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Research Article

An Investigation of Geography and Climate Induced Distresses Patterns on Airfield Pavements at US Air Force Installations

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This study investigated climate induced distresses patterns on airfield pavements at US Air Force installations. A literature review and surveys of Pavement Condition Index indicated that the predominant factor contributing to the development of pavement distress was climate. Results suggested that, within each type of pavement distress, a geographic pattern exists which is strongly correlated to conventional US climate zones. The US Air Force Roll-Up Database, housing over 50,000 records of pavement distress data, was distilled using a process designed to combine similar distresses while accounting for age and size of samples. The process reduced the data to a format that could be used to perform krig analysis and to develop pavement behavior models for runways built with asphalt cement (AC) and Portland cement concrete (PCC). Regression and krig analyses were conducted for each distress type to understand distress behavior among climate zones. Combined regression and krig analyses provided insight into the overall pavement behavior for AC and PCC runways and illustrated which climate zone was more susceptible to specific pavement distresses. Distress behavior tends to be more severe in the eastern US for AC and in the western US for PCC runway pavements, respectively.

1. Introduction

The United States Air Force (USAF) contains 1.6 billion square feet of concrete and asphalt pavement in its property inventory across 166 installations worldwide. A part of the inventory, airfield pavements alone have a plant replacement value of more than $27 billion and require millions of dollars in annual maintenance. The Budget Control Act, enacted by the United States Congress in 2011, requires the Department of Defense (DoD) to reduce its expenditures by approximately $487 billion over the next 10 years. This budget cut has forced Air Force engineers and asset managers, at all administrative levels, to reconsider their strategic approach to facility and infrastructure asset management [1].

The Air Force Civil Engineer Center (AFCEC) is responsible for strategic and long-term pavement management at the combined, joint, major command and installation levels [2, 3]. To manage the Air Force pavement inventory, AFCEC developed the Air Force Pavement Evaluation Program (AFPEP) to determine current pavement conditions; this program strategically allocates restoration and modernization funds to address future pavement and mission needs [4]. To determine each installation's pavement condition, the Pavement Evaluation Program obtains, compiles, and reports pavement strength, conditions, and performance by means of a rotation of pavement inspections, evaluations, and tests. As a result, engineers and asset managers are able to (1) determine the operational conditions of the pavement; (2) develop

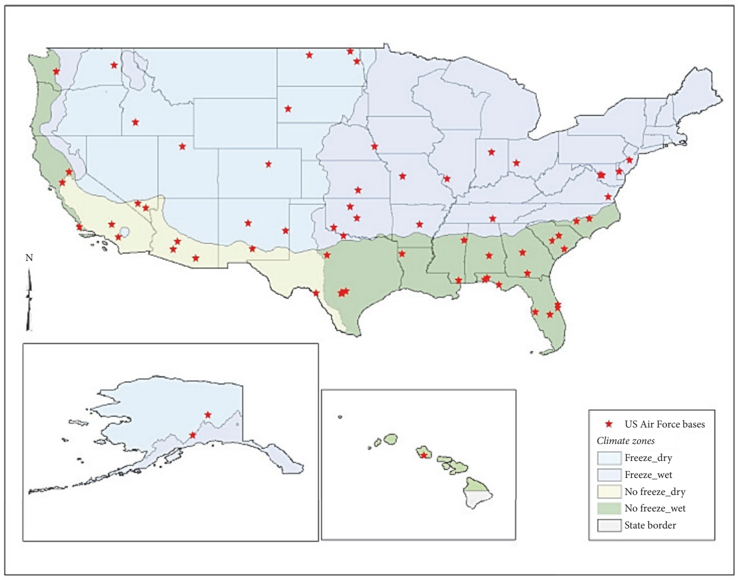

Figure 1: Climate model proposed by AFIT based on precipitation and temperature (source: [5]).

and prioritize sustainment, restoration, and modernization projects; and (3) determine whether additional pavement investigation is necessary.

One of the inspections used by AFCEC to evaluate the pavement's structural and operational integrity is the Pavement Condition Index (PCI) Survey. The results of these inspections are the catalyst and the basis from which this research has been conducted. From the compiled results of PCI surveys, pavement engineers at AFCEC-East, located at Tyndall Air Force Base near Panama City, Florida, noticed what they believe to be climatological trends within the pavement distress data. From these observations, they postulated that climate is the predominant contributing factor of pavement distresses.

To test their hypothesis, the Air Force Institute of Technology (AFIT), located at Wright-Patterson Air Force Base in Ohio, studied the relationship between climate and pavement deterioration rates. The objective was to answer the following 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?" [5]. In order to develop a climate model, AFCEC and AFIT used precipitation and temperature data that was collected from 1982 to 2011 at 1,700 National Oceanic and Atmospheric Administration, National Weather Service, and Federal Aviation Administration weather stations scattered across the United States. This climate model included four climate zones, depicted in Figure 1 [5]. The research team worked with engineers at the US Army Cold Regions Research and Engineering Laboratory, located in Hanover, New Hampshire, to develop the break points delineating freeze and no freeze zones and wet and dry zones [5]. The break point used to define a "wet" zone from a "dry" zone was 64 cm of annual precipitation, and the criterion used to delineate between a "freeze" climate and a "no freeze" climate was 750 freezing degree days. A freezing degree day is defined as the temperature of the mean daily air temperature from 0°C [6]. The four climate zones were "freeze_dry," "freeze_wet," "no freeze_dry," and "no freeze_wet."

After the climate model was developed, in order to calculate the pavement deterioration rates within each family of pavement, PAVER, a pavement management software program originally developed in the 1970s to assist the DoD in managing its large pavement inventory was used [7, 8]. These deterioration rates were statistically examined against other deterioration rates at bases within each of the four proposed climate zones.

The investigation concluded that, for the same pavement type, aprons typically deteriorated faster than taxiways, and taxiways deteriorated faster than runways. In addition, it was found that, for the same type of use, pavements built with asphalt concrete (AC) and asphalt-over-asphalt concrete (AAC) deteriorated much faster than Portland cement concrete (PCC) pavements. Finally, for all pavement families, with the minor exception of AC/AAC runways, the "freeze_dry" climate zone had the highest rate of deterioration, as shown in Tables 1 and 2 [5].

As follow-on research to the investigation of climate and deterioration rates accomplished by AFIT, pavement engineers at AFCEC-East requested that distress patterns within the four proposed climate regions be investigated [9]. Specifically, they wanted to know which types of distress were most prevalent in each of the four climate zones. This knowledge would provide valuable information to use during pavement maintenance planning and asset allocation; for example, if they know that alligator and longitudinal/transverse cracking are more prevalent in "freeze_wet" climates, then they could proactively allocate funds to address these distresses at Air Force installations located within the "freeze_wet" climate zone.

Table 1: Average rate of deterioration for runways, taxiways, and aprons in the four climate zones proposed by AFIT-AC/AAC.

	AC/AAC (AC age restricted) Average rate of deterioration		
Climate zone	Runway	Taxiway	Apron
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	1.8640	2.0205

Table 2: Average rate of deterioration for runway, taxiway, and aprons in the four climate zones proposed by AFIT-PCC.

	PCC Average rate of deterioration		
Climate zone	Runway	Taxiway	Apron
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	0.7632

This paper proposes an analysis of patterns within specific pavement distress types from a geographic and climatological vantage. The objective of this research is to investigate the existence of geography and/or climate induced distresses patterns on airfield pavements. As part of this research, answers to the following questions are sought: (i) Is a climate model based upon precipitation and temperature data appropriate for use to evaluate the relationship between climate and pavement deterioration behavior at the individual pavement distress level? (ii) Does a pattern emerge considering only the geographic location of specific pavement distresses? (iii) If a geographic or climatological pattern does not emerge, what other factors should be considered as contributing to the development of the surveyed pavement distresses?

2. Literature Review

2.1. Pavement Management System. A deliberate and purposeful approach to pavement management is essential for a prolonged airfield pavement life and uninterrupted operation. In 2013, the USAF accomplished over 5.9 million sorties. By using a Pavement Management System (PMS), airfield managers, pavement engineers, and asset managers at all levels work together to ensure that airfield pavements can safely support each and every one of those flying missions. A PMS effectively provides a systematic and consistent method for identifying maintenance and repair (M&R) requirements, highlights requirement priorities, and provides a framework for scheduling maintenance actions while optimizing cost and time [10].

Shahin [10] introduced two important concepts regarding PMS. The first is that a pavement rate of deterioration (ROD) is not constant. Initially, the ROD is very rapid; then, after the initial drop in pavement conditions, the ROD levels off for a number of years until it undergoes a second rapid decrease in pavement conditions. The second concept is that if maintenance action is accomplished to rehabilitate a pavement before the second rapid decrease in pavement condition occurs, then the overall cost of the rehabilitation is much less than if the rehabilitation is accomplished after the second major drop [10].

The first step in establishing a PMS is to classify the pavement within the system. A pavement network is the highest level of classification within the pavement system. Shahin [10] defines a pavement network as “a logical grouping of pavements for M&R management.” Examples of pavement networks within an Air Force installation are airfield pavement, roadways, and parking lots. Another way to create networks within an Air Force installation is to delineate between roadways associated with the base and roadways associated with family housing.

For this research, the pavement network was set as the airfield pavement at each AF installation. Within a pavement network, there are branches readily identifiable and with a unique use. This research focused on the pavement behavior of the runway branch within an airfield network. The smallest classification within a pavement system is a pavement section, which is created when the pavement characteristics within a branch are not consistent. Pavement characteristics to consider when defining sections are pavement structure, construction history, traffic, pavement function, drainage, condition, and size [10].

2.2. Pavement Condition Index. The second major component of PMS involves assessing the current condition of a pavement within the system and predicting how it will behave in the future. For conditions involving one pavement network compared to another pavement network, an objective and repeatable rating system must be used across all networks under consideration. The Pavement Condition Index (PCI) is a numerical index, ranging from “0” to “100,” where a rating of “100” corresponds to a pavement in perfect condition and a rating of 0 corresponds to a failed pavement. This rating system is used by AFCEC to standardize condition assessments across all Air Force installations. Developed by the US Army Corps of Engineers in the 1970s, the PCI was published under the American Society for Testing and Materials [11]. Other agencies that have used the PCI to assess conditions of their pavement systems include the US Navy, the US Army, the Federal Aviation Administration, and the Federal Highway Administration [7].

Calculation of the PCI is based on the results of an inspection of visual conditions, a PCI survey, which is used to identify the types, severity, and amount of distress caused by aircraft loadings as well as by vehicle traffic and environmental conditions. This survey is conducted by contracted personnel approximately every five years at all the main operating bases and auxiliary fields belonging to the Unites States Air Force. The pavement distress information collected during PCI surveys provides insight into the causes of pavement deterioration [10].

3. Methodology

The inspection data and PCI calculations collected over the past 50 plus years have been maintained by AFCEC and were made available for this research effort in the form of a database. This data was used in this study to evaluate if a relationship exists between climate and distress occurrences within the continental United States. Assumptions of the research needed to be defined, because the data was collected by a third party.

The first assumption of this research was that the rate of sampling within each pavement section followed the minimum sampling procedures as outlined in ASTM D5340, *Standard Test Method for Airport Pavement Condition Index Surveys* [11], and was consistent across all PCI surveys. This assumption had to be made because the dataset only included instances of distress findings. It did not include pavement sections that were inspected but did not contain a pavement distress, meaning that the data did not include sampling rates for sections of pavement void of distresses. Therefore, the data was insufficient to quantify if the sampling rate was consistent across the survey process.

The PCI surveys were completed by four different contractors. A second assumption was made that the expertise among these contractors was similar, and all PCI survey findings were comparable for any given inspection. However, the statistical analysis conducted on the data accounted for the variance among the four contracts.

The third assumption was that the PCI returned to "100" at the time of the last major/global renovation. This assumption was necessary because reliable maintenance records for each section of airfield pavement were not available. Therefore, the only method to reasonably estimate the pavement's deterioration behavior over time was to assume that the condition was returned to "100" on the date of the last major/global renovation and thus assess the changes in conditions at the last inspection since renovation occurred.

3.1. Air Force Roll-Up Database. The data used in this research was based on PCI surveys conducted during four different Air Force contracts over the past 16 years. The data was housed in an MS Access database, the Air Force Roll-Up Database, and consisted of over 50,000 lines of distress data from USAF installations across the globe. Table 3 shows the data fields pulled from the database and a description of each.

With regard to the methodology, regression analysis was conducted between the PCI deduct values and pavement age, measured in years since the last major/global renovation, for each unique combination of pavement type and distress type within runway pavements for each of the four climate zones presented by AFIT. The highest R^2 value of the distress data is 0.2. This value is very small and suggests that there is very little correlation between the proposed climate zones and the distress data; therefore, this value is not a strong representation of the distress data. However, the trend lines do suggest a notion of the distress propagation with time, which is why they were included in the analysis rather than being discarded completely.

3.2. Model Approach. Rather than trying to force the distress data into a predeveloped climate model and then performing an isolated geostatistical analysis within each zone, a pavement behavior model was created by kriging the distress data as it naturally occurs and assessing if any geographic patterns imbedded within the distress data were captured [12–15]. These patterns then could be compared to conventional climate models. Essential to utilizing this model is an understanding that all the distress contributors, that is, traffic load, climate, maintenance history, construction, and pavement structure [16], were woven into the geographic manifestation, because the value used for kriging was a derivation of the PCI deduct value.

The US Air Force Roll-Up Database contains distress data for over 50,000 surveyed pavement distresses. The largest component of this research was to develop a method that would distill this database from 50,000 plus distress instances down to a concentrated list that would represent the entire database. In this way, kriging analysis could be applied by using the geospatial tools within ArcMap, an application of ArcGIS (Esri®) [9, 17–19].

Initially, distress data outside the range of this research was filtered out. This included isolating and removing:

(i) Air Force installations located outside of the continental United States, including removing installations located in Alaska and Hawaii

(ii) Nonrunway pavement branches

(iii) Pavement types other than asphalt cement (AC)

(iv) Asphalt-over-asphalt cement (AAC)

(v) Asphalt-over-Portland cement concrete (APC) and Portland cement concrete (PCC)

Finally, the data was filtered to include only distress data for distress types. After these filters were performed, the dataset included more than 6,400 instances of distress data occurring at 77 installations.

In the second refinement, data was distilled further by breaking them into subdatasets specific to pavement type and distress code. For example, the PCI deduct value representative of an instance of alligator cracking (distress code 41) which occurred on an AC runway only was considered with other PCI deduct values of the same distress type and pavement family. Once these data groups were created, each line of data, representing one distress occurrence, was assigned a latitude and longitude corresponding to the Air Force installation at which it occurred. This data was fed into ArcMap and displayed as x and y data in a point shapefile. This approach proved problematic because if a specific pavement distress occurred in more than one section or at different severity levels within the same pavement family at any given air field, then coincidental points were created within ArcMap. Coincidental points are different data points with the same x and y coordinates. In the above example, known as *ball and blanket*, a coincidental point would be comparable with trying to have two balls in the exact same location. This is a problem in geospatial processing because the software only can consider one point at a time. Therefore,

Table 3: Data fields within the AF Roll-Up Database.

Data field title	Description
Name	Air force installation name, example: Altus AFB, Nellis AFB
Branch area	Total area of the branch in square feet
Branch use	Runway, taxiway, apron, etc.
Branch ID	Specific name assigned to branch, example: RW1028
Sections	Number of sections within specified branch
Section ID	Similar to branch ID
Section true area	Total area of section in square feet
Surface type	PCC, AC, AAC, APC
Years since global/major work	Years since the pavement section's PCI was returned to 100
Sample units inspected	Within the section number of sample units that were surveyed
Total sample units in section	Number of pavement samples the section was broken into for the purposes of inspection (based on procedure outlined in ASTM 5340)
Distress code	Code assigned by PAVER which represents a specific pavement distress
Distress description	Alligator cracking, rutting, pop-out, weathering, etc.
Distress mechanism	Force that causes the distress, example: climate, load, others
PCI deduct	Calculated value representing the impact the distress has on the overall condition of the section
PCI	Numerical value between 0 and 100 associated with pavement section's condition

to perform the spatial analysis, kriging tries to simplify the coincidental points by using only the largest and smallest values, taking an average or deleting points. An alternative method was needed to accurately represent the data because by simplifying the coincidental points to a maximum, a minimum, or an average, the differences in the frequency of distress occurrence among the airfields were lost.

The PCI deduct values could not be summed without considering the age of each individual pavement section. For example, the deterioration behavior that caused a PCI deduct of "5" in a 10-year-old section of pavement is not the same as the deterioration behavior that caused a PCI deduct of "5" in a 5-year-old section of pavement. The purpose of the pavement model developed in this research was to model typical or average behavior of runway pavements. This was why the rate of deterioration or PCI deduct points per year are needed to be considered. Creating this rating system puts all PCI deduct values on the same nominal scale in order to compare them equally and helped to identify airfields at which specific distresses were propagating faster than others.

Each line of data in the AF Roll-Up Database represents the total PCI deduct value for a given distress at a specific severity level for an entire pavement section. To calculate the PCI deduct value for the whole section, each section within a branch was divided into a number of inspection sample units, following the procedures outlined in ASTM D5340 [11]. Each inspection sample unit where the distress occurred had a PCI deduct value assigned to it, following the steps previously outlined. Once the entire section was surveyed, one PCI deduct value was calculated, using a straight average of the PCI deduct values of each individual inspection sample. If the size of each inspection sample differed or if additional sample units were needed, then an area weighted average was used to calculate the PCI deduct for the whole section. As the area of the section increased, so did the minimum number of inspection sample units required by ASTM D5340.

Each PCI deduct value in the database represented a pavement section of a unique size. A weighted average was used to combine the PCI deduct values from each pavement section to account for variations in size. To combine the PCI deduct values specific to each branch within an airfield, one more area weighted average needed to be accomplished. This was necessary because the areas of each branch within a network can vary drastically.

Completing this process consolidated the 6,400 plus lines of pavement distress data for runways to one normalized PCI deduct value that represented the average deterioration behavior of distresses for each of the four runway pavement types at each Air Force installation. For example, the value representing the deterioration behavior of PCC runway pavement at Andrews AFB caused by small patching (distress code 66) was 0.8475 points/yr. This value eliminated each of the 21 coincidental points while still representing the overall deterioration.

4. Results and Analysis

The following four maps were created using the normalized PCI deduct values. Each map was created by summing the normalized PCI deduct values for all distress types and then kriging the combined PCI deduct value. Mapping all the distresses at once provided insights into the average deterioration behavior of the pavement as a whole. This deterioration behavior is illustrated by the geographic patterns seen in the following four models for specific pavement types.

Figure 2, which depicts the average distress behavior in asphalt-over-asphalt runways, shows that airfields in the

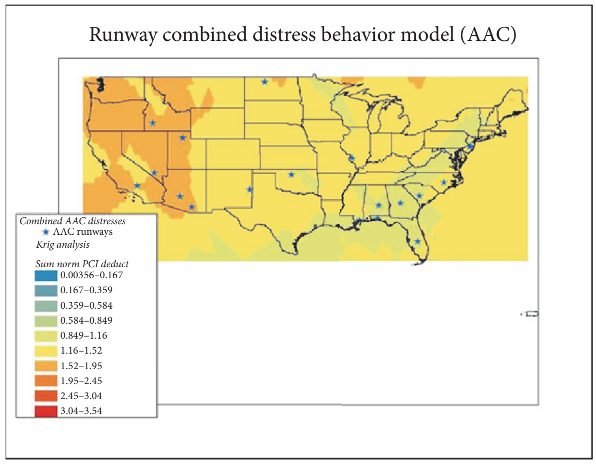

Figure 2: Krig image of normalized PCI deduct values for all distress types on AAC runways.

western third of the United States tended to have high normalized PCI deduct values. The second highest normalized PCI deduct values occurred in the middle third of the US and lowest in the eastern third of the US. However, there are very few data points located within the middle third, which introduced doubt as to the strength of the model.

This research considered 77 installations scattered across the entire United States, spanning more than 3.1 million sq mi (excluding Alaska and Hawaii). Only 19 installations contained AAC runway pavement sections. The ASTM D5922-96, *Standard Guide for Analysis of Spatial Variation in Geostatistical Site Investigation* [9], recommends at least 20 paired data values to be available for each lag. This dataset was right on the edge of this recommendation by the ASTM [20]. However, the area that the krig analysis considered was so large that 19 measured values spread across 3 million sq mi left large spans between measured points. Therefore, the variation in normalized PCI deduct value could not be predicted with a high level of confidence. Referring back to *ball and blanket* example, if the footprint of the blanket is very large and it is held up with only a few balls, it is very hard to predict the height of the blanket between the balls. The krig image presented in Figure 2 shows the trends that exist within the data; however, due to the lack of measured points, no additional analysis was performed on the data for AAC runway pavement sections, because any conclusions drawn would have been based on an uncertain model.

Figure 3 depicts distress behavior in asphalt-over-Portland cement concrete runways and shows a progressive increase in detrimental distress behavior in an eastward trend. However, the data only included 12 Air Force installations where APC runway pavements occur. For the deficiency in sample size discussed earlier, this krig image was created to investigate the geographic trends within the data; however, no additional analysis was conducted.

The krig image displayed in Figure 4 resulted from kriging the normalized PCI deduct values for the combination of all pavement distresses at 45 Air Force installations. There was a strong eastern trend in the magnitude of the normalized PCI deduct values. The map suggests that the distress behavior, represented by the normalized PCI deduct value used during kriging, was 2.5 to 3.5 times larger in asphalt cement runways located in the eastern US than in the western US. This trend is very different from the trend seen in Figure 5, which illustrates the combined distress behavior of PCC runways. The krig image in Figure 5 was produced by kriging the normalized PCI deduct value for all distresses occurring on PCC runways at 58 Air Force installations across the US. The krig image revealed two distress behavior zones embedded within the data.

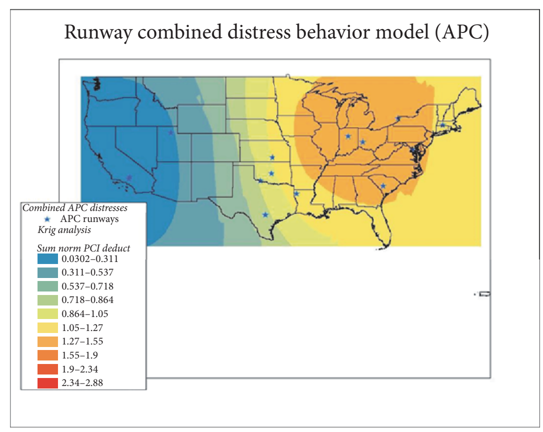

Figure 3: Krig image of normalized PCI deduct values for all distress types on APC runways.

Figure 5 illustrates that the greater and lesser distress behavior occurred, respectively, in the western and eastern regions of the US. The magnitude of the distress behavior at airfields in the western and northwestern regions of the US is almost 3.5 times the size of the distress behavior at airfields in the eastern region of the US. The trends for PCC runway pavements are almost exactly opposite those of AC runway pavements; however, attention should be paid to the difference in the scales used in each krig image. The AC scale

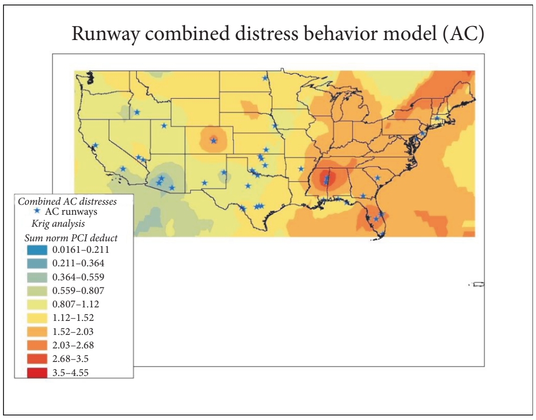

Figure 4: Krig image of normalized PCI deduct values for all distress types on AC runways.

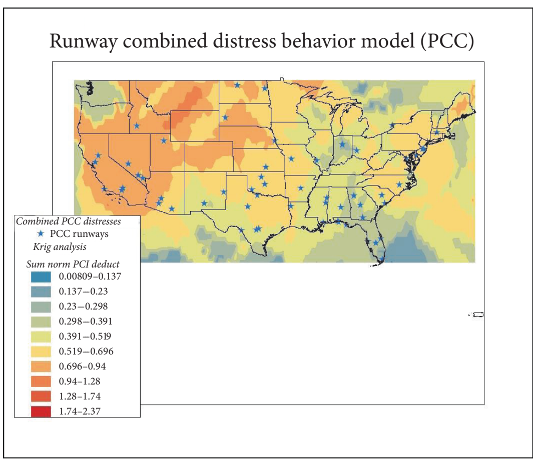

Figure 5: Krig image of normalized PCI deduct values for all distress types on PCC runways.

ranges from 0 to 4.55 PCI deduct points per year, whereas the PCC scale ranges from 0 to 2.37 PCI deduct points per year. This indicates that, overall, the PCI deduct values in PCC RW pavements are much smaller than those of AC RW pavements.

From the results of the krig analysis completed on each of the four runway pavement types, the following pavement distress-based models were developed for AC (Figure 6) and PCC (Figure 7) runways pavements. Notice that the line of demarcation between Zone 1 and Zone 2 is almost exactly the same in each pavement model and that the predominant distress behavior trends to the east for AC runway pavements, while it trends to the west for PCC runway pavements.

4.1. Statistical Investigation of Proposed RW Models Based on Average Deterioration Behavior. A statistical investigation was completed to determine if the deterioration behavior of the RW pavement in AC Zone 1 was statistically different from the pavement in AC Zone 2. Similarly, analysis was performed between PCC Zones 1 and 2. Two-sample t-test was used to compare the mean value of the normalized PCI deduct values

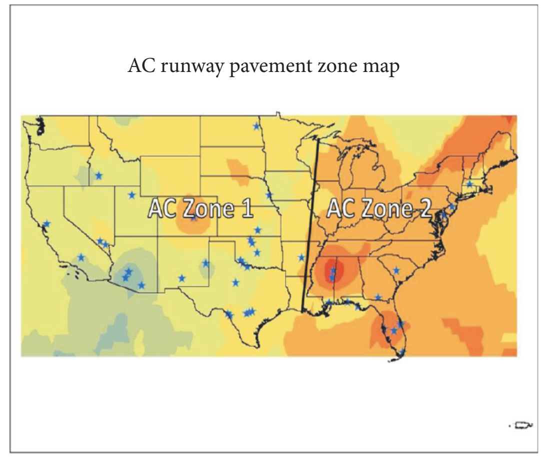

Figure 6: AC runway model, based on ADB.

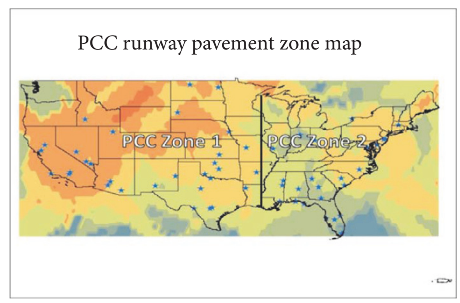

Figure 7: PCC runway model, based on ADB.

between Zones 1 and 2 for PCC and AC runway pavements. The test assumed that three criteria were met:

(1) Each group is a sample of a distinct population. For this research, the assumption was made that the pavement deterioration behavior recorded for the inspection sample units was representative of the pavement deterioration behavior for the entire runway.
(2) The observations in each group are independent of the other group.
(3) There is a normal distribution of observations within each group [21].

The results showed that the p value for AC Zone 1, from the Kolmogorov-Smirnov test of normality, was >.05, and the AC Zone 1 sample was normally distributed. AC Zone 2 sample was borderline normal (p value = .04). Moreover, for the sample distress data in PCC Zones 1 and 2, the p value of the Kolmogorov-Smirnov test of normality <.05, and the PCC sample data was nonnormally distributed [22].

For this reason, the nonparametric Mann–Whitney test was used to compare the true medians of both AC and PCC samples [23]. The true medians of pavement samples in each zone of both pavement models were not equal (AC at 5% and PCC at 10%), which indicated that the pavement deterioration behavior differed between zones. After establishing that the pavement models for Zones 1 and 2 were statistically different, regression analysis was conducted for each distress type occurring within each model by the application of a two-sided t-test and the Mann–Whitney test.

4.2. Regression Analysis of Distress Behavior within Each Pavement Model. Conducting a second round of regression analyses on the PCI deduct values within each zone of the pavement models provided insights into distress specific pavement behavior between the two climate zones. For example, the largest pavement distresses impact on the runway pavement in each of the zones. Additionally, regression analysis provides a quantitative evaluation of how well the model data fits the regression model by means of the R^2 value [24]. The last reason to conduct regression analysis on data within the new model is to evaluate if it is an improvement from the original climate-based model.

In addition, krig analysis was conducted for each distress type occurring on AC and PCC runways. The value used to krig upon was the normalized PCI deduct value calculated. The combined analysis of the regression analysis and the krig analysis presents insight into the overall deterioration behavior of each distress. The factors affecting pavement conditions, traffic load, climate, maintenance history, construction, and pavement structure, are contained within the PCI deduct value [16]. The value used to krig upon is a derivation of the PCI deduct value; therefore, the geographic pattern that emerged from the krig analysis was the result of all five factors.

The regression slopes were not the same as the pavement deterioration rates; however, they did provide insight into how distress propagates over time. These slopes were useful to consider because they suggested how fast distress develops in each pavement behavior zone, and they could determine which zone had the most dominant distress behavior.

The results indicated the following:

(i) Distress 52 (raveling) demonstrated the largest deterioration behavior in AC Zone 1.

(ii) Distresses 41 (alligator cracking) and 52 (raveling) exhibited the largest deterioration behaviors in AC Zone 2.

(iii) Distresses 63 (linear cracking) and 72 (shattered slab) demonstrated the largest deterioration behaviors in PCC Zone 1.

(iv) Distresses 62 (corner break) and 67 (large patch/utility cut) exhibited the largest deterioration behaviors in PCC Zone 2.

Such distresses as 66 (small patch), 70 (scaling), 74 (joint spalling), and 75 (corner spalling), where there is very little difference in the deterioration behavior across both zones, strongly suggest that these distresses are not correlated to climate. All these distresses happen to be specific to PCC runways, which may suggest that PCC pavement is less affected by climate than AC runway pavement.

Outliers throughout the regression and krig analyses tended to be at auxiliary and reserve bases or at bases with high traffic. These outliers suggest that distresses are the result of the combination of climate, traffic load, and maintenance strategies. PCC runway pavement tends to perform better in PCC Zone 2, while AC runway pavements tend to perform more favorably in AC Zone 1. This knowledge suggests that airfield planning should take into consideration AC construction in the western US while PCC construction in the eastern US. However, the overall PCC deterioration tended to be smaller than the AC deterioration behavior across both zones.

The regression analysis on the model based on pavement deterioration behavior did provide a better fit of the PCI deduct data than did the climate-based model proposed by AFIT; however, the R^2 values, representing how well the model fits the data, still were small (between 0.0008 and 0.3188, with an average of 0.09056). The small R^2 values suggest that additional analysis should be conducted to investigate if there were alternative trends within the data that may provide a better "fit."

5. Conclusions

Regression analysis performed on each distress type in the four proposed climate zones showed that pavement behavior improved with time in the "freeze_dry" zone. This trend was contradictory to all conventional knowledge of pavement behavior and provided enough evidence to conclude that the proposed model based on precipitation and temperature data was not appropriate to evaluate pavement behavior at the individual distress level [25, 26]. However, the process model developed to distill the AF Roll-Up Database was an effective consolidation method so that analytic tools could be applied to evaluate underlying data trends.

Krig analysis performed on the summation of all pavement distresses showed a distinct geographic difference in the pavement deterioration behavior of both AC and PCC runways. Deterioration behavior tends to be more severe in the eastern US for AC and in the western US for PCC runway pavements, respectively. Krig analysis performed at the individual distress level showed that some distresses occurred in more defined geographic regions than others. Examples of these distress types include raveling, linear cracking, and joint seal damage. However, this conclusion does not directly correlate these more location-specific distresses to climate causation because the geographic pattern was uncovered by using a derivation of the PCI deduct value; it included all five factors contributing to pavement distress. Examples of distresses that did not show a strong geographic pattern included alligator cracking and corner breaking. The analysis showed that traffic load and maintenance strategy seemed to play a large role in the development of these distresses.

Many of the distress types could not be analyzed in this research because there was not enough data from which to draw reliable conclusions. Regarding recommendations for future research, distress data from non-Air-Force installations (i.e., municipal airports, private airports, and international airports) should be included. While an investigation of the survey techniques used to inspect the pavement would have to be completed, this additional data may allow for a larger sample size for some of the less frequent distress types.

A trend notable in the "freeze_dry" climate zone suggests that as more time lapses between the date of the last major/global renovation and the PCI survey, the PCI deduct values decreased without any additional maintenance action. This trend was common to the following distress-specific PCI deduct values within PCC runway pavement sections: corner spalling (75), joint spalling (74), shrinkage cracking (73), scaling (70), large patch/utility cut (67), small patch (66), joint seal damage (65), durability cracking (64), and linear cracking (63). This trend also was observed in the flexible pavement data. This trend was not consistent with any conventionally known pavement behavior. A question arises, why does pavement in the "freeze_dry" climate behave in this manner? A potential reason from regression analysis is that the pavement located in this climate zone actually belongs to another climate zone; otherwise, an alternative modeling approach should be investigated. The conclusion in this study was that the pavement behavior in the "freeze_dry" climate zone necessitated an alternative model to evaluate distress patterns as they relate to geography and/or climate.

Finally, without an additional investigation of potential patterns within the other four pavement deterioration factors, this research cannot reject the hypothesis that climate is the predominant contributing factor [27]. The model for the data consolidation process and the pavement behavior models presented here provide a framework to conduct additional analysis (for more information, see the Thesis Dissertation [28]). For example, the approach proposed by Khadka and Paz [29–31] to estimate simultaneously clusters and their associated pavement performance models could be used with the data in this study to determine the significant factors influencing deterioration.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

References

[1] Chief Financial Officer, *Defense Budget Priorities and Choices*, Department of Defense, Washington, DC, USA, 2012.

[2] T. Byers, *Air Force Civil Engineer*, Almanac, USAF, 2012.

[3] Department of the Air Force, "Pavement evaluation program," Tech. Rep. AFCEC/COAP: AFI 32-1041, AFCEC, 2013.

[4] A. Davit, "U.S. Air Force Airfield Pavement Evaluation Program," in *proceedings of Federal Aviation Administration Airport Technology Transfer Conference*, USA, 2002.

[5] J. Meihaus, *Understanding the Effects of Climate on Airfield Pavement Deterioration Rates, Wright-Patterson AFB*, Air Force Institute of Technology, OH, USA, 2013.

[6] R. A. Assel, "Maximum freezing degree-days as a winter severity index for the Great Lakes 1897–1977.," *Monthly Weather Review*, vol. 108, no. 9, pp. 1440–1445, 1980.

[7] Colorado State University. PAVERTM, September 2014.

[8] U.S. Air Force Base Locator. Retrieved from airforce.com http://www.airforce.com/contact-us/base-locator/ 2014.

[9] ASTM D5922-96, Standard Guide for Analysis of Spatial Variation in Geostatistical Site Investigation, ASTM International, West Conshohocken, Pa, USA, 2010.

[10] M. Y. Shahin, *Pavement Management for Airports, Roads, and Parking Lots*, Springer, NY, USA, 2nd edition, 2005.

[11] ASTM D5340-11, Standard Test Method for Airport Pavement Condition Index Surveys, ASTM International, West Conshohocken, Pa, USA, 2011.

[12] R. E. Dickinson, R. M. Errico, F. Giorgi, and G. T. Bates, "A regional climate model for the Western United States," *Climatic Change*, vol. 15, no. 3, pp. 383–422, 1989.

[13] T. W. Simpson, A. J. Booker, D. Ghosh, A. A. Giunta, P. N. Koch, and R.-J. Yang, "Approximation methods in multidisciplinary analysis and optimization: a panel discussion," *Structural and Multidisciplinary Optimization*, vol. 27, no. 5, pp. 302–313, 2004.

[14] C. T. Omuto and R. R. Vargas, "Re-tooling of regression kriging in R for improved digital mapping of soil properties," *Geosciences Journal*, vol. 19, no. 1, pp. 157–165, 2015.

[15] J. A. Bruhn, W. E. Fry, and G. W. Fick, "Simulation of daily weather data using theoretical probability distributions," *Journal of Applied Meteorology*, vol. 19, no. 9, pp. 1029–1036, 1980.

[16] R. Haas, "Reinventing the (Pavement Management) Wheel," in *proceedings of the Distinguished Lecture at 5th International Conference on Managing Pavements*, Seattle, Wash, USA, 2001.

[17] B. B. Mitchell, *Getting Started with ArcGIS*, ESRI, Redlands, Calif, USA, 2001.

[18] J. M. Johnston, *Using ArcGIS Spatial Analyst*, ESRI, Redlands, CA, USA, 2002.

[19] M. Markieta, "Geographic Information Systems," StackExchange, 2014, http://gis.stackexchange.com/questions/18814/how-to-change-symbology-of-multiple-layers-at-once.

[20] V. A. Mayer, "Volume 04.09 Soil and Rock (II) D5877," in *American International, Annual Book of ASTM Standards*, American Society for Testing and Materials, West Conshohocken, Pa, USA, 2010.

[21] A. Hayter, *Probability and Statistics for Engineers and Scientists*, Thomson Higher Education, Belmont, Calif, USA, 2007.

[22] H. L. Crutcher, "A note on the possible misuse of the Kolmogorov-Smirnov test," *Journal of Applied Meteorology*, vol. 14, pp. 1600–1603, 1975.

[23] A. N. Pettitt, "A non-parametric approach to the change-point problem," *Applied Statistics*, vol. 28, no. 2, pp. 126–135, 1979.

[24] P. Mather and S. Openshaw, "Multivariate methods and geographical data," *Journal of the Royal Statistical Society. Series D (The Statistician)*, vol. 23, no. 3-4, pp. 283–308, 1974.

[25] H. E. Landsberg, "Meteorological observations in urban areas," *Meteorological Observations and Instrumentation*, vol. 11, pp. 91–99, 1970.

[26] H. R. Glahn and D. A. Lowry, "The use of model output statistics (MOS) in objective weather forecasting," *Journal of Applied Meteorology*, vol. 11, pp. 1203–1211, 1972.

[27] K. C. P. Wang, J. Zaniewski, and G. Way, "Probabilistic behavior of pavements," *Journal of Transportation Engineering*, vol. 120, no. 3, pp. 358–375, 1994.

[28] L. Sahagun, *Modeling Pavement Distress Rates within U.S. Air Force Airfields*, UNLV Theses, Dissertations, Professional Papers, and Capstones. 2295, Las Vegas, Nev, USA, 2014, http://digitalscholarship.unlv.edu/thesesdissertations/2295.

[29] M. Khadka and A. Paz, “Limitations of existing pavement performance models and a potential solution,” in *proceedings of the World Conference on Pavement and Asset Management*, Baveno, Italy, 2017.

[30] M. Khadka and A. Paz, “Estimation of optimal pavement performance models for highways,” in *proceedings of the 10th International Conference on the Bearing Capacity of Roads, Railways and Airfields*, Athens, Greece, 2017.

[31] M. Khadka and A. Paz, “Comprehensive clusterwise linear regression for pavement management systems,” *ASCE Journal of Transportation Engineering, Part B: Pavements*, In press.