



# WPI

## Real-Time Airport Pavement Damage Monitor

A Major Qualifying Project Report  
submitted to the faculty of the  
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Degree of Bachelor of Science

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**Submitted by:**

Isaac Stilwell

Jacob Vanscoy

**Project Advisor:**

Professor Rajib Mallick

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# Abstract

Every time an aircraft takes off, a small amount of damage is caused to the runway pavement. The amount of damage caused by a takeoff to a specific runway is dependent on the load of the aircraft, the gear configuration of the aircraft, and the elastic modulus of the pavement, which is dependent on the pavement temperature which is a function of the air temperature. Currently, airports have no way of monitoring the amount of damage a runway has experienced from aircraft takeoffs. In this project, an airport pavement monitor was developed for Runway 9/27 at Boston Logan Airport for six of the most popular commercial aircraft used at Logan. The pavement monitor tracks the damage caused by takeoffs in real-time and displays the cumulative damage and percent of remaining damage until failure for fatigue cracking and rutting.

# Executive Summary

## Problem statement

A primary commercial service airport such as Boston's Logan International Airport handles thousands of flights every month. For example, in 2019, it had a total of 15,172 departing flight operations in January. Each departing aircraft utilizes a runway for take-off. As a result of the passage of each fully loaded aircraft, the runway pavement suffers incremental damage. Over the design life, these damages accumulate, and ultimately lead to the full damage of the pavement (end of life). A typical runway is designed for the projected traffic for a design life of 20 years. However, in reality, once designed and constructed, the actual air traffic could be significantly different from that assumed during design, and hence the rate of deterioration of the pavement could be significantly different from that assumed during design. Typically, expensive manual surveys with or without testing are conducted periodically to evaluate the condition/damage of the pavement. Currently, there is no real-time monitoring ability for the airport manager to evaluate the current condition of the airport pavements (runways and taxiways).

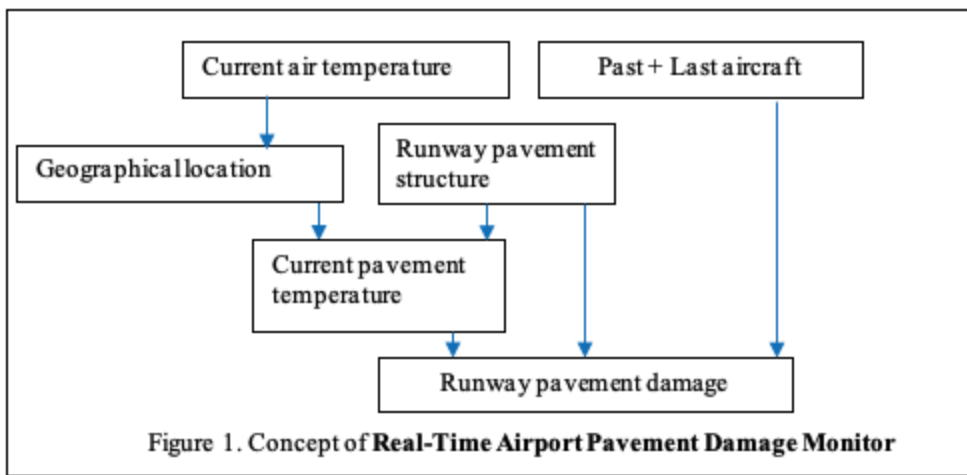
## Objective

The objective of this project was to develop a user-friendly application (app) that records, tracks, and shows the fatigue cracking and rutting damage of an airport pavement that is caused by the take-off of each departing aircraft in real-time. For designing this app, Runway 9/27 in Logan Airport, (7,001 feet long and 150 feet wide) was utilized. The pavement structure consists of 5 inches of Hot Mix Asphalt (HMA) surface, 9 inches of stabilized base, 9 inches of crushed aggregate base, and 16 inches of uncrushed aggregate subbase layers.

## Methodology

The concept of the app is shown in Figure 1. The first step in developing the Excel macro-based app was setting up an algorithm that calculates the damage caused by a single aircraft takeoff at a stated temperature. The FAA FAARFIELD software was used to create a model of the pavement design for runway 9/27, as well as the gear layout of a Boeing 777, a

common aircraft at Logan. A layered elastic analysis program (WinJULEA) was utilized to conduct a structural analysis of the runway pavement under a fully-loaded Boeing 777 aircraft. FAA transfer functions relating responses to performances (repetitions to failure for fatigue cracking and rutting damage) were used to determine the fatigue damage from the radial tensile strain at the bottom of the asphalt stabilized layer and the rutting damage from the vertical compressive strain at the top of the subgrade. The damage caused by a single pass of a specific aircraft was computed from the reciprocal of the number of passes of that same aircraft that are required to cause failure.



The Long Term Pavement Performance (LTPP) Online Climate Tool was used to determine the range of air temperature at Logan airport and was utilized with documented equations to calculate pavement temperatures. The results were compiled to allow the user to input the specific air temperature at the time of take-off of any aircraft. The air temperature is automatically utilized by the app to calculate the pavement temperature and the corresponding asphalt layer modulus, strain, and the corresponding damage. Data for temperature versus modulus and strain versus modulus were generated from the repeated layered elastic analyses with a range of air temperatures and moduli values, and best-fit regression equations were determined. This process was repeated for the other most common aircraft that use Logan Airport: Boeing B747, B787, and the Airbus A320, A350, and A380.

For the app, an interface was created that allows the user to input each take-off and the corresponding air temperature. These inputs trigger the algorithm to calculate the pavement temperature, HMA elastic modulus, radial tensile strain, vertical compressive strain, repetitions

to failure for fatigue, fatigue cracking per takeoff, repetitions to failure for rutting, rutting per takeoff, cumulative fatigue cracking, and cumulative rutting. The cumulative fatigue cracking and rutting damage values are then instantaneously displayed on the interface.

The application screen (see Figure 2) displays the buttons for the six most common types of aircraft and a drop-down menu for selecting the air temperature. The application monitor displays the real-time cumulative rutting and fatigue cracking damage being accumulated after an aircraft takes off. Each aircraft that takes off is assigned a serial number in chronological order that records the plane type and temperature at the time of takeoff. Currently, this app is designed for one runway in Logan International airport, with six commonly used aircraft – it can be extended for multiple runways and taxiways, and additional aircraft, and can be designed for any other airport in any location.

## **Significance and Expected Use of the App**

The proposed app utilizes aircraft and air temperature data along with engineering analyses to provide up-to-date damage and the remaining life information of an airport pavement. The system will allow airport authorities to 1. understand damage caused by each aircraft; 2. use it as a diagnostic tool – if some distress shows up when damage is predicted to be low then an investigation could be made to detect localized problems and fix them before the problem increases in extent; 3. avoid costly testing for evaluation; 4. have a rational basis for charging aircraft for their contributions towards the damage; 5. validate existing design procedures and calibrate them.



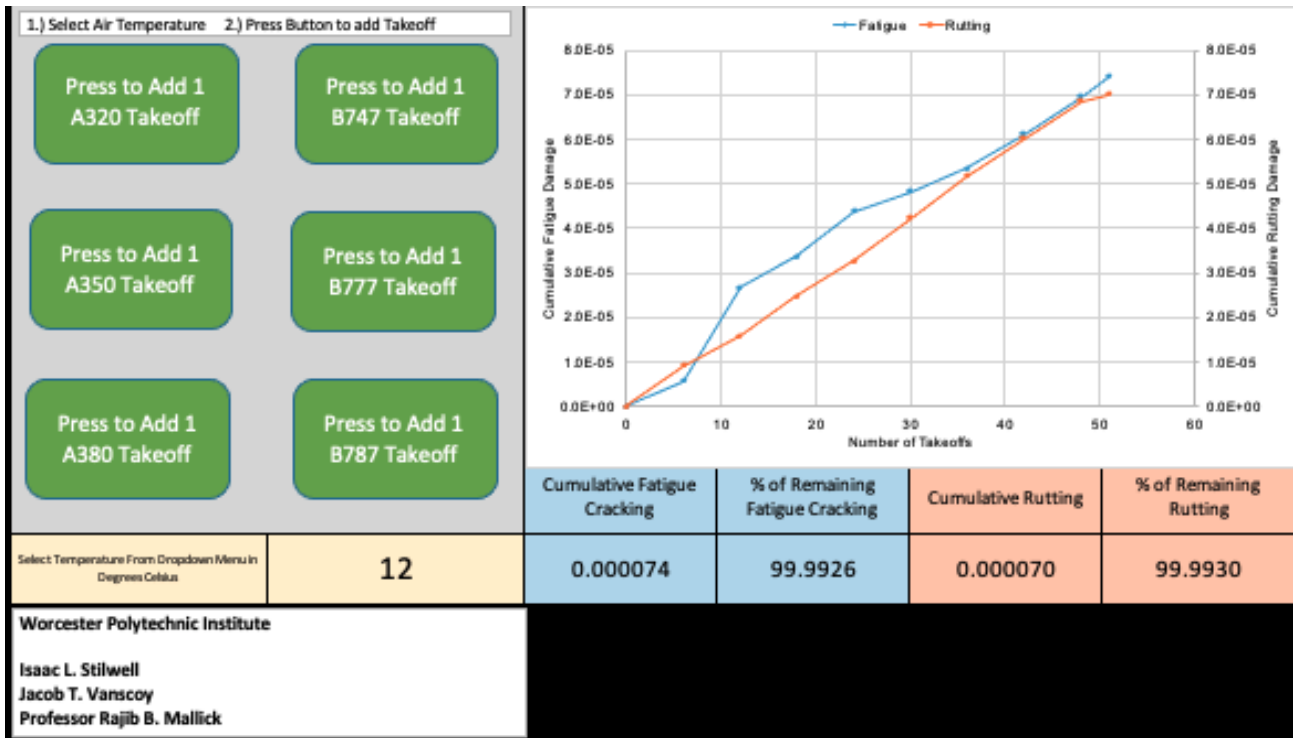


Figure 2: A Real-Time Airport Pavement Damage Monitor App

# Introduction

A primary commercial service airport such as Boston's Logan International Airport handles thousands of flights every month. Each departing aircraft uses a runway to take off. Every time an aircraft takes off incremental damage is done to the runway pavement. Pavement runways are typically designed for a twenty-year life span. However, changes in aircraft traffic volume can significantly impact the life of a runway. A typical pavement structure for a runway consists of a surface layer of hot mix asphalt (HMA), an HMA stabilized base, a crushed aggregate subbase, and an uncrushed aggregate subbase before the subgrade. The Federal Aviation Administration evaluates horizontal tensile strain at the bottom of the asphalt and vertical compressive strain at the top of the subgrade for runway pavement structure design. [3] Horizontal tensile strain at the bottom of the asphalt causes fatigue cracking, and vertical compressive strain at the top of the subgrade causes rutting. Pavement damage due to fatigue cracking and rutting vary based on several factors: The pavement design, the gross taxi weight, the number of gears on the aircraft, the location of gears on the aircraft, and the modulus of elasticity of the pavement. The modulus of elasticity of the pavement is a function of the pavement temperature, which is a function of the air temperature.

Currently, there is no way for the airport manager to track in real-time how much damage has been done to a runway or taxiway. Instead, periodic and expensive manual surveys with or without testing are conducted to evaluate the condition and damage of a pavement runway. Because there is currently no real-time pavement damage monitoring ability, there is no accurate way of validating why a current runway condition may be different from what is expected. The objective of this project was to develop a user-friendly application that records, tracks, and shows the fatigue cracking and rutting damage of an airport pavement that is caused by the take-off of each departing aircraft in real-time.

For this project, Boston Logan Airport's Runway 9/27 was used for design, along with six popular aircraft used at Logan: The Boeing B747, B777, B787, and the Airbus A320, A350, and A80. Although this project is specific to Runway 9/27 at Logan Airport and the six aircrafts listed, this project can be replicated for any runway and for any type of aircraft.

# Literature Review

## Airport Runway Design and Engineering Standards

Runway designs are developed off the FAA runway design standards, which are found in FAA AC 150/5300-13A. Critical airplane characteristics that are used in runway designs include airplane weight distribution, landing gear layout, and landing gear type. The FAA design standard uses a coding system in order to have a safe and efficient airport that uses both the physical and operational characteristics of the design aircraft to properly design the runways with safety distances created from the airport facility. The length, width, and depth of the runway are dependent on the type of airport, the design aircraft, volume of traffic, and location. Specifically, FAA AC 150/5230-6E provides the requirements that the runway designs must be in accordance with. A design aircraft is selected as the most demanding aircraft that will be predicted to be used on a regular basis. The design aircraft isn't always the heaviest aircraft but the aircraft that will require the thickest layers of the runway. The design aircraft will have more than 500 annual takeoffs and can be a single aircraft or a grouping of aircrafts. [4] The material of the runway is typically constructed of asphalt or concrete. Typically, concrete is used at most commercial airports in the United States as it is more durable and has a longer lifespan than asphalt.

In FAA AC 150/5320-6F, the design considerations are given with the interaction of different variables with the use of the FAARFIELD computer program. For flexible pavement design, FAARFIELD uses the max vertical strain at the top of the subgrade and the max horizontal strain at the bottom of all the asphalt layers. The FAARFIELD tool will also provide the surface, base, and subbase required thickness that will support the given airplane traffic mix. For rigid pavements, FAARFIELD uses the max horizontal stress at the bottom of the PCC slab. The required thickness will also be given of the rigid pavement slab in order to support the given airplane traffic mix. [5]

One of the current methods for predicting how long a pavement will last is using the structural life in FAARFIELD. The structural life refers to the total number of loads cycles a pavement structure will experience before failure. The structural design of the runways involves computing the pavement thickness and the thickness of the component parts of the pavement structure. These pavements were designed with the intention of having a finite structural life at

design fatigue limits. Runways, that are Federally funded by the FAA, are typically built to last anywhere between 20-30 years before the requirement of full rehabilitation. Generally, the runway pavements will do a good job at performing throughout its life until it reaches a critical condition, in which the runway quickly deteriorates. [6] Most airports choose to conduct runway maintenance and rehabilitation on immediate need and experience. This process is inconvenient and as a result, can be very expensive and can lead to an inefficient way of allocating funds for the maintenance programs. The current prediction methods the FAA uses for pavement conditions do not take into account the rapid increase in flight operations and aircraft loadings. As a result, the only way to check for load damages is to conduct on site testing.

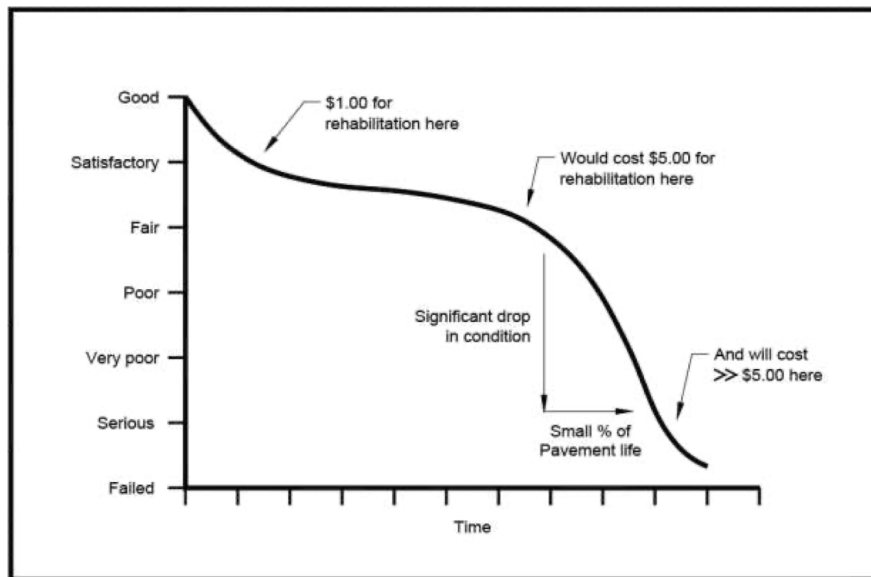
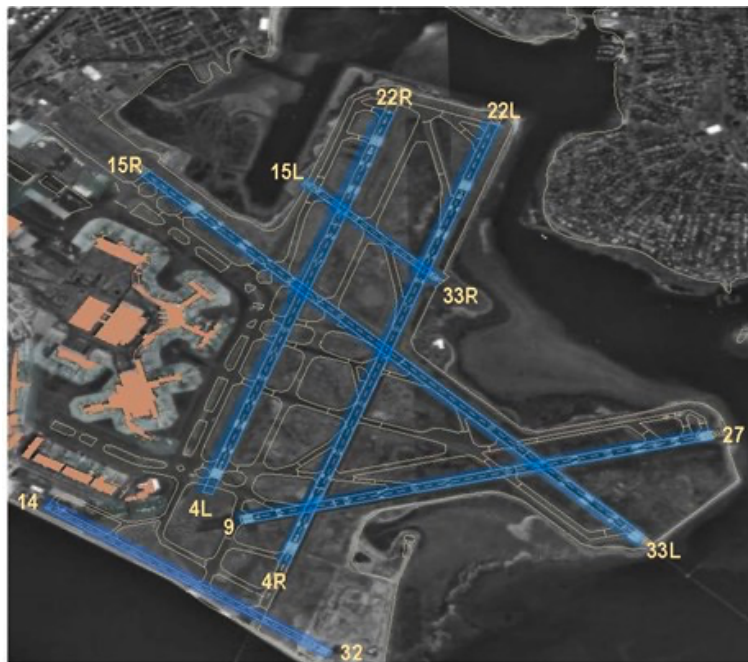


Figure 3: Life Cycle of Pavement (AC 150/5380-7B)

## Boston Logan Airport

The application's purpose is to record the cumulative fatigue cracking and rutting damage for every aircraft that takes off. The application allows the user to accurately record the data live in addition to the current prediction methods. Predictions are not always accurate as a live monitor as there are a variety of factors that can change the runway's use and volume. Logan-Boston is a busy airport with a large volume of aircraft throughout the year. Logan Airport is located right on the coast with harsher weather conditions such as wind, snow, and

rain. The FAA decides which runway to use based on aircraft fleet and peak operational times, inspections, ground visibility, cloud coverage, and runway/taxiway closures. With good weather conditions, the airport is able to complete 120 operations per hour with a three-runway configuration. It can also be reduced based on conditions to only 60 operations per hour with a single runway configuration. There are six runways that vary in length from 2,557 feet to 10,081 feet. The runways are constructed in three different directions with a distinct magnetic heading as shown in figure 4.



*Figure 4: Logan-Boston International Airport Runway Configuration*

## Airport Traffic History

The runway use is defined as the frequency of which the aircraft use the runways for takeoffs. Certain conditions such as wind, weather, aircraft performance, air traffic controls, and availability dictate the amount of use on a specific runway. The conditions on a day-to-day basis may not be the same, making it often hard to predict how much damage the runway will experience over a 20 year period. [3] The Logan Airport Runway usage reports show the total number of aircraft that have used the runway each month of the year for 2019.

| 2019 Jet     | YTD     |         | January |        | February |        | March  |        | April  |        | May    |        | June   |        | July   |        | August |        | September |        | October |        | November |        | December |        |
|--------------|---------|---------|---------|--------|----------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|-----------|--------|---------|--------|----------|--------|----------|--------|
|              | Arr     | Dep     | Arr     | Dep    | Arr      | Dep    | Arr    | Dep    | Arr    | Dep    | Arr    | Dep    | Arr    | Dep    | Arr    | Dep    | Arr    | Dep    | Arr       | Dep    | Arr     | Dep    | Arr      | Dep    | Arr      | Dep    |
| 04L          | 6,416   | 0       | 266     | 0      | 167      | 0      | 494    | 0      | 422    | 0      | 907    | 0      | 697    | 0      | 767    | 0      | 742    | 0      | 1,015     | 0      | 718     | 0      | 138      | 0      | 83       | 0      |
| 04R          | 58,519  | 7,162   | 2,597   | 331    | 2,780    | 362    | 3,204  | 504    | 4,840  | 475    | 7,846  | 856    | 6,157  | 699    | 5,221  | 837    | 5,691  | 722    | 5,846     | 754    | 7,935   | 865    | 3,458    | 319    | 3,144    | 438    |
| 9            | 0       | 55,783  | 0       | 2,287  | 0        | 2,740  | 0      | 3,239  | 0      | 4,560  | 0      | 7,557  | 0      | 5,782  | 0      | 5,189  | 0      | 5,096  | 0         | 5,908  | 0       | 7,305  | 0        | 3,376  | 0        | 2,744  |
| 14           | 0       | 0       | 0       | 0      | 0        | 0      | 0      | 0      | 0      | 0      | 0      | 0      | 0      | 0      | 0      | 0      | 0      | 0      | 0         | 0      | 0       | 0      | 0        | 0      | 0        | 0      |
| 15R          | 627     | 7,910   | 0       | 469    | 261      | 449    | 96     | 497    | 1      | 649    | 0      | 812    | 53     | 1,148  | 2      | 902    | 1      | 874    | 48        | 577    | 100     | 497    | 128      | 353    | 137      | 663    |
| 22L          | 52,070  | 3,096   | 3,825   | 345    | 2,707    | 115    | 4,427  | 281    | 4,969  | 305    | 4,214  | 208    | 4,492  | 277    | 6,008  | 411    | 5,167  | 360    | 4,313     | 230    | 3,943   | 217    | 3,623    | 214    | 4,382    | 148    |
| 22R          | 19      | 53,015  | 1       | 4,017  | 1        | 2,585  | 1      | 4,862  | 2      | 4,956  | 0      | 4,184  | 2      | 4,134  | 1      | 5,669  | 6      | 5,219  | 4         | 4,613  | 0       | 4,371  | 0        | 4,261  | 1        | 4,144  |
| 27           | 38,656  | 23,015  | 3,881   | 2,221  | 4,262    | 2,390  | 4,347  | 2,309  | 3,586  | 1,916  | 1,730  | 1,478  | 2,743  | 1,273  | 2,417  | 1,321  | 3,208  | 1,455  | 2,316     | 1,948  | 2,162   | 1,450  | 4,021    | 2,717  | 3,983    | 2,537  |
| 33L          | 26,468  | 36,423  | 2,796   | 3,956  | 2,471    | 4,388  | 2,564  | 3,777  | 1,991  | 3,336  | 1,717  | 1,504  | 1,683  | 2,785  | 1,637  | 1,863  | 1,900  | 3,000  | 1,969     | 1,737  | 1,644   | 2,031  | 3,118    | 3,572  | 2,978    | 4,474  |
| 32           | 3,199   | 0       | 230     | 0      | 386      | 0      | 318    | 0      | 381    | 0      | 167    | 0      | 261    | 0      | 150    | 0      | 220    | 0      | 193       | 0      | 215     | 0      | 294      | 0      | 384      | 0      |
| <b>Total</b> | 186,174 | 186,394 | 13,696  | 13,626 | 13,035   | 13,029 | 15,451 | 15,449 | 16,192 | 16,197 | 16,581 | 16,619 | 16,088 | 16,098 | 16,203 | 16,192 | 16,735 | 16,728 | 15,704    | 15,767 | 16,717  | 16,736 | 14,780   | 14,812 | 15,062   | 15,143 |
| <b>Total</b> | 372,568 |         | 27,222  |        | 26,064   |        | 30,900 |        | 32,389 |        | 33,200 |        | 32,196 |        | 32,395 |        | 33,461 |        | 31,471    |        | 33,453  |        | 29,592   |        | 30,235   |        |

Figure 5: 2019 Boston-Logan Airport Runway Usage Reports [3]

# Methodology

## Process of Creating Application

### Step 1: Determine Strain caused by one Aircraft Takeoff at a Specific Temperature

The first step to developing the application was determining a process that accurately calculates the damage caused by a single aircraft takeoff at a fixed temperature. To do this, a Boeing 777-200ER was selected because this is one of the most popular aircraft at Logan Airport in Boston, Massachusetts. Several pieces of information were needed in order to determine the damage caused by one Boeing 777 takeoff. This included the pavement design at Logan Airport, the total weight of a Boeing 777, the gear layout of a Boeing 777, and equations that link horizontal tensile strain at the bottom of the asphalt stabilized base to fatigue cracking, link and vertical compressive strain at the top of the subgrade to rutting damage. THE FAA FAARFIELD software was used to create a model of the pavement design of runway 9/27 at Boston Logan Airport. The runway structure at Logan Airport consists of five inches of P-401 surface, which is a hot mix asphalt, nine inches of P-401 asphalt stabilized base, nine inches of P-209 crushed aggregate, and sixteen inches of P-154 uncrushed aggregate subbase. The total thickness before the subgrade is thirty-nine inches.

| Layer Material          | Thickness (in) | Modulus or R (psi) |
|-------------------------|----------------|--------------------|
| P-401/P-403 HMA Surface | 5.00           | 200,000            |
| P-401/P-403 St (flex)   | 9.00           | 400,000            |
| P-209 Cr Ag             | 9.00           | 75,000             |
| P-154 UnCr Ag           | 16.00          | 40,000             |
| Subgrade                | CBR = 10.0     | 15,000             |

**Total thickness to the top of the subgrade, t = 39.00 in**

Figure 6: Logan Airport Runway Design Created in FAARFIELD with 200,000 Pounds per Square Inch Surface Layer Modulus

The FAARFIELD software fixed the P-401 hot mix asphalt surface layer to a 200,000 pounds per square inch modulus of elasticity value. However, in actuality, this value will change based on the pavement temperature which is a function of the air temperature. The modulus of elasticity values of the P-401 stabilized base, the P-209 crushed aggregate, the P-154 uncrushed aggregate, and the subgrade are accurate and will not change based upon different air temperatures. For step one of the application development process, the modulus of elasticity of the surface hot mix asphalt layer was fixed at 200,000 pounds per square inch. This means that a fixed undetermined air temperature was being used during this process. Later in the project,



different temperatures were evaluated, and the relationship between air temperature, pavement temperature, and pavement modulus of elasticity was determined.

FAARFIELD software was also used to determine the gear layout for each aircraft evaluated in this project.

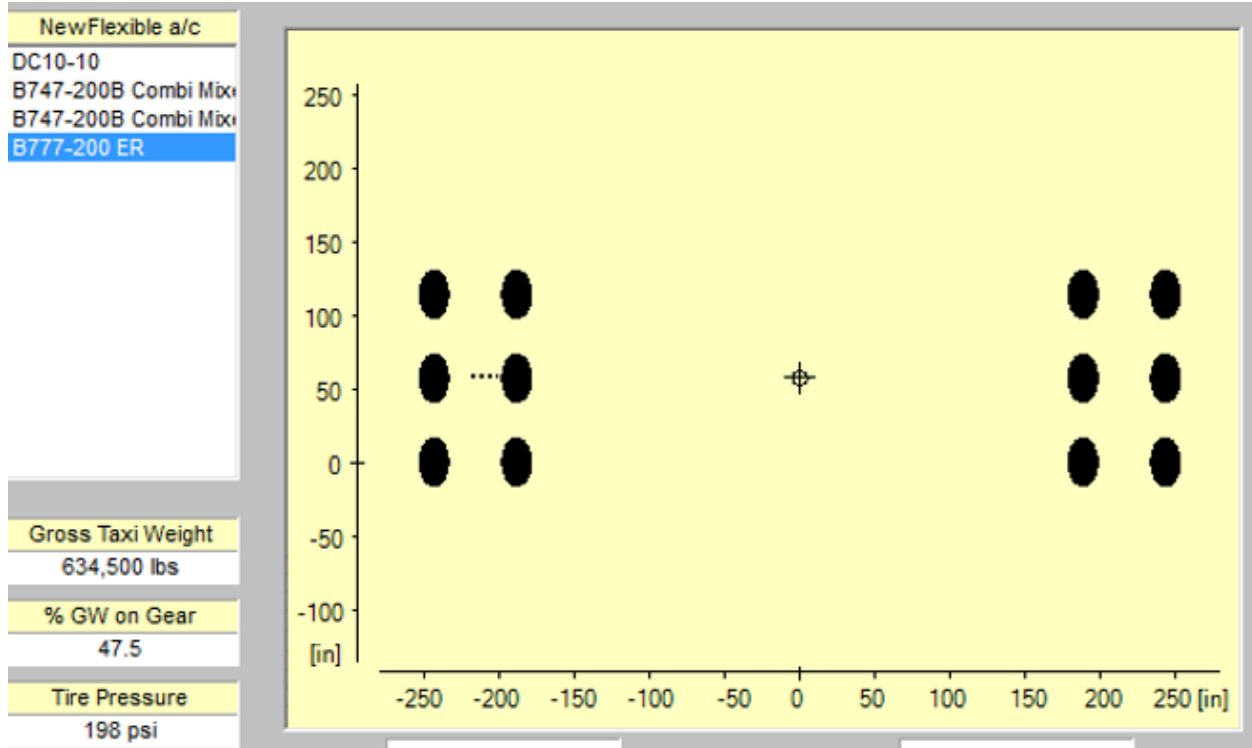


Figure 7: Gear Layout of Boeing 777 Depicted by FAARFIELD Software

Once the pavement structure was created, layered elastic analysis software was needed to calculate strain caused at different points in the pavement structure. For this project, WinJULEA was used for layered elastic analysis. The depths of each layer and the modulus of elasticity values were inputted directly from the values displayed in FAARFIELD.

| Input Layers |           |             |         |        |
|--------------|-----------|-------------|---------|--------|
|              | Thickness | E-Modulus   | PR      | Slip   |
| 1            | 5.0000    | 0.20000E+06 | 0.35000 | 0.0000 |
| 2            | 9.0000    | 0.40000E+06 | 0.35000 | 0.0000 |
| 3            | 9.0000    | 75000.      | 0.35000 | 0.0000 |
| 4            | 16.000    | 40000.      | 0.35000 | 0.0000 |
| 5            | 0.0000    | 15000.      | 0.40000 | 0.0000 |
| 6            |           |             |         |        |

| Input Loads |          |          |        |              |
|-------------|----------|----------|--------|--------------|
|             | X-Coord. | Y-Coord. | Load   | Contact Area |
| 1           | 0.0000   | 0.0000   | 50231. | 253.69       |
| 2           | 55.000   | 0.0000   | 50231. | 253.69       |
| 3           | 0.0000   | 57.000   | 50231. | 253.69       |
| 4           | 55.000   | 57.000   | 50231. | 253.69       |
| 5           | 0.0000   | 114.00   | 50231. | 253.69       |

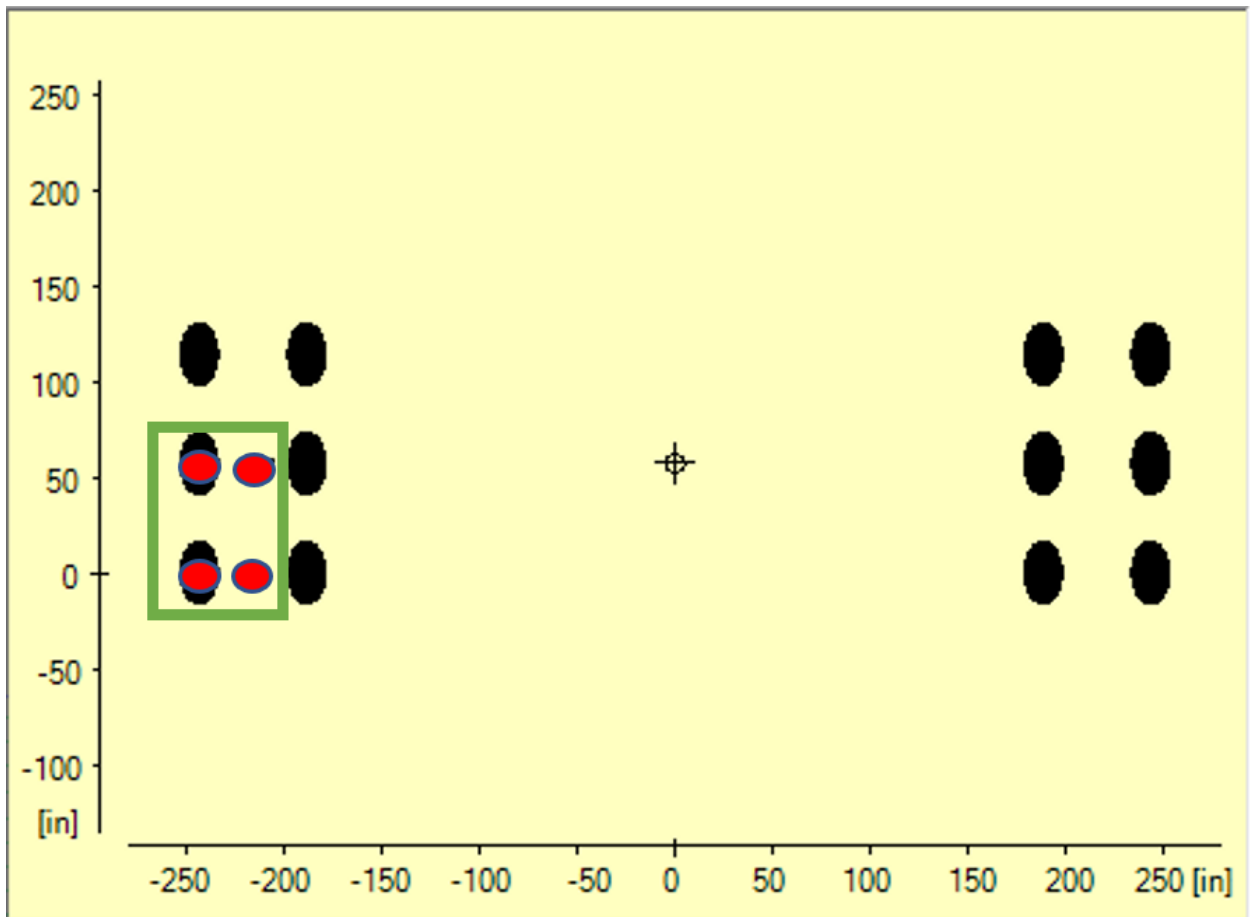
| Input Evaluation Points |          |          |
|-------------------------|----------|----------|
|                         | X-Coord. | Y-Coord. |
| 1                       | 0.0000   | 0.0000   |
| 2                       | 27.500   | 0.0000   |
| 3                       | 0.0000   | 57.000   |
| 4                       | 27.500   | 57.000   |
| 5                       |          |          |
| 6                       |          |          |

| Input Calculation Depths |        |
|--------------------------|--------|
|                          | Depth  |
| 1                        | 4.9900 |
| 2                        | 13.990 |
| 3                        | 39.010 |
| 4                        |        |
| 5                        |        |
| 6                        |        |

Figure 8: WinJULEA Input Values for a Boeing 777 with 200,000 Pounds per Square Inch Surface Layer Modulus

After reviewing the manual for FAARFIELD design, the Poisson's Ratio of each layer was assumed to be 0.35, except for the subgrade, which was assumed to be 0.40. Slip was assumed to be 0 between all layers. The X and Y coordinates are the location of the gears on the Boeing 777, measured in inches. The load was calculated by dividing the total load of the

aircraft, which is 634,500 pounds, by the number of gears on a Boeing 777, six, and multiplying by 47.5 percent, which is the percent of the weight on each gear. The contact area was provided in FAARFIELD, but can also be determined by dividing the tire pressure, 198 pounds per square inch as indicated in FAARFIELD, by the load per gear. The X-coordinates and Y-coordinates for the input evaluation loads changed for each aircraft. After viewing the gear layout for the Boeing 777, there were four locations where the maximum strain was likely to occur.



*Figure 9: Red Markers Indicating Input Evaluation Points used in Layered Elastic Analysis*

Because there is an equal distribution of weight and each wing has the same six-gear configuration, it is assumed that the strain values for the same points under each wing will be identical. Therefore, a six-gear configuration was evaluated. Due to the symmetry of the configuration, four input evaluation points were selected. The bottom-left gear, the middle-left gear, the mid-point between all gears, and the mid-point between bottom gears were selected as

input evaluation points. Each of the four input evaluation points was evaluated at three different depths. The first depth was 4.99 inches, which is the bottom of the surface P-401 hot mix asphalt layer. The second depth was 13.99 inches, which is the bottom of the P-401 asphalt stabilized base layer. The third depth was 39.01 inches, which is the top of the subgrade, just below the P-154 uncrushed aggregate subbase layer. The bottom of the surface level P-401 and the bottom of the P-401 stabilized base were evaluated for horizontal tensile strain. The top of the subgrade was tested for vertical compressive strain. The results were calculated through layered elastic analysis in WinJULEA.

| Results at Calculations Points |              |              |              |
|--------------------------------|--------------|--------------|--------------|
|                                | Point 7      | Point 8      | Point 9      |
| X-Coord.                       | 0.0000       | 0.0000       | 0.0000       |
| Y-Coord.                       | 57.000       | 57.000       | 57.000       |
| Z-Coord                        | 4.9900       | 13.990       | 39.010       |
| Stress_X                       | 112.73       | -120.26      | 1.6254       |
| Stress_Y                       | 108.01       | -110.76      | 2.5936       |
| Stress_Z                       | 171.90       | 44.990       | 11.698       |
| ShearStress_XZ                 | -1.1898      | -3.3571      | -2.0732      |
| ShearStress_YZ                 | 0.27756E-16  | 0.0000       | -0.55511E-16 |
| ShearStress_XY                 | 0.0000       | 0.0000       | 0.0000       |
| Strain_X                       | 0.73820E-04  | -0.24310E-03 | 0.27275E-03  |
| Strain_Y                       | 0.41966E-04  | -0.21104E-03 | -0.18238E-03 |
| Strain_Z                       | 0.47318E-03  | 0.31462E-03  | 0.66736E-03  |
| ShearStrain_XZ                 | -0.16063E-04 | -0.22660E-04 | -0.38700E-03 |
| ShearStrain_YZ                 | 0.37470E-21  | 0.0000       | -0.10362E-19 |
| ShearStrain_XY                 | 0.0000       | 0.0000       | 0.0000       |
| Displ_X                        | 0.24190E-02  | -0.12063E-02 | -0.71718E-02 |
| Displ_Y                        | 0.0000       | 0.54210E-19  | 0.21684E-18  |
| Displ_Z                        | 0.11033      | 0.10811      | 0.96543E-01  |
| PrincStress_1                  | 171.92       | 45.058       | 12.108       |
| PrincStress_2                  | 112.71       | -110.76      | 2.5936       |
| PrincStress_3                  | 108.01       | -120.33      | 1.2154       |
| PrincStrain_1                  | 0.47334E-03  | 0.31485E-03  | 0.70563E-03  |
| PrincStrain_2                  | 0.73659E-04  | -0.21104E-03 | -0.18238E-03 |

Figure 10: Maximum Strain Values of Boeing 777 with 200,000 Pounds per Square Inch Surface Layer Modulus

For both the vertical and horizontal strain, the maximum value took place underneath the middle-left gear. Although not evaluated in WinJULEA, the middle gear on the right, as well as

both middle gears underneath the other wing, also experience the maximum strain values depicted in figure 5. At this point, the location under the gears, the depth in the pavement structure, and the magnitude were determined for horizontal tensile strain and for vertical compressive strain.

## Step 2: Determine Fatigue and Rutting Damage caused by One Aircraft Takeoff at a Specific Temperature

The fatigue damage caused by a single aircraft takeoff is a function of the maximum horizontal tensile strain, which is at the bottom of the surface P-401 hot mix asphalt stabilized base layer, as determined in step one. The rutting damage is a function of the maximum vertical compressive strain at the top of the subgrade. To determine the fatigue damage and the rutting based on the horizontal strain and vertical strain respectively, transfer functions from the Federal Aviation Administration were used in a spreadsheet.

$$\log_{10}(C) = \left( \frac{1}{-0.1638 + 185.19\varepsilon_v} \right)^{0.60586} \quad (\text{Equation 1})$$

Where  $C > 1,000$  coverages:

$$C = \left( \frac{0.00414}{\varepsilon_v} \right)^{0.60586}$$

Where  $C \leq 1,000$  coverages:

$\varepsilon_v$  = vertical strain at the top of the subgrade

For rutting damage, Equation 1 was used to calculate the number of passes until failure. The reciprocal of the number of passes to failure (Equation 1) is the rutting damage caused by one take-off. The equations were linked in an Excel spreadsheet so that as soon as the strain values from the layered elastic analysis were put into their respective cells, the rutting damage caused by one take-off at a fixed temperature was determined.

$$N_f = 0.4801PV^{-0.9007} \quad (\text{Equation 2})$$

$$PV = 44.422\varepsilon_h^{5.140}S^{2.993}VP^{1.850}GP^{-0.4063}$$

Where:

PV - estimated value of the Ratio of the Dissipated Energy Change (RDEC)

S = the initial flexural stiffness of an asphalt beam specimen subjected to fatigue cycles

$\epsilon_h$  = horizontal strain at the bottom of the asphalt layer

VP, volumetric parameter =  $\frac{V_a}{V_a + V_b}$

Where,  $V_a$  = air voids;  $V_b$  = asphalt content by volume

GP, gradation parameter =  $\frac{P_{NMS} - P_{PCS}}{P_{200}}$

Where:

$P_{NMS}$  = the percent of aggregate passing the nominal maximum size sieve

$P_{PCS}$  = the percent of aggregate passing the primary control sieve

$P_{200}$  = the percent of aggregate passing the #200 (0.075mm) sieve

The default values are: S = 600,000 pounds per square inch;  $V_a$  = 3.5%;  $V_b$  = 12.0%;

$P_{NMS}$  = 95%;

$P_{PCS}$  = 58%;  $P_{200}$  = 4.5%.

The number of passes to failure for fatigue cracking was determined by inputting the maximum horizontal strain at the bottom of the asphalt stabilized base into equation 2. The damage caused by one takeoff is the reciprocal of the number of passes to failure, as determined in equation 2.

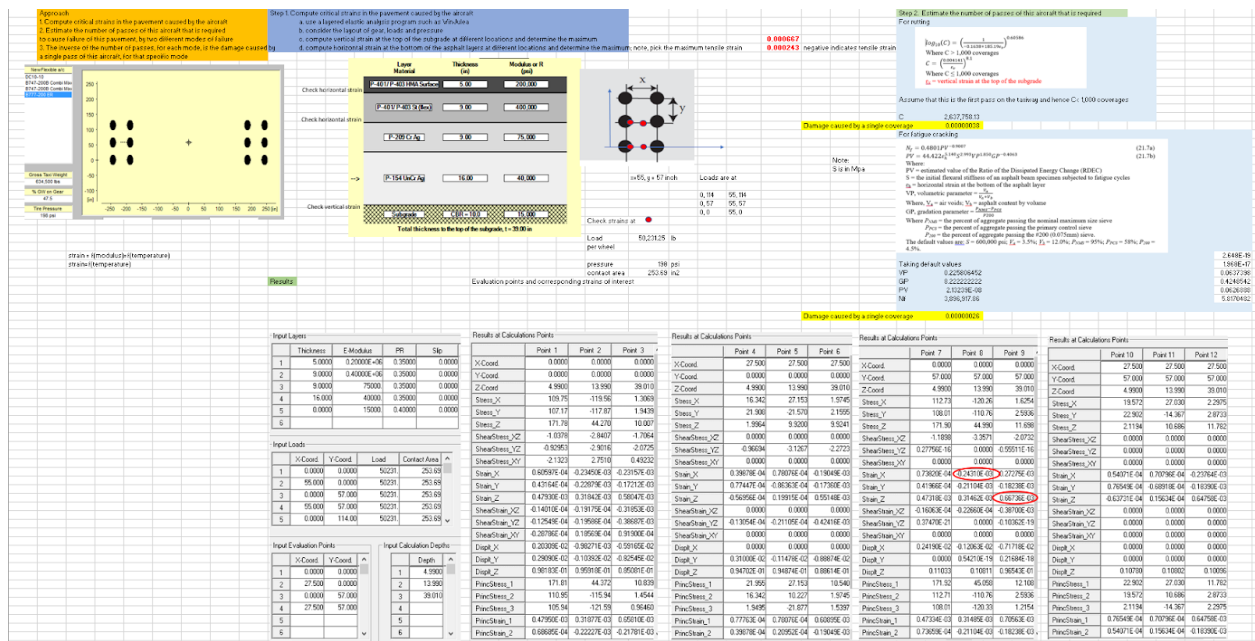


Figure 11: Spreadsheet to Solve for Damage caused by Boeing 777 Take-Off with Surface HMA Layer Modulus of 200,000 Pounds per Square Inch

A spreadsheet was used to calculate the damage caused by a single take-off. Figure 11 shows the sheet used to calculate the damage caused by one Boeing 777 take-off when the surface asphalt layer had a modulus of elasticity value of 200,000 pounds per square inch. The sheet includes the approach and steps on how to determine the damage in orange and blue, as discussed in steps one and two, FAARFIELD models of runway 9/27 at Logan Airport and a Boeing 777 gear configuration, the FAA transfer functions for rutting and fatigue cracking (Equations 1 and 2), and the maximum strain results from layered elastic analysis. Equations 1 and 2 were used in the spreadsheet so that as soon as the maximum strain results from WinJULEA were determined, the values were put into their respective cells and the damage for rutting and fatigue cracking were automatically calculated.



### Step 3: Determine Fatigue and Rutting Damage caused by One Aircraft Takeoff for the Range of Temperatures that occur at Logan Airport

The amount of damage caused to the runway pavement for a given takeoff is partially dependent on the modulus of elasticity of the pavement, which is a function of the pavement temperature. The pavement temperature is a function of the air temperature. To ensure that an accurate temperature range for Logan Airport would be used in this application, the LTPP (Long-Term Pavement Performance) online climate tool was used. The temperature range for this application was selected to be from -27°C to 35°C, in one-degree increments. After determining the average temperature range at Logan Airport, FAA transfer equations were implemented into a spreadsheet to calculate the pavement temperature from the air temperature. The spreadsheet then used equations that calculated the surface P-401 layer modulus of elasticity based on the pavement temperature. In total, the spreadsheet was designed so that the air temperature can be manually inputted, and the spreadsheet automatically calculates the pavement temperature and modulus of elasticity.

| Air Temperature, C | Pavement Temperature, C | Modulus, psi |
|--------------------|-------------------------|--------------|
| -10                | 13.00699987             | 431671.4368  |
| -5                 | 18.00699987             | 375277.1186  |
| 0                  | 23.00699987             | 326250.2536  |
| 5                  | 28.00699987             | 283628.3447  |
| 10                 | 33.00699987             | 246574.6373  |
| 15                 | 38.00699987             | 214361.6916  |
| 20                 | 43.00699987             | 186357.1019  |
| 25                 | 48.00699987             | 162011.0813  |

Figure 12: Spreadsheet Calculating Pavement Elastic Modulus based on Air Temperature

The Modulus of elasticity decreases as temperature increases. To complete step three, the Boeing 777 was evaluated using different modulus of elasticity values for the surface P-401 layer. All other inputs were the same. After conducting layered elastic analysis for the range of elastic modulus values that reflect the range of air temperature in Boston, both the horizontal

strain at the bottom of the stabilized base and vertical strain at the top of the subgrade were plotted as a function of elastic modulus. Regression equations were then derived to determine the relationship between air temperature and maximum strain for horizontal tensile strain at the bottom of the asphalt, and for vertical compressive strain at the top of the subgrade. To accomplish this, a separate sheet was used for each different modulus of elasticity value in order to determine horizontal tensile strain at the bottom of the asphalt and vertical compressive strain at the top of the subgrade. Each sheet was formatted as shown in figure 11. In total, eight different modulus values were selected to accurately develop a relationship of modulus to strain for the air temperature in the range of -27°C to 35°C. The modulus of elasticity values for regression analysis were as follows, in pounds per square inch: 125,000; 150,000; 200,000; 250,000; 315,000; 380,000; 500,000; and 600,000. The sheet shown in figure 12 was a part of the spreadsheet that the application was designed in, unlike the sheet shown in figure 11, which was solely used for layered elastic analysis to develop regression equations. After this was complete, steps one through three were repeated for the five other aircraft included in the application: the Boeing B747, B787, and the Airbus A320, A350, and A380.

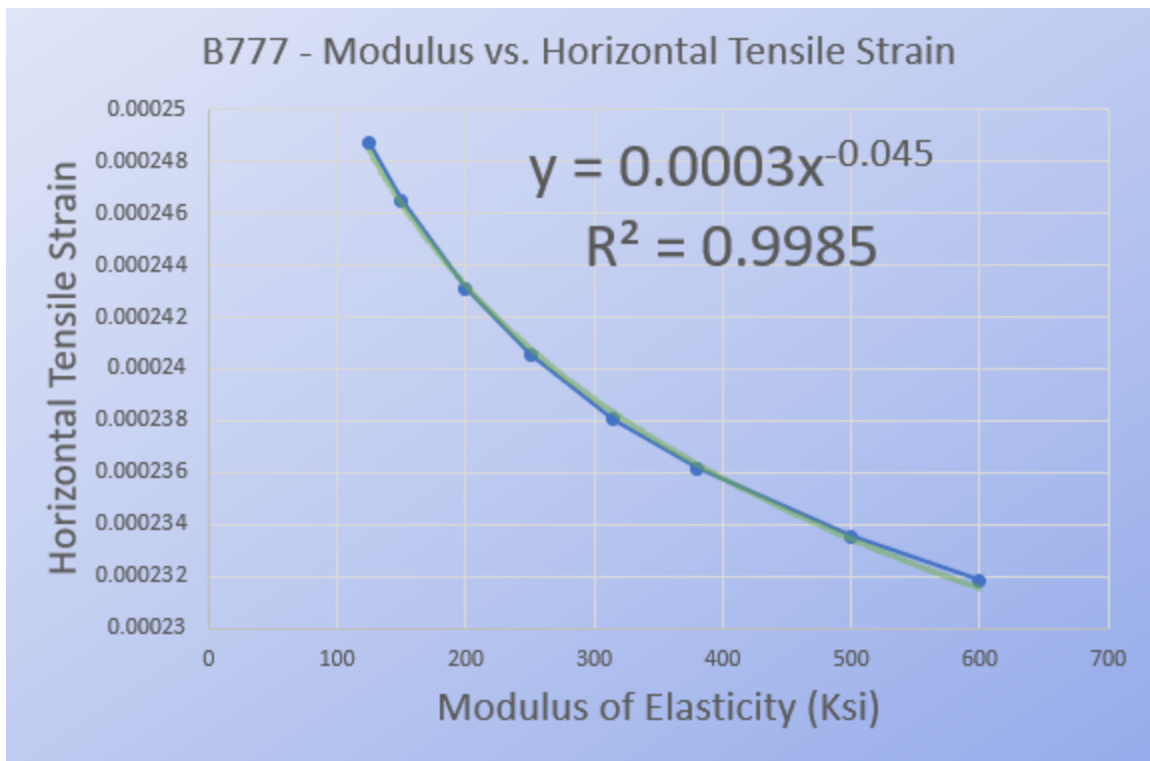


Figure 13: Plot and Regression Equation for Boeing 777 - Horizontal Tensile Strain

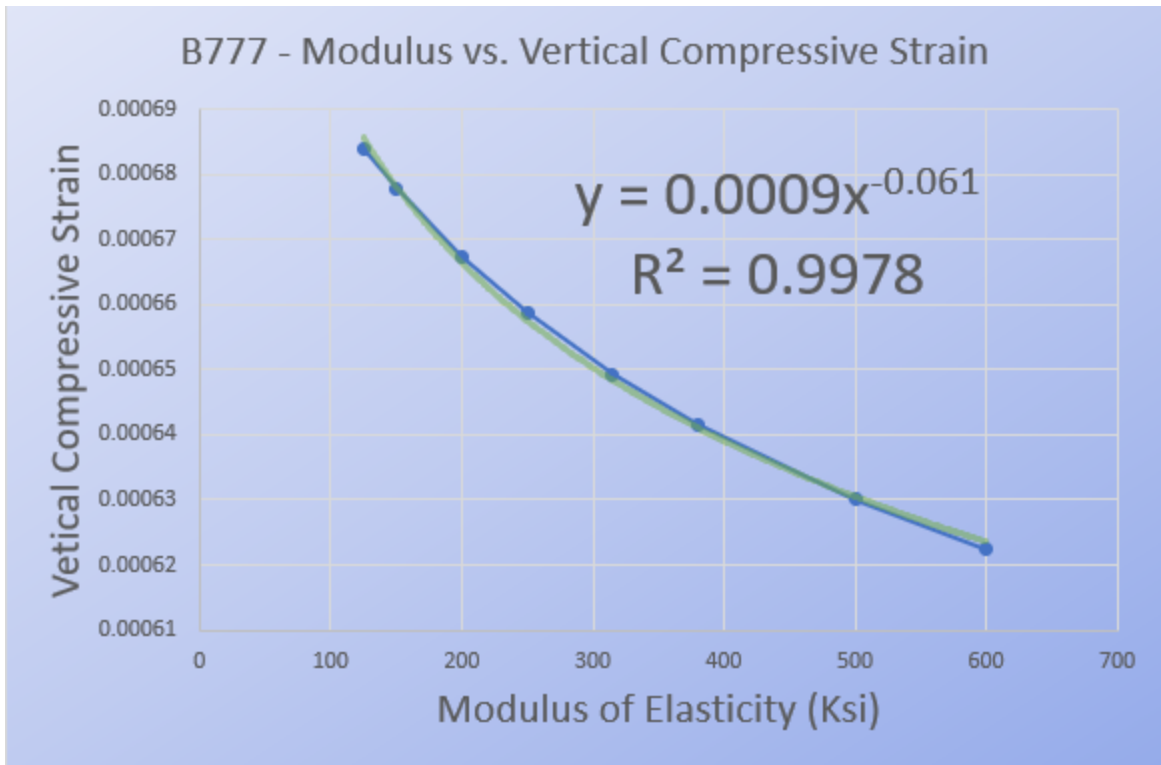


Figure 14: Plot and Regressions Equation for Boeing 777 - Vertical Compressive Strain

Figure 13 and figure 14 show the plots and regression equations for the Boeing 777. By the end of step three, plots and regression equations were completed for all six aircraft included in the application both for vertical compressive strain at the top of the subgrade and for horizontal tensile strain at the bottom of the asphalt. Once the relationships between the air temperature and horizontal tensile strain and vertical compressive strain were established, equations 1 and 2 were used to solve for the damage for rutting and fatigue cracking for any air temperature within the range of -27°C to 35°C.

| Insert 11 under Takeoff for each Takeoff and Corresponding Air Temperature |         |                    |                         | Latitude of airport |                             | 42.36                     |                                 | Cumulative Total Coverage  |                                 | 20                         |                           |                           |
|--|---------|--------------------|-------------------------|---------------------|-----------------------------|---------------------------|---------------------------------|----------------------------|---------------------------------|----------------------------|---------------------------|---------------------------|
| Serial Number  | Takeoff | Air Temperature, C | Pavement Temperature, C | Modulus, psi        | Vertical Compression Strain | Horizontal Tensile Strain | Repetitions to failure, Fatigue | Fatigue Damage Per Takeoff | Repetitions to failure, Rutting | Rutting damage Per Takeoff | Cumulative Fatigue Damage | Cumulative Rutting damage |
| 1  | 1       | 22                 | 45.00699987             | 176207.9331         | 0.00043076                  | 0.000174201               | 3195475.8                       | 3.20558E-08                | 65084844.06                     | 1.4475E-08                 | 3.20558E-08               | 1.4475E-08                |
| 2  | 1       | -17                | 6.006999872             | 525139.9171         | 0.000403001                 | 0.000165847               | 2172314.245                     | 4.60339E-07                | 18497584.1                      | 8.43899E-09                | 4.60339E-07               | 8.43899E-09               |
| 3  | 1       | 1                  | 24.00699987             | 317241.9513         | 0.000495863                 | 0.000165852               | 743032.194                      | 1.34596E-07                | 32375504.73                     | 1.02635E-08                | 6.26386E-07               | 3.37329E-08               |
| 4  | 1       | 33                 | 56.00699987             | 129437.9392         | 0.000436929                 | 0.000176632               | 6641280.74                      | 1.51192E-08                | 5932224.5                       | 1.69542E-08                | 6.42039E-07               | 5.65352E-08               |
| 5  | 1       | 19                 | 42.00699987             | 191648.8294         | 0.000428558                 | 0.000173544               | 2543327.04                      | 3.93478E-08                | 7202504.79                      | 1.38958E-08                | 6.4447E-07                | 6.4447E-07                |
| 6  | 1       | 33                 | 56.00699987             | 129437.9392         | 0.000436929                 | 0.000176632               | 6641280.74                      | 1.51192E-08                | 5932224.5                       | 1.69542E-08                | 6.42039E-07               | 6.42039E-07               |
| 7  | 1       | 33                 | 56.00699987             | 129437.9392         | 0.000436929                 | 0.000176632               | 6641280.74                      | 1.51192E-08                | 5932224.5                       | 1.69542E-08                | 7.19686E-07               | 9.19686E-08               |
| 8  | 1       | 10                 | 33.00699987             | 246574.6373         | 0.000422021                 | 0.000176887               | 13141673.42                     | 7.27713E-08                | 87651144.1                      | 1.22607E-08                | 1.10445E-07               | 1.10445E-07               |
| 9  | 1       | 10                 | 33.00699987             | 246574.6373         | 0.000422021                 | 0.000176887               | 13141673.42                     | 7.27713E-08                | 87651144.1                      | 1.22607E-08                | 8.57228E-07               | 1.2277E-07                |
| 10   | 1       | -15                | 8.006999872             | 498503.3435         | 0.00040438                  | 0.000166266               | 2490374.427                     | 4.07546E-07                | 15235748.2                      | 8.97579E-09                | 1.25877E-08               | 1.91988E-07               |
| 11   | 1       | 31                 | 54.00699987             | 196956.6888         | 0.000437432                 | 0.000176787               | 5783393.63                      | 1.73328E-08                | 6099646.94                      | 1.63343E-08                | 1.2781E-08                | 1.4778E-07                |
| 12   | 1       | 35                 | 58.00699987             | 122445.3412         | 0.000440431                 | 0.000170718               | 75625380.49                     | 1.31882E-08                | 57719030.12                     | 1.7327E-08                 | 1.2893E-08                | 1.65107E-07               |
| 13   | 1       | 12                 | 35.00699987             | 233145.9695         | 0.000423485                 | 0.000172022               | 15753685.55                     | 6.34773E-08                | 7935305.76                      | 1.26047E-08                | 1.35277E-08               | 1.77752E-07               |
| 14   | 1       | -8                 | 15.00699987             | 408182.2373         | 0.000406243                 | 0.000167739               | 4071553.244                     | 2.48508E-07                | 104624668.9                     | 9.55738E-09                | 1.60195E-08               | 1.8727E-07                |
| 15   | 1       | 1                  | 24.00699987             | 317241.9512         | 0.000455863                 | 0.000169652               | 743032.194                      | 1.34596E-07                | 32375504.73                     | 1.02635E-08                | 1.38052E-08               | 1.38052E-07               |
| 16   | 1       | 1                  | 24.00699987             | 317241.9512         | 0.000455863                 | 0.000169652               | 743032.194                      | 1.34596E-07                | 32375504.73                     | 1.02635E-08                | 1.07095E-08               | 2.0932E-07                |
| 17   | 1       | 16                 | 39.00699987             | 219442.6762         | 0.000426989                 | 0.000172993               | 20710461.48                     | 4.62886E-08                | 79164231.97                     | 1.3323E-08                 | 1.91918E-08               | 2.22243E-07               |
| 18   | 1       | 12                 | 35.00699987             | 233145.9695         | 0.000423485                 | 0.000172022               | 15753685.55                     | 6.34773E-08                | 7935305.76                      | 1.26047E-08                | 1.96263E-08               | 2.34847E-07               |
| 19   | 1       | 7                  | 30.00699987             | 268181.7            | 0.000418864                 | 0.000170339               | 1195065.17                      | 8.93255E-08                | 86017521.73                     | 1.17623E-08                | 2.07199E-08               | 2.46609E-07               |
| 20   | 1       | 9                  | 28.00699987             | 282628.3441         | 0.000418432                 | 0.000170559               | 9785278.377                     | 1.02404E-07                | 67402763.8                      | 1.14419E-08                | 2.17436E-08               | 2.5855E-07                |

Figure 15: Boeing 777 Sheet Calculating Damage for Rutting and Fatigue Cracking at Different Temperatures

Figure 15 shows the sheet that was used to calculate the damage for rutting and fatigue cracking for Boeing 777 take-offs at different temperatures. The regression equations from figures 13 and 14 as well as equations 1 and 2 were included in this sheet. Collectively, the sheet was designed to calculate the damages for rutting and fatigue cracking for any air temperature in the range of -27°C to 35°C and sum up the damages. This sheet displayed the damage per takeoff as well as the cumulative damage for fatigue cracking and rutting. This sheet was replicated for the other five aircraft included in this application.

### Step 4: Compute cumulative damage of a runway pavement caused by different aircraft take-offs at different temperatures

The next step to developing the application was computing the cumulative damage for rutting and fatigue cracking caused by all aircraft take-offs within the temperature range of -27°C to 35°C. To accomplish this, an additional sheet was added to the Excel file linking together each aircraft's individual sheet (figure 15).

| Serial Number for A220 | Total Takeoff A220 | Serial Number A220 | Total Takeoff A220 | Serial Number A320 | Total Takeoff A320 | Serial Number B747 | Total Takeoff B747 | Serial Number B777 | Total Takeoff B777 | Serial Number B787 | Total Takeoff B787 | Total Planes for row | Total Damages for Row | Cumulative Fatigue Damage | Cumulative Rutting Damage |
|------------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|----------------------|-----------------------|---------------------------|---------------------------|
| 1                      | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                    | 1                     | 1                         | 1                         |
| 2                      | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 2                    | 2                     | 2                         | 2                         |
| 3                      | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 3                    | 3                     | 3                         | 3                         |
| 4                      | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 4                    | 4                     | 4                         | 4                         |
| 5                      | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 5                    | 5                     | 5                         | 5                         |
| 6                      | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 6                    | 6                     | 6                         | 6                         |
| 7                      | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 7                    | 7                     | 7                         | 7                         |
| 8                      | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 8                    | 8                     | 8                         | 8                         |
| 9                      | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 9                    | 9                     | 9                         | 9                         |
| 10                     | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 10                   | 10                    | 10                        | 10                        |
| 11                     | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 11                   | 11                    | 11                        | 11                        |
| 12                     | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 12                   | 12                    | 12                        | 12                        |
| 13                     | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 13                   | 13                    | 13                        | 13                        |
| 14                     | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 14                   | 14                    | 14                        | 14                        |
| 15                     | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 15                   | 15                    | 15                        | 15                        |
| 16                     | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 16                   | 16                    | 16                        | 16                        |
| 17                     | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 17                   | 17                    | 17                        | 17                        |
| 18                     | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 18                   | 18                    | 18                        | 18                        |
| 19                     | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 19                   | 19                    | 19                        | 19                        |
| 20                     | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 1                  | 20                   | 20                    | 20                        | 20                        |

Figure 16: Sheet Calculating Cumulative Damage due to all aircrafts

Figure 16 shows the sheet that was used to calculate the total damage due to all aircraft. For this sheet, the number of takeoffs for each aircraft was tracked, and the cumulative damage

for rutting and fatigue cracking was calculated by summing up the damages caused by each aircraft. The cumulative damages, as well as the cumulative takeoffs, were used to create a plot. In addition to a plot for cumulative damage for rutting and fatigue cracking, separate plots were created for each aircraft. These plots were used later as part of the user-friendly interface. To create individual plots for each aircraft, a separate sheet was created.

| A320 | Fatigue     | Rutting     | A350 | Fatigue     | Rutting     | A380 | Fatigue     | Rutting     | B747 | Fatigue     | Rutting     | B777 | Fatigue     | Rutting     | B787 | Fatigue     | Rutting     | Cumulative Fatigue Damage | Cumulative Rutting damage |
|------|-------------|-------------|------|-------------|-------------|------|-------------|-------------|------|-------------|-------------|------|-------------|-------------|------|-------------|-------------|---------------------------|---------------------------|
| 1    | 1.78224E-09 | 3.16442E-11 | 1    | 6.54773E-08 | 3.27075E-08 | 1    | 9.88100E-07 | 2.34225E-06 | 1    | 2.81433E-06 | 7.30729E-06 | 1    | 3.20559E-08 | 1.44750E-08 | 1    | 6.88686E-08 | 6.40414E-09 | 5.96844E-06               | 9.70318E-06               |
| 2    | 3.94923E-09 | 6.14489E-11 | 2    | 3.12385E-07 | 5.76218E-08 | 2    | 3.63378E-06 | 4.13088E-06 | 2    | 1.33073E-05 | 1.27240E-05 | 2    | 4.92394E-07 | 2.29139E-08 | 2    | 2.09466E-07 | 1.15975E-08 | 1.79595E-05               | 1.69671E-05               |
| 3    | 6.11527E-09 | 9.12544E-11 | 3    | 3.92032E-07 | 8.90205E-08 | 3    | 1.24700E-05 | 5.43209E-06 | 3    | 1.67600E-05 | 1.97250E-05 | 3    | 6.20900E-07 | 3.37201E-08 | 3    | 3.50244E-07 | 1.67920E-08 | 2.33820E-05               | 2.23821E-05               |
| 4    | 9.31098E-09 | 1.17096E-10 | 4    | 5.07699E-07 | 1.17958E-07 | 4    | 1.66923E-05 | 7.14956E-06 | 4    | 2.18242E-05 | 2.60667E-05 | 4    | 6.42090E-07 | 5.05931E-08 | 4    | 4.91026E-07 | 2.10842E-08 | 4.01660E-05               | 3.3437E-05                |
| 5    | 1.06869E-08 | 1.51970E-10 | 5    | 3.55998E-07 | 1.52495E-07 | 5    | 2.14694E-05 | 8.69828E-06 | 5    | 2.98734E-05 | 3.38549E-05 | 5    | 8.81447E-07 | 6.44800E-08 | 5    | 8.14583E-07 | 2.73793E-08 | 4.73195E-05               | 4.27977E-05               |
| 6    | 1.31528E-08 | 1.86909E-10 | 6    | 6.19475E-07 | 1.82202E-07 | 6    | 2.35941E-05 | 1.06468E-05 | 6    | 2.80038E-05 | 4.11622E-05 | 6    | 6.96567E-07 | 8.13348E-08 | 6    | 6.67499E-07 | 2.42905E-08 | 3.23024E-05               | 3.20993E-05               |
| 7    | 1.56186E-08 | 2.09247E-10 | 7    | 7.08800E-07 | 2.13759E-07 | 7    | 2.55387E-05 | 1.25737E-05 | 7    | 3.07124E-05 | 4.73926E-05 | 7    | 7.11686E-07 | 9.81885E-08 | 7    | 7.62674E-07 | 4.01118E-08 | 5.84490E-05               | 6.08702E-05               |
| 8    | 1.84257E-08 | 2.38766E-10 | 8    | 7.98125E-07 | 2.46315E-07 | 8    | 2.92125E-05 | 1.42330E-05 | 8    | 3.51731E-05 | 5.45229E-05 | 8    | 7.84457E-07 | 1.10449E-07 | 8    | 8.57812E-07 | 4.59311E-08 | 6.68443E-05               | 6.91388E-05               |
| 9    | #N/A        | #N/A        | 9    | 9.00529E-07 | 2.76051E-07 | 9    | 3.28833E-05 | 1.58922E-05 | 0    | #N/A        | #N/A        | 9    | 8.51228E-07 | 1.22710E-07 | 9    | 9.86297E-07 | 5.15396E-08 | 7.08019E-05               | 7.08019E-05               |

Figure 17: Sheet Calculating Damage for each Individual Aircraft

Figure 17 shows the sheet that was used for calculating damage caused by each aircraft. This sheet was used to create a plot for each aircraft that would eventually be displayed as part of the application interface.

### Step 5: Develop a working interface to run the application

Step five for this project was to develop a working interface where each aircraft along with a corresponding air temperature can be selected to generate the rest of the calculations. An additional sheet was created where each aircraft was dedicated two columns: one column to add a take-off, and one column to select an air temperature.

| A320 | Air Temperature, C | B777 | Air Temperature, C | B747 | Air Temperature, C | B787 | Air Temperature | A350 | Air Temperature, C | A380 | Air Temperature, C |
|------|--------------------|------|--------------------|------|--------------------|------|-----------------|------|--------------------|------|--------------------|
| 1    | 10                 | 1    | 22                 | 1    | 10                 | 1    | 10              | 1    | 10                 | 1    | 27                 |
| 1    | 9                  | 1    | -11                | 1    | 9                  | 1    | 9               | 1    | 9                  | 1    | 12                 |
| 1    | 8                  | 1    | 8                  | 1    | 8                  | 1    | 8               | 1    | 8                  | 1    | 8                  |
| 1    | 3                  | 1    | 33                 | 1    | 3                  | 1    | 3               | 1    | 3                  | 1    | 9                  |
| 1    | 16                 | 1    | 16                 | 1    | 16                 | 1    | 16              | 1    | 16                 | 1    | 2                  |
| 1    | 7                  | 1    | 33                 | 1    | 12                 | 1    | 12              | 1    | 12                 | 1    | 16                 |
| 1    | 7                  | 1    | 33                 | 1    | 7                  | 1    | 7               | 1    | 7                  | 1    | 16                 |
| 1    | 5                  | 1    | 10                 | 1    | 5                  | 1    | 7               | 1    | 7                  | 1    | 7                  |

Figure 18: Interface Tab

This sheet was designed so that adding a takeoff would consist of two criteria: 1. Adding “1” to the cell underneath the aircraft name, and 2. Adding the numerical value for the current air temperature under the temperature column, which is the cell adjacent to the aircraft takeoff cell, in degrees Celsius. This sheet was linked together with each aircraft’s calculation sheet (figure 15) so that the single interface sheet controlled all manual inputs to run the application. After

completing step five, the application allowed users to select an aircraft and an air temperature for a take-off, and all calculations were performed automatically resulting in the damage due to fatigue and rutting for each individual take-off as well as the cumulative damages being tracked.

## Step 6: Develop a user-friendly interface to run the application

The user-friendly interface was designed to control the ‘Interface’ tab, as depicted in figure 17, from a separate tab in the spreadsheet. The user-friendly interface was designed to have a macro-based algorithm for adding takeoffs. To accomplish this, in addition to a drop-down menu to select the air temperature during take-off, six buttons were added: one for each aircraft.

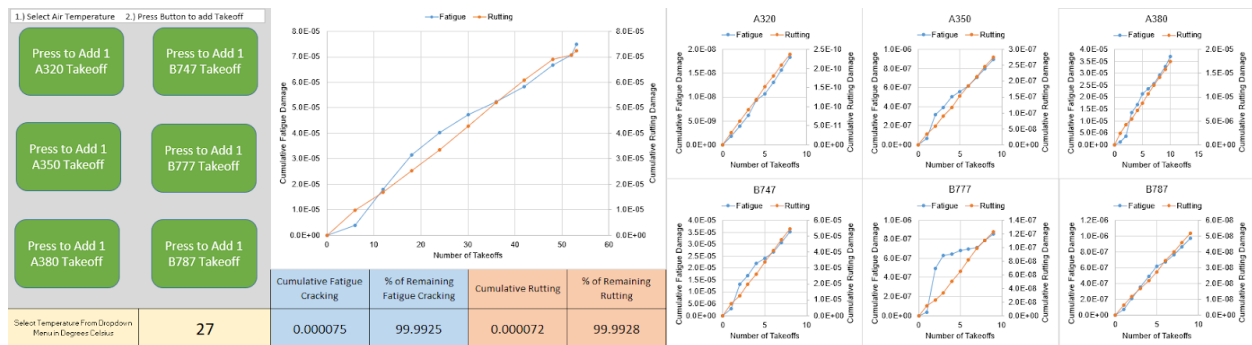


Figure 19: Application Tab - User-friendly Interface

The interface was designed for a user to perform two separate tasks in sequence: 1. Select the air temperature from the drop-down menu, in degrees Celsius, and 2. Press the corresponding button for the specific aircraft that is taking off. The drop-down menu was assigned the values -27 through 35 in one-degree increments. A macro was assigned to each of the six buttons. Each macro performs the same operations, with the only difference being the type of aircraft that is taking off. Each macro was recorded. The macro was designed to perform the following: 1. Copy the cell from the drop-down menu (air temperature) and ‘paste cell value’ into a separate cell; 2. Select the two cells directly underneath the aircraft name and temperature heading in the ‘Interface’ tab and ‘insert cell values - shift cells down’; 3. Type “1” in the cell directly underneath the aircraft name; 4. Copy the cell where the air temperature value was pasted and ‘paste cell value’ into the cell directly underneath the temperature heading (cell adjacent to the

“1” value previously entered); 5. Select the tab for the aircraft that is taking off and reset the serial number column and temperature column to correctly align with the interface tab; 6. Return to the ‘Application’ tab.

```

Sub Button_for_777()
' Button_for_777 Macro
'
'
Range("F32:I35").Select
Selection.Copy
Range("C43").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
:=False, Transpose:=False
Application.CutCopyMode = False
Sheets("Interface").Select
Range("E5:F5").Select
Selection.Insert Shift:=xlDown, CopyOrigin:=xlFormatFromLeftOrAbove
Range("E5").Select
ActiveCell.FormulaR1C1 = "1"
Range("F5").Select
Sheets("App").Select
Range("C43").Select
Selection.Copy
Sheets("Interface").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
:=False, Transpose:=False
Application.CutCopyMode = False
Sheets("B777").Select
Range("B4").Select
ActiveCell.FormulaR1C1 = "=Interface!R[1]C[3]"
Range("B4").Select
Selection.AutoFill Destination:=Range("B4:C4"), Type:=xlFillDefault
Range("B4:C4").Select
Selection.AutoFill Destination:=Range("B4:C1000")
Range("B4:C1000").Select
Range("B4").Select
Sheets("App").Select
Range("B2:I31").Select
ActiveWindow.SmallScroll Down:=-72
End Sub

```

*Figure 20: Code for Button for Boeing 777 Take-Off (Macro)*

Figure 19 shows the code created from recording a macro for the button assigned to add one Boeing 777 takeoff. The ‘insert cells down’ function was chosen so that each take-off will continue in sequence, rather than re-writing the previous take-off. The ‘paste cell value’ function was chosen to avoid previous air temperatures changing when a new air temperature is selected for a future takeoff. Resetting the serial number and air temperature columns on the selected aircraft’s tab was necessary because the ‘shift cells down’ function previously used also applied to the selected aircraft’s tab since the sheets are linked together by formula. The ‘Application’ tab was selected to conclude the macro so that the user-friendly interface is displayed following use, rather than a separate tab.

A plot of the total cumulative damage for fatigue and rutting was added for a visual perspective. Beneath the plot, a chart was created displaying the cumulative fatigue cracking and rutting, and the percent of remaining life for fatigue cracking and rutting. Additionally, the individual plots for each aircraft from step four were added.

In total, eleven tabs were created in the spreadsheet. There was one tab for each aircraft, a tab for cumulative damage, a tab for damage caused by each individual aircraft that was used to create plots, a working interface tab titled 'Interface,' a user-friendly interface tab titled 'Application,' and a tab that tracked and organized the regression equations for modulus of elasticity and strain for each aircraft. The spreadsheet shown in figure 11 was solely used for structural analysis and was not linked to the spreadsheet with the application.

## How to use Application

The application was designed to be user-friendly and easily operated by an airport manager. The first step in using the application is to select the current air temperature in degrees Celsius from a dropdown menu at the bottom left of the application. Second, the user will press the green button on the left side of the application corresponding to the aircraft that is taking off. This process will be repeated after each aircraft takes off. The center graph will update after each take-off to display the total amount of aircraft in relation to the cumulative fatigue cracking damage and cumulative rutting damage. At the bottom of the center graph, the cumulative fatigue cracking damage, percent of remaining fatigue cracking damage, cumulative rutting damage, and percent of remaining rutting damage will be updated after each takeoff. To the right of the center graph, each individual aircraft has an independent graph that shows the resulting cumulative fatigue cracking damage and cumulative rutting damage caused by that specific aircraft.



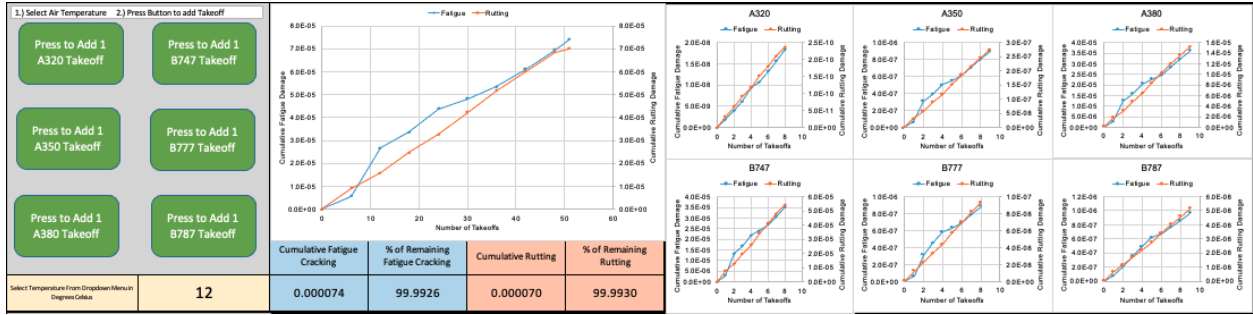


Figure 21: Application Tab (1st Tab on Excel Sheet on Application)

The second tab on the excel sheet is the ‘Interface’ tab which tracks the total amount of takeoffs for each aircraft with the corresponding air temperature recorded in degrees Celsius. The data on this spreadsheet is recorded after the button is pressed on the application. After the button is pressed for a specific aircraft, it will record the takeoff with the number “1” added for the column of the aircraft that takes off with the temperature at the time of takeoff in the column to the right.

| A320 | Air Temperature, C | B777 | Air Temperature, C | B747 | Air Temperature, C | B777 | Air Temperature, C | A350 | Air Temperature, C | A380 | Air Temperature, C |
|------|--------------------|------|--------------------|------|--------------------|------|--------------------|------|--------------------|------|--------------------|
| 1    | 17                 | 1    | 17                 | 1    | 17                 | 1    | 17                 | 1    | 17                 | 1    | 17                 |
| 1    | 9                  | 1    | 9                  | 1    | 9                  | 1    | 9                  | 1    | 9                  | 1    | 9                  |
| 1    | 9                  | 1    | 9                  | 1    | 9                  | 1    | 9                  | 1    | 9                  | 1    | 9                  |
| 1    | 16                 | 1    | 16                 | 1    | 16                 | 1    | 16                 | 1    | 16                 | 1    | 16                 |
| 1    | 16                 | 1    | 16                 | 1    | 16                 | 1    | 16                 | 1    | 16                 | 1    | 16                 |
| 1    | 7                  | 1    | 7                  | 1    | 7                  | 1    | 7                  | 1    | 7                  | 1    | 7                  |
| 1    | 5                  | 1    | 5                  | 1    | 5                  | 1    | 5                  | 1    | 5                  | 1    | 5                  |

Figure 22: Interface Spreadsheet

Each aircraft has its own spreadsheet that records the takeoff from the ‘Interface’ tab with a serial number assigned in chronological order. The serial number is the number of the take-off for the aircraft. Each row for the serial number will also display the air temperature and pavement temperature in degrees Celsius, the modulus of elasticity of the surface asphalt layer in pounds per square inch, the vertical compressive strain at the top of the subgrade, the horizontal tensile strain at the bottom of the stabilized base, the repetitions to failure for fatigue and rutting, the fatigue and rutting damage per takeoff, the cumulative fatigue and rutting damage.

| Serial Number | Takeoff | Air Temperature, C | Pavement Temperature, C | Modulus, psi | Vertical Compressive Strain | Horizontal Tensile Strain | Repetitions to Failure, Fatigue | Fatigue Damage Per Takeoff | Repetitions to Failure, Rutting | Rutting damage Per Takeoff | Cumulative Fatigue Damage | Cumulative Rutting damage |
|---------------|---------|--------------------|-------------------------|--------------|-----------------------------|---------------------------|---------------------------------|----------------------------|---------------------------------|----------------------------|---------------------------|---------------------------|
| 1             | 1       | 17                 | 35.00699987             | 233145.9695  | 0.00020209                  | 8.43989E-05               | 56077855.6                      | 1.78324E-09                | 31603374840                     | 3.18442E-11                | 1.78324E-09               | 3.18442E-11               |
| 2             | 1       | 9                  | 32.00699987             | 253576.2929  | 0.00020072                  | 8.37038E-05               | 46167727.7                      | 2.16602E-09                | 33551307261                     | 2.80051E-11                | 3.94925E-09               | 6.14492E-11               |
| 3             | 1       | 9                  | 32.00699987             | 253576.2929  | 0.00020072                  | 8.37038E-05               | 46167727.7                      | 2.16602E-09                | 33551307261                     | 2.80051E-11                | 6.15272E-09               | 9.12446E-11               |
| 4             | 1       | 3                  | 26.00699987             | 299964.6804  | 0.000197774                 | 8.27247E-05               | 312919545.4                     | 3.19517E-09                | 37819552365                     | 2.64413E-11                | 9.31098E-09               | 1.17698E-10               |
| 5             | 1       | 16                 | 39.00699987             | 208442.8152  | 0.000204212                 | 8.48586E-05               | 72876713.9                      | 1.73968E-09                | 29176600265                     | 3.4274E-11                 | 1.06869E-08               | 1.13976E-10               |
| 6             | 1       | 7                  | 30.00699987             | 268181.7     | 0.000199738                 | 8.33758E-05               | 40554267.2                      | 2.46583E-09                | 34912664816                     | 2.86388E-11                | 1.35128E-08               | 1.80609E-10               |
| 7             | 1       | 7                  | 30.00699987             | 268181.7     | 0.000199738                 | 8.33758E-05               | 40554267.2                      | 2.46583E-09                | 34912664816                     | 2.86388E-11                | 1.55186E-08               | 2.09247E-10               |
| 8             | 1       | 5                  | 28.00699987             | 283628.3447  | 0.000198751                 | 8.30496E-05               | 356233392.8                     | 2.80715E-09                | 36339649839                     | 2.75182E-11                | 1.84257E-08               | 2.38766E-10               |

Figure 23: Example of Total Take-offs for A320

# Progress of Project

The MQP was scheduled to be completed over the course of three terms beginning with B term and ending with D term. Weekly meetings were conducted to show an update on the status of the project and to discuss any weekly updates. A Gantt Chart was used each term displaying future goals and deadlines to hit in order to track the group's progress. The Gantt chart displays the dates of the weekly meetings with the color of the box indicating the status of the objective being worked on. For the spring semester, the term was split up showing black boxes for C term and Orange boxes displaying D term. A blue circle in the box indicates how much has been completed for that specific step, for example, if the blue dot was in the middle of the box, it means that the corresponding task is approximately halfway complete.

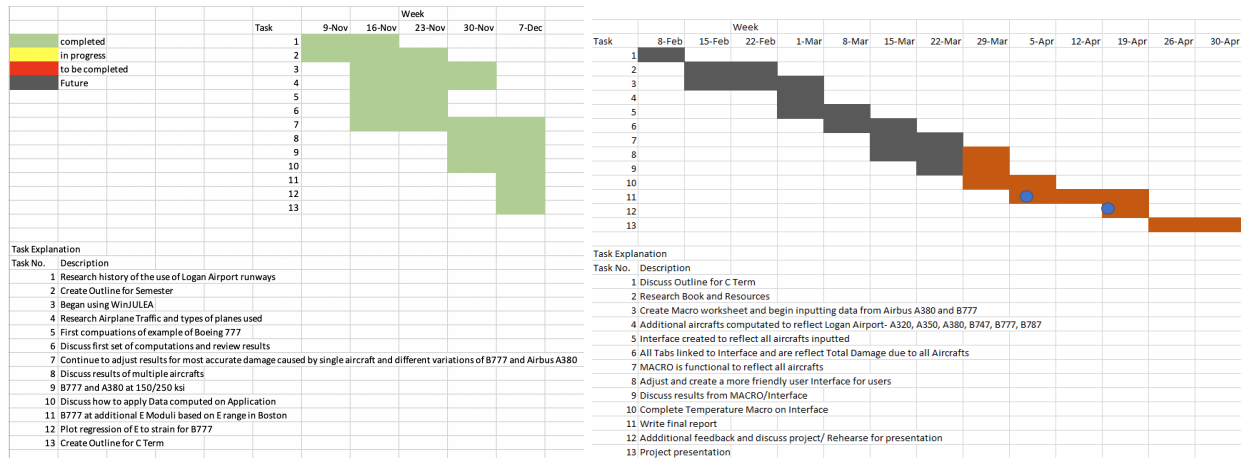
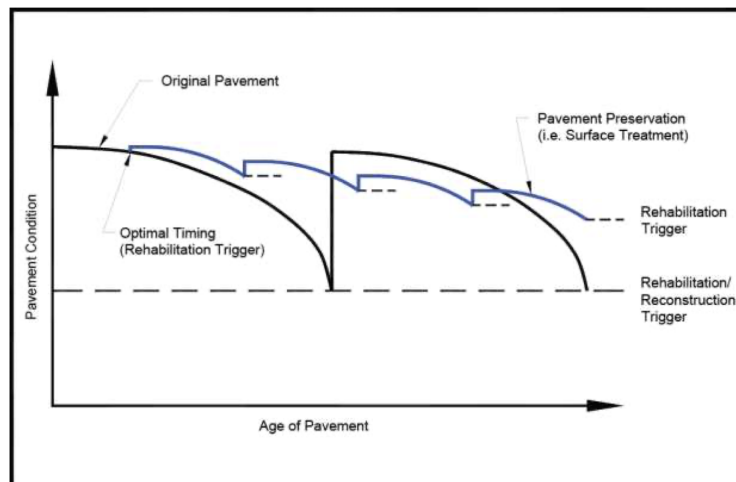


Figure 24: Gantt Chart used to Plan out Semester

# Conclusion/Recommendations

The application could be implemented into the airport's pavement management programs by allowing airport authorities to provide up-to-date damage and remaining life reports of the runway pavement. The FAA currently does not have an application that is able to monitor the current condition of runways.

Even though airport runways are designed to be used for 20 years before any major rehabilitation, changes in the volume of traffic and changes in airplane configurations can change over the course of the 20 years. As a result, the damages on the runway may not be the same as they were predicted to be when they were designed. The application created was designed to take these small factors into consideration to get accurate and reliable data.



*Figure 25: Relationship between Pavement Age and Condition*

This application can be implemented in an airport's Pavement Management Programs, which facilitates a procedure for establishing facility policies, setting priorities and schedules, allocating resources, and budgeting for pavement maintenance and rehabilitation. [5] The application can assist in allocating funds for runway rehabilitation programs and maintenance to not only ensure the runway can be operable but also minimize the costly repairs and postpone unnecessary rehabilitation and reconstruction

# Design Statement

The design problem for this project was to develop an application that records the current cumulative damage and percent of damage remaining to failure after every aircraft takes off on runway 9/27 at Logan Airport. The application was designed to be user-friendly and easily managed for Air Traffic Controllers, airport authorities, FAA, and maintenance managers. To use the application, the user simply selects the current air temperature and presses the button for the aircraft taking off. As a result, the application will display two types of accumulating damages after an aircraft takes off, fatigue cracking and rutting, which will display on a graph with the total amount of aircraft that have taken off.

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