages over 40 years old with abnormally high PCI values. These points were heavily influencing the average rate of deterioration trend model. To eliminate the effect of this potential error, a constraint for AC pavement age was used to only allow PAVER^{TM} to use pavement sections with ages less than 40 to generate the average rate of deterioration model. The accuracy of the AC deterioration models did increase, with the age of 40 years constraint, for approximately 21% of the total AC average rate of deterioration models. This constraint was only applied to AC pavement families and was not applied to any of the PCC pavement families. It should be noted that for the Freeze-Wet climate zone there was not enough data to support generating an average rate of deterioration for AC apron family of pavements category. Because of this, the AC apron family of pavements was not included in the following ANOVA analysis.

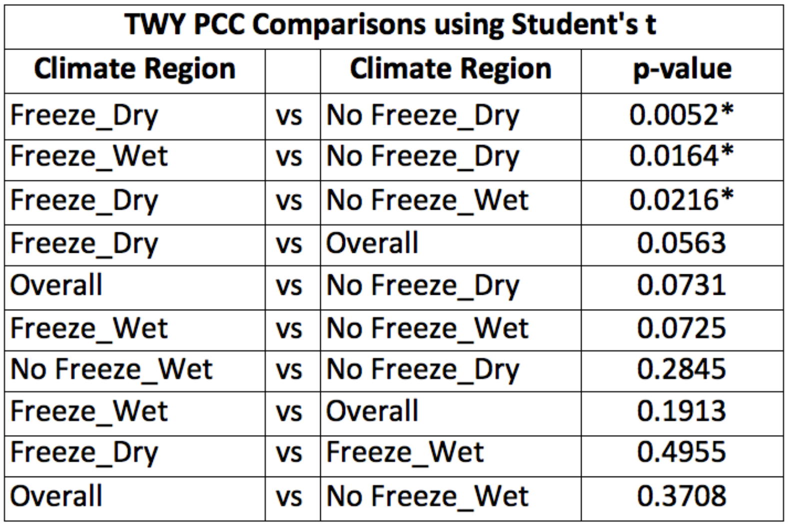
4.3.6 ANOVA Results

This section presents the results of the statistical analysis conducted to test if there is a significant statistical difference between the average rate of deteriorations among the different climatic regions for a given pavement family. This analysis was conducted utilizing the ANOVA capabilities in the JMP software. To identify which regional average rates of deterioration are statistically different from each other, a pairwise Student’s t-test comparison was executed using JMP. For the pairwise Student t-test, the null hypothesis (H_o) states that there are no differences between each pairwise group. The alternative hypothesis (H_a) states that the difference between each pairwise group is statistically different. For all tests, a 95% confidence interval ($\alpha=0.05$) was applied. Therefore, if the corresponding p-value for the Student’s t-test is less than 0.05, the null hypothesis (H_o) can rejected and it can be concluded that there is a statistical difference between the two average rates of deteriorations being compared. Tables 18, 19 and 20 show the Student’s t-test comparison and the corresponding p-values for the PCC runway, taxiway and apron pavement families.

Table 18. Student's T-Test Comparison for PCC Runways

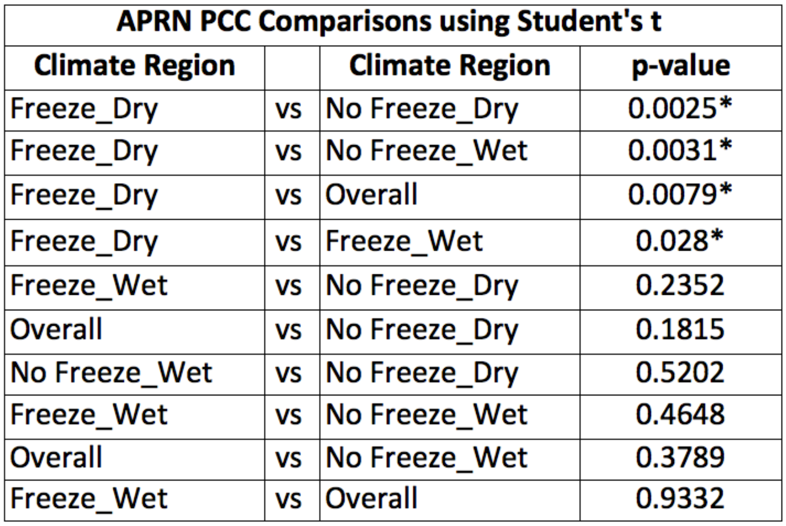
RWY PCC Comparisons using Student's t			
Climate Region		**Climate Region**	**p-value**
Freeze_Dry	vs	No Freeze_Wet	0.0092*
Freeze_Dry	vs	No Freeze_Dry	0.0626
Freeze_Dry	vs	Overall	0.0481*
Freeze_Dry	vs	Freeze_Wet	0.1801
Freeze_Wet	vs	No Freeze_Wet	0.1112
Overall	vs	No Freeze_Wet	0.1754
Freeze_Wet	vs	No Freeze_Dry	0.434
No Freeze_Dry	vs	No Freeze_Wet	0.5886
Freeze_Wet	vs	Overall	0.5215
Overall	vs	No Freeze_Dry	0.6947

Table 19. Student's T-Test Comparison for PCC Taxiways



TWY PCC Comparisons using Student's t			
Climate Region		**Climate Region**	**p-value**
Freeze_Dry	vs	No Freeze_Dry	0.0052*
Freeze_Wet	vs	No Freeze_Dry	0.0164*
Freeze_Dry	vs	No Freeze_Wet	0.0216*
Freeze_Dry	vs	Overall	0.0563
Overall	vs	No Freeze_Dry	0.0731
Freeze_Wet	vs	No Freeze_Wet	0.0725
No Freeze_Wet	vs	No Freeze_Dry	0.2845
Freeze_Wet	vs	Overall	0.1913
Freeze_Dry	vs	Freeze_Wet	0.4955
Overall	vs	No Freeze_Wet	0.3708

Table 20. Student's T-Test Comparison for PCC Aprons



APRN PCC Comparisons using Student's t			
Climate Region		**Climate Region**	**p-value**
Freeze_Dry	vs	No Freeze_Dry	0.0025*
Freeze_Dry	vs	No Freeze_Wet	0.0031*
Freeze_Dry	vs	Overall	0.0079*
Freeze_Dry	vs	Freeze_Wet	0.028*
Freeze_Wet	vs	No Freeze_Dry	0.2352
Overall	vs	No Freeze_Dry	0.1815
No Freeze_Wet	vs	No Freeze_Dry	0.5202
Freeze_Wet	vs	No Freeze_Wet	0.4648
Overall	vs	No Freeze_Wet	0.3789
Freeze_Wet	vs	Overall	0.9332

Table 18 shows that the regional average rate of deterioration for the Freeze-Dry runway pavement family is statistically different than the No Freeze-Wet and overall categories. For the taxiway pavements shown in Table 19, the Freeze-Dry climate region is statistically different than the No Freeze-Dry and No Freeze-Wet regions. Additionally, Freeze-Wet region is statistically different than the No Freeze-Dry region.

For apron PCC pavements shown in Table 20, the Freeze-Dry region is statistically different than the No Freeze-Wet, No Freeze-Dry regions and the overall apron pavement family rate of deterioration. Overall, the Freeze-Dry region has multiple comparisons where this zone is statistically different than the other zones for PCC pavements. A viable explanation for this trend could be due to this climate region is prone to high numbers of freeze/thaw cycles compared to the rest of the United States. The effects of multiple freeze/thaw cycles could potentially cause D-cracking, scaling, or other material related distresses, that lead to rapid deterioration without the proper maintenance. These reasons could potentially explain why the rate of deterioration is higher or this region compared with the rest of the regions. As seen in Table 16, the Freeze-Dry region had the highest rate of deterioration for all three PCC pavement usage types. However, there are many factors that affect deterioration rates besides environmental effects to include the quality of the materials used, construction techniques, and even the initial design could play a significant role in the deterioration rates. Typically, concrete pavements on airfields in this climate region are designed to be able to withstand the effects of freeze/thaw cycles. Also the construction placement techniques have been developed in such a way as to minimize the effects that construction could potentially have on the lifespan of the concrete slab. Therefore, without further analysis of the exact distresses that are observed at each of these locations, it is difficult to discern whether or not the high rates of deterioration can be full attributed to the possible environmental effects that occur more frequently in this region than in any of the other regions.

From the analysis, none of the AC pavement families showed any statistical difference for any of the pairwise comparisons. Tables 21 thru 23 show the Student's t-test pairwise comparisons for each of the AC pavement families. A viable explanation for pairwise comparison returning results that show no statistical significance could be that asphalt binders are selected to account for temperature ranges found in each particular region within the United States. Typically, asphalt binders are selected and the asphalt concrete mixes are designed to withstand aircraft loads and thermal loading throughout the observed temperature range at a given location. Therefore, by design the effects of climate are being accounted for by selecting materials that perform better in that specific climate zone. The statistical results from this research are similar to the results that were found from the 1990's asphalt pavement study conducted by the Federal Highway Administration (FHWA). The study identified that a statistical difference between AC viscosity and temperature did not exist. The study concluded that the AC binder for test sections of the pavements studied were properly selected for the climate and traffic conditions.

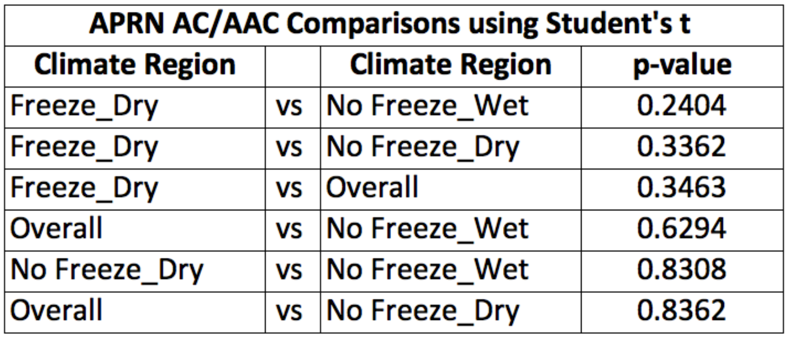
Table 21. Student's T-Test Comparison for AC Runways

RWY AC/AAC Comparisons using Student's t			
Climate Region		**Climate Region**	**p-value**
No Freeze_Dry	vs	No Freeze_Wet	0.5682
Freeze_Dry	vs	No Freeze_Wet	0.6078
Freeze_Wet	vs	No Freeze_Wet	0.5822
Overall	vs	No Freeze_Wet	0.6217
No Freeze_Dry	vs	Overall	0.8091
Freeze_Dry	vs	Overall	0.8372
Freeze_Wet	vs	Overall	0.8277
No Freeze_Dry	vs	Freeze_Wet	0.985
Freeze_Dry	vs	Freeze_Wet	0.992
No Freeze_Dry	vs	Freeze_Dry	0.9942

Table 22. Student's T-Test Comparison for AC Taxiways

TWY AC/AAC Comparisons using Student's t			
Climate Region		**Climate Region**	**p-value**
Freeze_Dry	vs	No Freeze_Wet	0.0916
Freeze_Dry	vs	No Freeze_Dry	0.2585
Freeze_Dry	vs	Overall	0.2165
Freeze_Dry	vs	Freeze_Wet	0.4056
Freeze_Wet	vs	No Freeze_Wet	0.5114
Overall	vs	No Freeze_Wet	0.397
No Freeze_Dry	vs	No Freeze_Wet	0.7402
Freeze_Wet	vs	No Freeze_Dry	0.7777
Overall	vs	No Freeze_Dry	0.7844
Freeze_Wet	vs	Overall	0.9261

Table 23. Student's T-Test Comparison for AC Aprons



APRN AC/AAC Comparisons using Student's t			
Climate Region		**Climate Region**	**p-value**
Freeze_Dry	vs	No Freeze_Wet	0.2404
Freeze_Dry	vs	No Freeze_Dry	0.3362
Freeze_Dry	vs	Overall	0.3463
Overall	vs	No Freeze_Wet	0.6294
No Freeze_Dry	vs	No Freeze_Wet	0.8308
Overall	vs	No Freeze_Dry	0.8362

Although the analysis did not show any comparisons that were statistically different there were still a few comparisons that had relatively low p-values. For example, there were multiple pairwise comparisons in the taxiway and apron pavement categories that had p-values less than 0.35. Primarily the Freeze-Dry climate region compared to the other zones for both pavement usage categories showed relatively low p-values. Even though the asphalt was designed for the specific region, overtime asphalt pavements harden and become brittle with age. With age asphalt pavement becomes susceptible to transverse cracking and block cracking which allows moisture to infiltrate the underlying subgrade and subbase materials. Increased moisture in the underlying layers leads to further distresses, especially in regions that are prone to freeze/thaw cycles. These observations create the question of whether or not a statistical difference can be found if this analysis is conducted by looking at individual climate related distresses such as transverse cracking or raveling/weathering.

5.0 Conclusions and Recommendations

The purpose of this chapter is to present the conclusions of this research effort. The chapter is organized into three main sections: Conclusions of Research, Limitations, and Future Research. The first section addressees how the results of the study specifically satisfy the research questions presented in Chapter 1 and layout a proof of concept plan for this research topic. The second section address the limitations discovered while conducting the research. The final section discusses a way ahead for the research topic and potential future research topics.

5.1 Conclusions of Research

The primary push behind this research effort was to answer the question, "How can climate regions, within the United States, be used to understand and quantify the effects of climatic conditions on the deterioration rates of airfield pavements?" Specifically, the research sought to answer the following three questions, which are answered in detail:

1. What climatic/environmental variables should be used to develop a regional climate model for pavement deterioration modeling?
2. How do the regional climate-based average rates of deterioration for each family of pavements compare to the individual base average rates of deterioration for each family of pavements within the same region?
3. Are the regional average rates of deterioration statistically different from one another?

The first research question was centered on establishing predominant environmental factors from the relevant literature to create a climate region model. Precipitation, temperature, subsurface moisture, and freeze/thaw cycles were identified as the four predominate factors that have a significant influence on pavement performance and deterioration. Building an accurate climate model can be rather complex. The model built for this research only used two environmental factors, which may have over simplified the climate regions that exist in the United States. This model may not account for the transition areas in between each of the zones. These transition zone areas may not share 100% of the characteristics of one of the 4 zones.

The second research question was developed to explore the relationship between an individual base rate of deterioration and the climate zone average regional rate of deterioration. The main objective of this question was to identify the family of pavements at individual bases with average rates of deterioration more than one standard deviation from the regional rate of deterioration. This list of bases can be used for future in-depth research/analysis to identify factors significantly influencing the rate of deterioration. From this portion of the analysis, it was established that a number of bases have multiple family of pavements that have rates of deterioration that fall into the top and bottom 16% of the distribution in terms of average rate of deterioration. For example, bases such as Charleston, Nellis, Wright-Patterson, and Moody have rates of deterioration that were above 1 standard deviation from the regional rate of deterioration for two of the three PCC pavement usage families. Bases such as Dyess, Davis-Monthan, and Altus all had AC pavements that were identified as having rates of deterioration that were 1 standard deviation above the regional rate of deterioration. This analysis also provided a list of bases where the rate of deterioration for a particular family of pavements was at least 1 standard deviation below the regional rate of deterioration. In the PCC category, Vandenberg, March, Altus, and Elmendorf all had at least two families of pavements meet these criteria. Altus was identified as a unique situation in which the PCC pavements were having a low rate of deterioration but the AC pavements were having a high rate of deterioration.

The third research question's focus was to determine if a statistical difference exists between the regional climate regions average rate of deterioration for each for each family of pavements. First and foremost, the climate region average rates of deterioration observed in both PCC and AC are all within parameters of the conventional wisdom for average rate of deterioration for airfield pavements. Overall, the Freeze-Dry Region had multiple comparisons where the zone is statistically different than the other zones for PCC pavements at the 5% significance level. The PCC pavements in this climate region are subjected to high numbers of freeze/thaw cycles when compared to the rest of the United States. The effects of multiple freeze/thaw cycles could potentially cause durability cracking, scaling, and other material related distresses, all which can lead to a rapid deterioration rate without the proper execution of maintenance and rehabilitation projects. Further analysis of the exact distress that are observed on the airfields located in this region is needed to discern whether or not the high rates of deterioration can be fully attributed to the possible environmental effects that occur more frequently in this region than any of the other regions.

None of the AC pavement families showed any statistical difference for any of the pairwise comparisons at the 5% significance level. Typically, asphalt binders are selected and the asphalt concrete mixes are designed to withstand aircraft loads and thermal loading throughout the observed temperature range at a given location.

Therefore, by design the effects of climate are being accounted for by selecting materials that perform better in that specific climate zone.

5.2 Limitations

As with will all research, there are a varying degree of limitations; this research effort was not an exception. Through the analysis portion of this research, limitations were discovered with the current PAVER^{TM} roll up data. The rollup database utilized in the research was missing the most recent airfield PCI inspections from various installations within the database. Approximately 32% of the bases in the database were missing one airfield inspection and approximately 42% of the bases in the database were missing two or more inspections from the past two decades. When the rollup database was created, not all of the existing PCI inspections were captured in the creation of the Air Force Airfield Pavement Rollup database. As outlined in Chapter 2, PAVER^{TM} generates a pavement performance predictive model that best fits the PCI data in the database. If there is a limited amount of data associated with a particular family of pavements, there is an increased potential for an inaccurate assessment of the true deterioration rate for a specific pavement family to be generated. In the future, adding the most recent inspection data to the database provides an opportunity to refine the results and the conclusions from this research. Furthermore, building a more robust database will provide a solid foundation for future pavement deterioration research.

Accuracy of the data is another issue/limitation that was discovered through the analysis. In particular, the accuracy of the age of the pavement recorded during the inspections was sometimes questionable. Observations from multiple bases proved that some of the ages associated with certain inspections sections were highly inaccurate. For example, the PCI data associated with the Seymour Johnson AFB AC runway pavements revealed sections that are 40 years old with PCIs as high as 100. These PCI values are not realistic for asphalt pavements, especially at that age. Inaccuracies such as this example create additional variance within the models and result in high standard deviations. Typically, when a prediction model has a standard deviation of error above 15 or more, there are underlying problems with the data associated with that model. The issues that have been addressed are two of the main observed issues through the analysis. To conduct this research in the future, these issues will have to be addressed to guarantee the accuracy of the prediction models that PAVER^{TM} produces and the statistical analysis results that are based on the average rate of deterioration trend models.

First, the accuracy of the pavement sections age and the accuracy of the PCI values for each of the inspected sections on each individual airfield need to be verified. This process will allow for a thorough scrub of the existing data to locate and eliminate suspect PCI data points that have the potential to heavily influence the pavement prediction model. As discussed in the previous section, inaccurate data PCI data points do have a significant influence on the accuracy of the prediction models that PAVER^{TM} produces. This step provides a solid foundation for future airfield pavement research past the scope of this effort. The second step needs to be focused on updating the Air Force rollup with the installation PCI surveys that are not currently in the database. Having a complete database will allow for a more accurate assessment of the true pavement deterioration trends at each installation, as well as at the regional and the Air Force wide levels. The third item that needs to be explored is whether or not the full rollup database can support breaking down the runway, taxiway, and aprons into primary, secondary, and tertiary pavements. In order for PAVER^{TM} to generate a performance predictive model, at least five PCI data points need to exist. On most Air Force airfields, AFCEC pavement engineers tend to see a high percentage of environmentally related distresses vice load related distresses. However, these load related distresses tend to be observed more frequently in the center (keel) section of the runway and taxiways as aircraft loading tends to be concentrated in these areas. Distinguishing between deterioration cause by load related distress, construction-related distresses, and environmental distressed would provide greater fidelity to the analysis and reveal trends that were not evident in the current analysis.

5.3 Future Research

The last main objective of the research was to provide a proof of concept for conducting this type of research in the future. First and foremost, the limitations of the rollup database must be addressed. This will ensure that the data being analyzed is the most up-to-date and accurate. Once the database has been updated and associated data has been scrubbed and verified, the methodology that was outlined in Chapter 3 can be repeated to verify the results and trends of this research.

Despite the issues with the data identified in section 5.2, this effort clearly showed that there were trends in the data for different PCC regions. While the AC analysis showed no statistical difference between regions at the 5% significance level, the search for an explanation of this behavior leads to several other possible research opportunities. One potential explanation of this phenomenon was that binder selection in mix designs compensates for variations in climate. Additional research could shed more light on the validity of this hypothesis. This research also identified a number of bases that had deterioration rates both one standard deviation above and below the mean for both PCC and asphalt pavements. This result presents an opportunity for further research to determine causal factors for these variations. In the case of those bases with deterioration rates above the mean, we can identify strategies to mitigate the issues; similarly for bases with rates below the mean, we can search for best practices that can be applied to other bases. While the overall data shows that Air Force airfields tend to have more environmentally related distresses than load related distresses, these differences have not been quantified statistically; this presents another opportunity for research. Finally, this research effort highlighted an issue with how that Air Force records Longitudinal/Transverse (L/T) cracking distresses in AC pavements. Anecdotally, pavement evaluators say that a high percentage of L/T cracking is due the poor compaction on paving lane joints. L/T cracking is categorized as an environmental distress vice a construction-related distress. This disconnect provides an opportunity to look at avenues for more accurately recording the nature of the mechanism driving pavement deterioration. If research identifies a better procedure, there would be greater fidelity in the data, which would result in greater fidelity in overall trends of construction, environmental, and load related distresses.

Appendix A - JMP Models

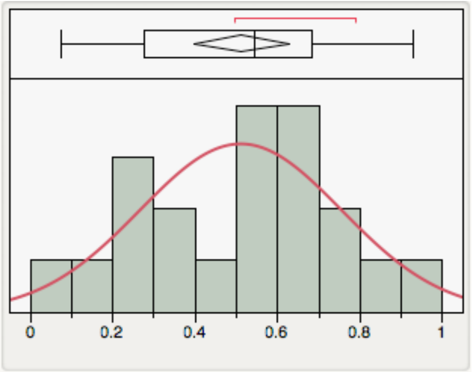


Figure 12. No Freeze-Wet Runway-PCC Distribution

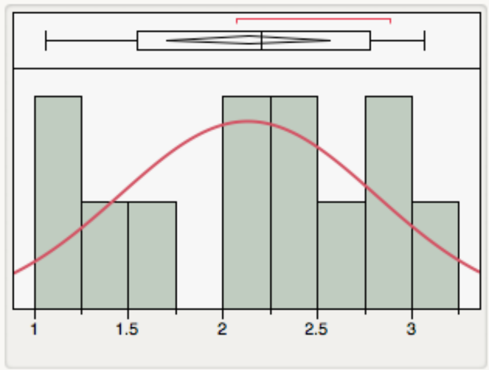


Figure 13. No Freeze-Wet Runway-AC/AAC Distribution

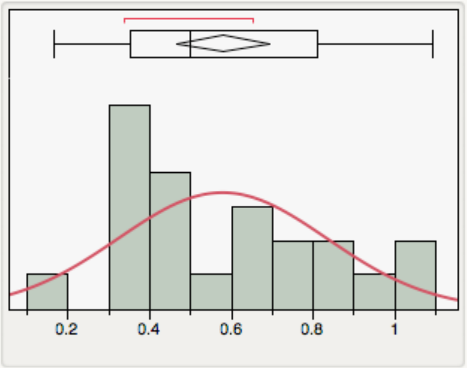


Figure 14. No Freeze-Wet Taxiway-PCC Distribution

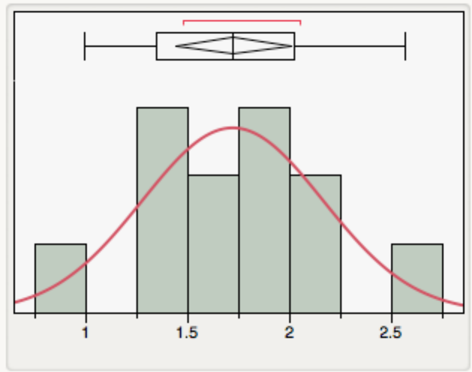


Figure 15. No Freeze-Wet Taxiway-AC/AAC Distribution

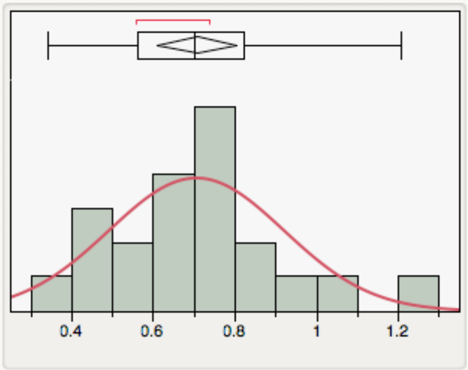


Figure 16. No Freeze-Wet Apron-PCC Distribution

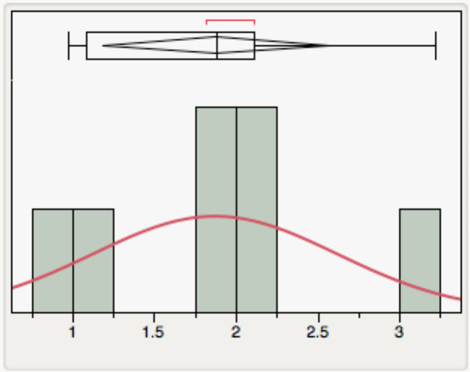


Figure 17. No Freeze-Wet Apron-AC/AAC Distribution

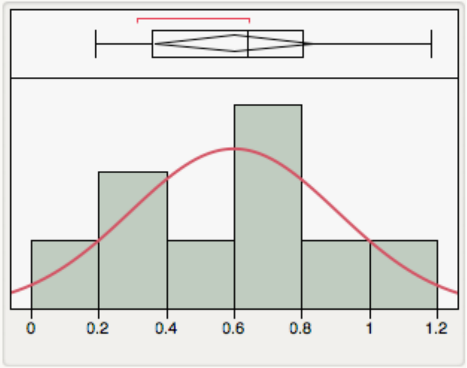


Figure 18. No Freeze-Dry Runway PCC Distribution

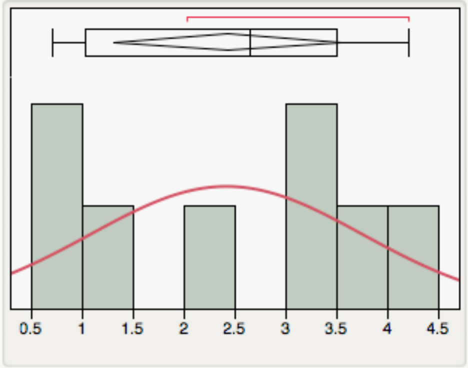


Figure 19. No Freeze-Dry Runway AC/AAC Distribution

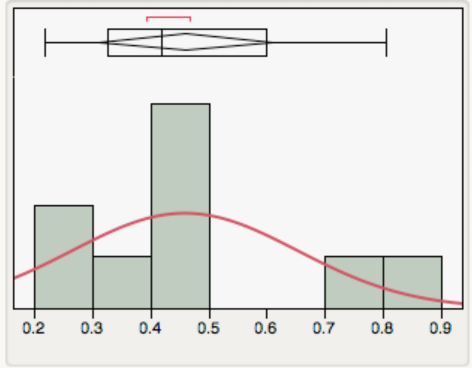


Figure 20. No Freeze-Dry Taxiway PCC Distribution

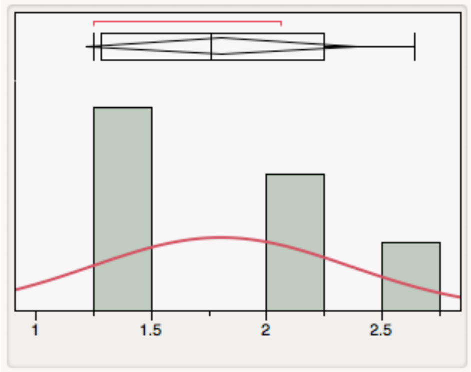


Figure 21. No Freeze-Dry Taxiway AC/AAC Distribution

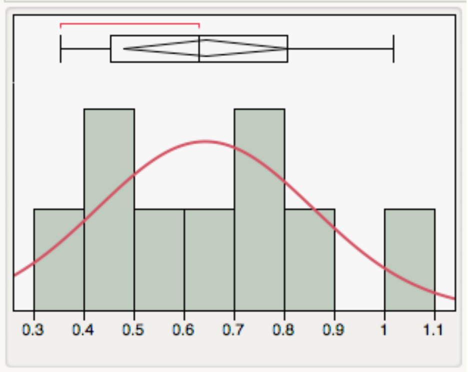


Figure 22. No Freeze-Dry Apron PCC Distribution

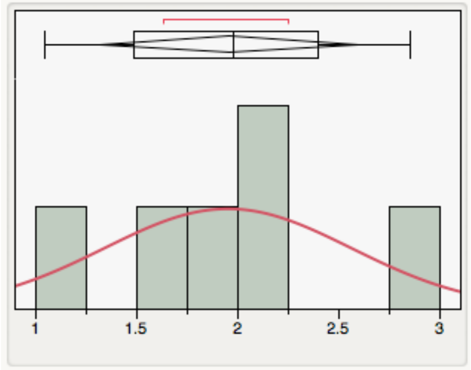


Figure 23. No Freeze-Dry Apron AC/AAC Distribution

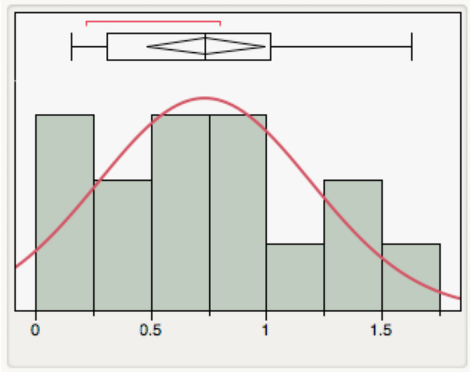


Figure 24. Freeze-Wet Runway PCC

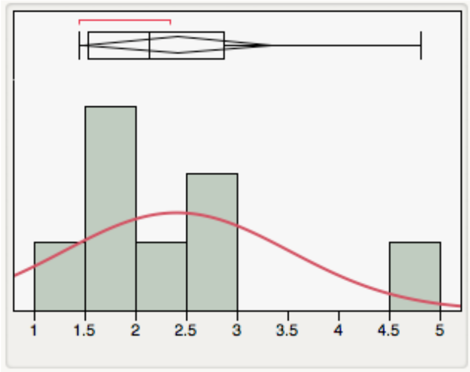


Figure 25. Freeze-Wet Runway AC/AAC

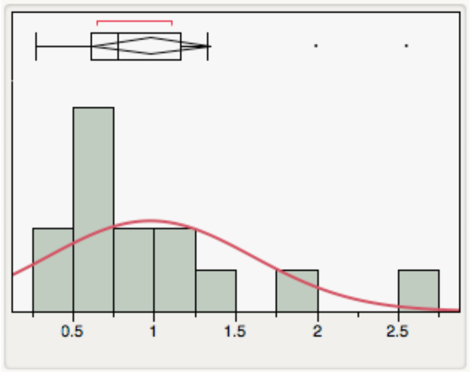


Figure 26. Freeze-Wet Taxiway PCC (with Outliers)

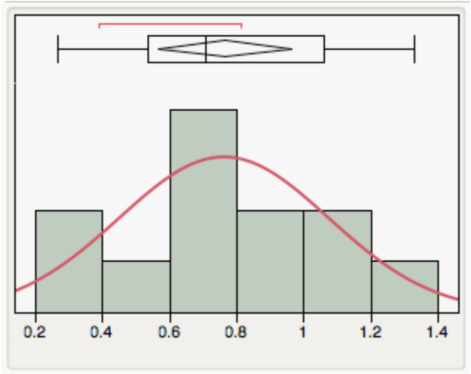


Figure 27. Freeze-Wet Taxiway PCC (with outliers removed)

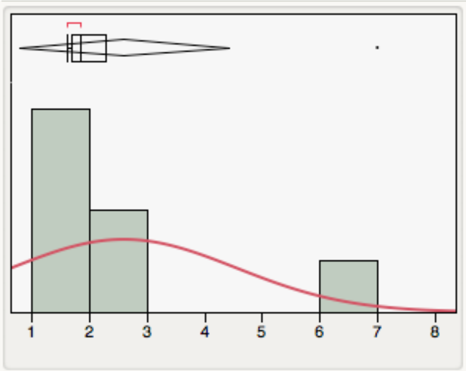


Figure 28. Freeze-Wet Taxiway AC/AAC (with outliers)

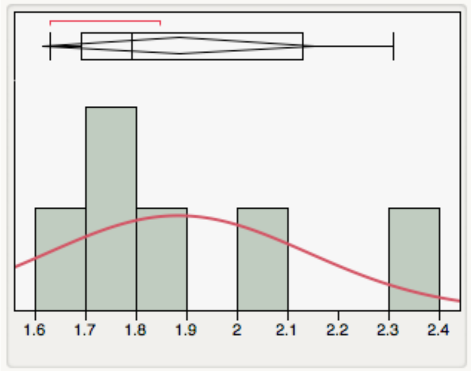


Figure 29. Freeze-Wet Taxiway AC/AAC (with outliers removed)

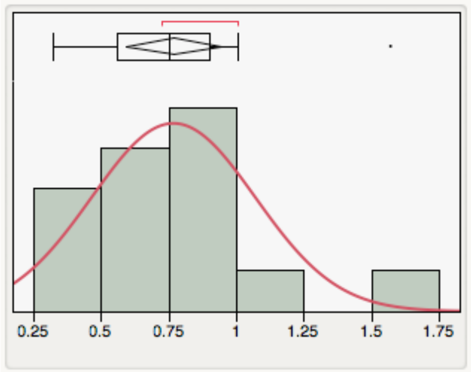


Figure 30. Freeze-Wet Apron PCC (with outliers)

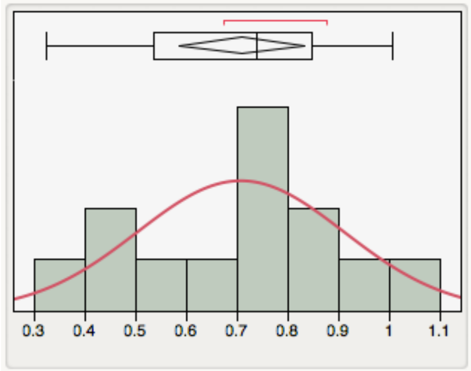


Figure 31. Freeze-Wet Apron PCC (with outliers removed)

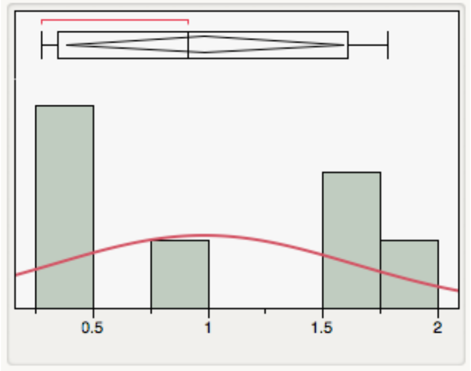


Figure 32. Freeze-Dry Runway PCC

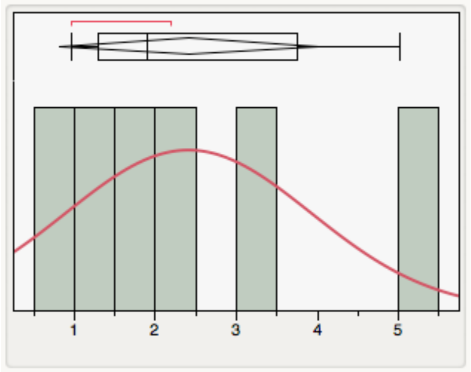


Figure 33. Freeze-Dry Runway AC/AAC

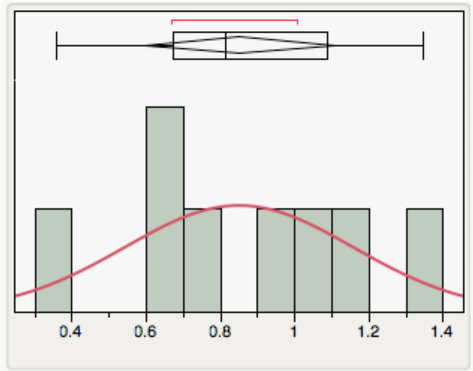


Figure 34. Freeze-Dry Taxiway PCC

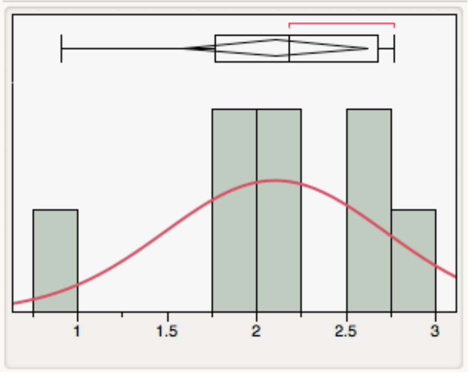


Figure 35. Freeze-Dry Taxiway AC/AAC

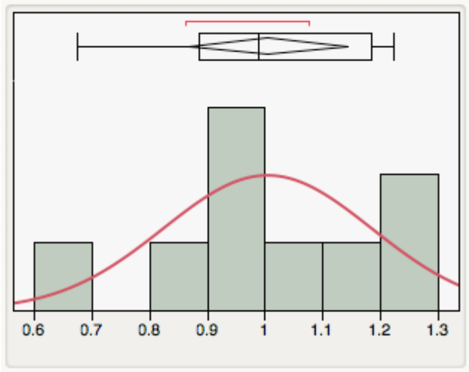


Figure 36. Freeze-Dry Apron PCC

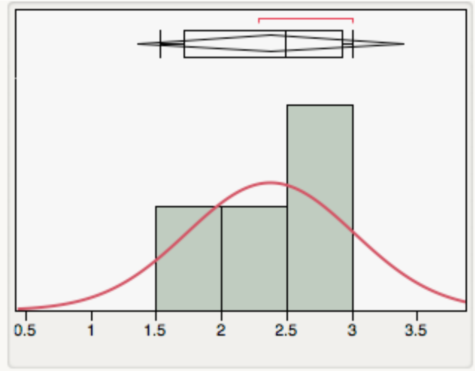


Figure 37. Freeze-Dry Apron AC/AAC

Table 24. No Freeze-Wet Rates of Deterioration Data

		RUNWAY PAVEMENTS				TAXIWAY PAVEMENTS				APRON PAVEMENTS			
		PCC		AC		PCC		AC		PCC		AC	
Base	**Climate Zone**	**ROD**	**Stnd Dev**	**ROD**	**Stnd Dev**	**ROD**	**Stnd Dev**	**ROD**	**Stnd Dev**	**ROD**	**Stnd Dev**	**ROD**	**Stnd Dev**
Barksdale	No Freeze_Wet	0.5666	8.9730			0.63395	14.357			0.66254	16.143		28.685
Beale	No Freeze_Wet	0.1281	4.8760			0.16462	4.269			0.34105	14.172		
Cape Canaveral	No Freeze_Wet			2.2859	1.1711								
Charleston	No Freeze_Wet	0.6903	9.0960	2.1222	14.2970	1.09119	9.261	2.56396	22.554	1.20843	13.524	1.87646	11.857
Columbus	No Freeze_Wet	0.4962	6.1600	2.8860	9.7360	0.44326	10.276			0.73863	18.965		
Dyess	No Freeze_Wet	0.9297	9.2370	2.6958	14.3070	0.90638	14.127	1.92862	12.664	0.70727	7.023		
Eglin	No Freeze_Wet	0.2503	4.0170	2.3073	8.2360	0.48607	5.637	1.58866	10.196	0.62763	13.492	2.1109	24.161
Hickam	No Freeze_Wet					0.30162	11.77	2.20274	13.824	0.49709	14.117	2.04389	13.858
Hurlburt	No Freeze_Wet	0.7885	6.0420			0.34679	3.47	1.89866	22.695	0.60252	10.775		
Keesler	No Freeze_Wet	0.5275	0.9050	1.4953	5.3540	0.51192	2.104			0.7564	21.011		
Lackland	No Freeze_Wet	0.5299	3.3610			0.33706	5.208			0.56532	8.433		
MacDill	No Freeze_Wet					0.35603	6.168			0.73344	18.938	1.81295	18.409
Maxwell	No Freeze_Wet	0.3543	10.3820			0.42855	5.801	1.47766	17.974	0.55925	19.364		
McChord	No Freeze_Wet	0.8753	19.5510			0.69166	8.064	1.3013	11.907	0.45321	7.956	1.07987	5.892
Moody	No Freeze_Wet	0.0734	0.9550			0.85849	8.882			1.08669	10.358		
North Auxillary Field	No Freeze_Wet	0.6594	1.5120	1.1200	10.0720	0.70563	12.295	1.29024	14.274				
Patrick	No Freeze_Wet												
Pope	No Freeze_Wet	0.6532	4.4660	2.8047	6.4180	0.79388	5.51	1.84669	13.895	0.70831	10.527	3.2181	16.057
Robins	No Freeze_Wet	0.3565	6.2200			0.47807	10.42			0.44952	9.761		
Randolph	No Freeze_Wet	0.2273	3.2720	2.0732	8.6800	0.86502	11.475	0.99192	28.87	0.89521	11.018	0.9722	15.098
Seymour Johnson	No Freeze_Wet	0.7226	14.3760	1.0587	28.9250	1.00197	13.53	2.05242	21.514	0.70265	14.358		
Shaw	No Freeze_Wet	0.2358	4.9890	1.6937	6.8940	0.35093	5.854			0.98365	15.125		
Tyndall	No Freeze_Wet	0.5560	4.0660	3.0676	8.9250	0.35131	6.863			0.67737	8.953		
Travis	No Freeze_Wet	0.6221	6.8540			0.6526	7.722			0.88959	9.439		

Table 25. No Freeze-Dry Rates of Deterioration Data

		RUNWAY PAVEMENTS				TAXIWAY PAVEMENTS				APRON PAVEMENTS			
		PCC		AC		PCC		AC		PCC		AC	
Base	**Climate Zone**	**ROD**	**Stnd Dev**	**ROD**	**Stnd Dev**	**ROD**	**Stnd Dev**	**ROD**	**Stnd Dev**	**ROD**	**Stnd Dev**	**ROD**	**Stnd Dev**
Creech	No Freeze_Dry	0.8442	9.893	3.5318	7	0.46706	7.09	1.2951	4.171	0.72588	9.267	2.10679	13.786
Davis-Monthan	No Freeze_Dry	0.3126	4.47	4.1985	7.098	0.40862	7.379	2.64052	22.476	0.43841	10.609	1.84243	10.357
Edwards	No Freeze_Dry	0.6398	10.65	2.0357	5.053	0.72919	15.835	2.06164	5.72	0.78989	11.832	0	0
Gila Bend AF Aux Field	No Freeze_Dry	0.7582	3.906	0	0	0	0	0	0	0	0	0	0
Holloman	No Freeze_Dry	0.437	9.873	0.7168	4.153	0.39439	9.855	1.25132	23.669	0.62893	11.058	1.63709	10.986
Laughlin	No Freeze_Dry	0	0	3.3723	8.102	0.21895	1.722	1.46173	7.633	1.01763	11.777	2.24579	5.686
Luke	No Freeze_Dry	0.3997	2.519	1.3344	5.556	0.41967	7.38	0	0	0.54495	9.373	0	0
March	No Freeze_Dry	0.6424	11.879	0.9263	32.728	0.43934	11.479	0	0	0.47061	11.212	1.04438	13.848
Nellis	No Freeze_Dry	1.1804	12.322	3.2547	13.64	0.80276	6.563	2.1154	13.835	0.82083	9.277	2.84747	8.441

Table 26. Freeze-Wet Rates of Deterioration Data

		RUNWAY PAVEMENTS				TAXIWAY PAVEMENTS				APRON PAVEMENTS			
		PCC		AC		PCC		AC		PCC		AC	
Base	**Climate Zone**	**ROD**	**Stnd Dev**	**ROD**	**Stnd Dev**	**ROD**	**Stnd Dev**	**ROD**	**Stnd Dev**	**ROD**	**Stnd Dev**	**ROD**	**Stnd Dev**
Altus	Freeze_Wet	0.2193	6.867	4.7985	6.27	0.26873	7.564			0.32585	8.358		
Andrews	Freeze_Wet	0.7365	8.738	1.4408	3.359	0.96395	11.918	1.73883	11.975	0.73914	10.921		
Arnold	Freeze_Wet												
Dover	Freeze_Wet	0.965	18.84	1.5048	15.375	1.32545	12.628	2.30718	15.994	0.98279	15.312	2.30718	15.994
Grissom	Freeze_Wet	0.507	4.574										
Langley	Freeze_Wet	1.3586	12.88			0.7368	16.95			0.81573	19.677		
Little Rock	Freeze_Wet	0.7918	6.28			0.81155	10.014			0.67323	10.347		
McConnel	Freeze_Wet	0.3795	5.526	2.7081	15.275	1.10201	9.581	1.84705	13.121	0.76857	9.805		
McGuire	Freeze_Wet	0.668	15.096	2.3344	11.369	0.5	7.683	2.0699	13.852	0.58101	12.725		
Offutt	Freeze_Wet	0.7951	25.494			0.6549	12.622			0.72739	14.844		
Scott	Freeze_Wet	0.312	13.973	1.6498	22.329					0.87591	21.134		
Sheppard	Freeze_Wet	0.1793	9.557	1.9385	4.632	0.38999	6.739	1.71073	11.915	0.7764	13.684	1.77102	9.513
Tinker	Freeze_Wet	1.3078	6.254			1.0884	9.064	1.63198	17.612	1.00381	12.647		
Vance	Freeze_Wet	1.015	12.581	2.9129	7.383	0.67545	10.909			0.49198	11.114		
Whiteman	Freeze_Wet	0.1575	1.694			0.64425	10.205			0.44132	6.227		
Wright Patterson	Freeze_Wet	1.6279	9.84										

Table 27. Freeze-Dry Rates of Deterioration Data

		RUNWAY PAVEMENTS				**TAXIWAY PAVEMENTS**				**APRON PAVEMENTS**			
		PCC		**AC**		**PCC**		**AC**		**PCC**		**AC**	
Base	Climate Zone	ROD	Stnd Dev	ROD	Stnd Dev	ROD	Stnd Dev	ROD	Stnd Dev	ROD	Stnd Dev	ROD	Stnd Dev
Buckley	Freeze_Dry												
Cannon	Freeze_Dry	0.277	2.899	0.9676	3.292	0.68922	11.577	1.78604	9.487	0.86176	11.109		
Eielson	Freeze_Dry			2.1909	10.823			1.75879	8.773	1.2155	5.356	1.52388	5.6
Ellsworth	Freeze_Dry	0.352	4.812										
Elmendorf	Freeze_Dry	1.6028	4.462	1.6029	4.462	0.357	6.877	2.18423	9.187	0.67618	12.644	2.70446	9.377
Fairchild	Freeze_Dry	1.533	18.414			0.72452	10.964	2.5256	17.748	0.98877	19.13	2.99913	29.261
Grand Forks	Freeze_Dry	0.4386	0.667			1.11533	8.203			1.1498	15.998		
HIll	Freeze_Dry	1.7805	10.085	1.4012	14.081	0.90212	9.124	2.76813	18.711	1.07519	13.412		
Kirtland	Freeze_Dry					1.34538	11.589	2.18194	21.101	1.2211	26.733	2.28258	26.289
Minot	Freeze_Dry	0.912	11.673	5.0236	12.237	1.00843	13.543	2.72411	9.728	0.94295	13.137		
Mountain Home	Freeze_Dry			3.316	7.378	0.66968	5.471	0.91347	12.194	0.91227	9.804		

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

Over the past two decades, pavement engineers at the Air Force Civil Engineer Center have noticed the majority of identified distresses from PCI airfield surveys are climate related. To verify these trends, a comprehensive analysis of the current airfield pavement distress database was accomplished based on a climate region perspective. A four-zone regional climatic model was created for the United States using geospatial interpolation techniques and climate data acquired from WeatherBank Inc. Once the climatic regional model was developed, the climate information for each installation was imported into the Air Force pavement distress database within PAVER. Utilizing the pavement condition prediction modeling function in PAVER, pavement deterioration models were created for every pavement family at each base in each climatic zone. This was done to generate a list of bases that may have multiple pavement families with rates of deterioration that are better or worse than the regional rates of deterioration. The average regional rates of deterioration for each pavement family were found to be within the parameters of conventional wisdom observed in Asphalt Concrete (AC) and Portland Cement Concrete (PCC). The results of the pairwise comparisons using the Student's T-test determined the Freeze-Dry climate region deterioration rates for the PCC pavement family were statistically different than the other three regions. No significant statistical differences were observed in the AC pavement comparisons. This analysis established a foundation to investigate and identify variables causing the rates of deterioration at specific installations to differ from the regional rates of deterioration.

15. SUBJECT TERMS

Pavement Condition Index, Rate of Deterioration, Airfield Pavement Distresses, Portland Cement Concrete, Asphalt Concrete

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