An Overview and Analysis of the Impacts of Extreme Heat on the Aviation Industry

Brandon T. Carpenter
*University of Tennessee, Knoxville*, bcarpen5@vols.utk.edu

Follow this and additional works at: [https://trace.tennessee.edu/utk_chanhonoproj](https://trace.tennessee.edu/utk_chanhonoproj)

![Part of the Business Administration, Management, and Operations Commons, Business Analytics Commons, Operations and Supply Chain Management Commons, and the Tourism and Travel Commons](https://trace.tennessee.edu/utk_chanhonoproj)

**Recommended Citation**

This Dissertation/Thesis is brought to you for free and open access by the Supervised Undergraduate Student Research and Creative Work at TRACE: Tennessee Research and Creative Exchange. It has been accepted for inclusion in Chancellor’s Honors Program Projects by an authorized administrator of TRACE: Tennessee Research and Creative Exchange. For more information, please contact trace@utk.edu.
An Overview and Analysis of the Impacts of Extreme Heat on the Aviation Industry

And How to Best Mitigate the Negative Effects of Heat on Both Small and Large Aircraft

Brandon Thomas Carpenter
The University of Tennessee, Knoxville
The Chancellor’s Honors Program
Haslam College of Business
Spring 2018 Honors Thesis/Capstone
Faculty Advisor: Dr. Mary Holcomb
# Table of Contents

I. Introduction ......................................................................................................................... 3  
II. The Effect of Heat on Airline Operations: The Phoenix Case Study ................................... 4  
III. A System that Encourages the Use of Regional Jets .......................................................... 8  
V. Phoenix Case Study Continued ......................................................................................... 15  
VI. How Heat Significantly Affects Large Aircraft: Part II ..................................................... 17  
VII. Additional Effects of Heat on Aviation ............................................................................ 20  
VIII. Potential Solution: Increasing Runway Lengths .............................................................. 23  
IX. Potential Solution: Changing Flight Route Structure ...................................................... 27  
X. Potential Solution: Changes and Improvements in Plane Structure and Technology ........ 31  
XI. Conclusion ....................................................................................................................... 35  
XII. Appendix ......................................................................................................................... 36  
XIII. Bibliography .................................................................................................................. 44
Introduction

There are many issues that can lead to a delayed or cancelled flight: maintenance problem, scheduling issue, late aircraft arrival, security threat, heavy air traffic, etc. However, one of the most common causes is weather. From heavy fog, to convective weather, to snowstorms, there are many ways Mother Nature can cause headaches within the travel industry. While there has been a gradual downwards trend in the percentage of weather’s impact on total delay minutes, it still holds a significant portion of the overall delay minutes – above 30% in 2016.¹

Within the first couple of days of 2018, the bomb cyclone resulting from Winter Storm Grayson wreaked havoc on transportation along the Eastern United States, resulting in thousands of cancelled flights. This incident is just one of countless examples of how weather has impacted airlines. Likewise, this incident is just one of many examples of the type of weather people associate with airline delays and cancellations. Interestingly, the exact opposite of winter weather can cause similar issues.

Heat alone – no fog, haze, or thunderstorms required – can be enough to significantly affect airline operations.

As global temperatures rise and extreme weather conditions become more common, how will incidents of extreme heat affect the future of both the airline and aerospace industries? Furthermore, what are some ways to help mitigate the effects of extreme heat on aviation?

The purpose of this research is to examine how heat affects both small and large aircraft and to explore potential solutions that can mitigate the negative effects of heat on aviation.
The Effect of Heat on Airline Operations: The Phoenix Case Study

On Tuesday, June 20, 2017, temperatures sweltered at the Phoenix Sky Harbor International Airport (PHX) in Arizona. More specifically, they treaded dangerously high on the thermometer, close to the record high of 122 degrees Fahrenheit.

Canadair Regional Jets (CRJs), manufactured by Bombardier, have a maximum operating temperature of 118 degrees Fahrenheit. However, for four hours, temperatures at PHX remained at or above 118 degrees, reaching their peak at 118.9°F at 15:51. In fact, from 12:51 to 18:51 (the time frame could possibly be slightly longer – historical temperature records are available at an hourly rate), the temperature did not dip below 110 degrees. Additionally, the temperature on the actual tarmac was likely even higher than the reported temperatures because of the sun reflecting off the land mass of concrete.

<table>
<thead>
<tr>
<th>Time</th>
<th>Temperature</th>
<th>Cancellations</th>
</tr>
</thead>
<tbody>
<tr>
<td>09:51</td>
<td>104.0 °F</td>
<td></td>
</tr>
<tr>
<td>10:51</td>
<td>108.0 °F</td>
<td></td>
</tr>
<tr>
<td>11:51</td>
<td>108.0 °F</td>
<td></td>
</tr>
<tr>
<td>12:51</td>
<td>111.9 °F</td>
<td>2</td>
</tr>
<tr>
<td>13:51</td>
<td>116.1 °F</td>
<td>1</td>
</tr>
<tr>
<td>14:51</td>
<td>118.0 °F</td>
<td>5</td>
</tr>
<tr>
<td>15:51</td>
<td>118.9 °F</td>
<td>6</td>
</tr>
<tr>
<td>16:51</td>
<td>118.0 °F</td>
<td>2</td>
</tr>
<tr>
<td>17:51</td>
<td>118.0 °F</td>
<td>3</td>
</tr>
<tr>
<td>18:51</td>
<td>117.0 °F</td>
<td>5</td>
</tr>
<tr>
<td><strong>19:51</strong></td>
<td><strong>No Temperature Data</strong></td>
<td></td>
</tr>
<tr>
<td>20:51</td>
<td>109.0 °F</td>
<td>1</td>
</tr>
<tr>
<td>21:51</td>
<td>105.1 °F</td>
<td></td>
</tr>
</tbody>
</table>

(Sources: Weather Underground² & Bureau of Transportation³)

In response to these extreme temperatures, a significant number of flights were cancelled. The vast majority of these cancelled flights were operated by SkyWest Airlines, under contract as American Eagle. All of the canceled SkyWest flights were scheduled to fly with the Canadair Regional Jet.

Why were only flights operated as American Airlines cancelled? American is the only passenger airline to operate a hub at PHX, so they have a larger number of inbound and outbound flights there. Likewise, they would have a larger number of regional jets operating through the airport because of the hub-and-spoke system. While no other airline treats PHX as a hub, Southwest does include the airport as one of its focus cities, but Southwest only operates Boeing 737 variants, which can operate in hotter temperatures than CRJs, in its fleet.
**Important Note**

The flight scheduled to depart at 08:45 was excluded from the analysis. That flight was scheduled to depart to Newark Liberty International Airport (EWR), which was experiencing rain that morning. There were 11 other flights from various airports scheduled to depart their origin for EWR before 0900 that were cancelled due to “Weather” or “NAS.”

**Why are there two codes for cancelled flights?** There are actually four descriptions for why flights are cancelled – “Carrier,” “Weather,” “National Air System” (or NAS), and “Security.” For purposes of this paper, I sorted the data to reflect only fights cancelled because of “Weather” and “NAS.” According to the Bureau of Transportation, NAS cancellations are
“attributable to the national aviation system” and “refer to a broad set of conditions, such as non-extreme weather conditions, airport operations, heavy traffic volume, and air traffic control.”

It is important to note that, according to the Federal Aviation Administration, weather is clearly the largest cause of delay in the NAS. Sixty-nine percent of NAS delays are because of weather (the next closest category is “Volume,” at 19%). Therefore, it is safe to assume in this case that the NAS cancellations on June 20, 2017 at PHX are due to weather for numerous reasons: the extreme heat on June 20, the fact that weather is a significant portion of NAS delays, and other June days at PHX normally have very few, if any, cancellations due to NAS.

While some news sources reported there being approximately 40-50 flight cancellations that day due to the heat in PHX, data from the Bureau of Transportation suggests there were 25 cancellations due to the heat. Although 25 might sound like less than the media’s 40-50 number, it is still significantly higher than other days at PHX. Looking at cancellations due to “Weather” and “NAS” for other days in June 2017 at PHX, there are usually only 0-3 cancellations per day.

Airlines certainly are not saving any money when a flight is cancelled. While they may save on landing costs and fuel costs in the sense they are no longer going to burn the fuel on that route for that particular scheduled flight, they still have to pay the flight crew and airport fees, in addition to other costs. Furthermore, they must rebook passengers on other flights, which may already be full or oversold. All of this is not to mention that the airline must figure out how they can position their current, available fleet to best deal with the cancellations and avoid any subsequent cancellations or delays. If aircraft cannot get to where they are scheduled, problems arise. This problem is exacerbated by regional aircraft because they operate more daily flights on average than other types of aircraft, and flights later in the day require that aircraft be at the planned and scheduled node.

<table>
<thead>
<tr>
<th>Daily flights by route by aircraft type scheduled</th>
<th>Specific Equipment on Route</th>
<th>All Equipment on Route</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily Flights</td>
<td>Daily Seats</td>
<td>Daily Flights</td>
</tr>
<tr>
<td>Regional Jets</td>
<td>2.9 flights</td>
<td>176 seats</td>
</tr>
<tr>
<td>Narrowbodies</td>
<td>2.4 flights</td>
<td>344 seats</td>
</tr>
<tr>
<td>Small Widebodies</td>
<td>1.1 flights</td>
<td>257 seats</td>
</tr>
<tr>
<td>Large Widebodies</td>
<td>1.1 flights</td>
<td>320 seats</td>
</tr>
</tbody>
</table>

(Source: masFlight)

masFlight is a platform owned by Global Eagle and “offers a single source for operations data in real-time for day-of-decision making and historic data for predictive analytics.” The company has completed extensive research outlining airline cancellation costs and the subsequent passenger disruption. According to their analysis, the average cost per flight segment cancelled for a regional jet is $1,050. By masFlight’s numbers, the cost of all the cancelled flights on June 20 was approximately $26,250. But the events on that day go beyond costs. Time and effort had to be spent to rebook a large number of passengers (masFlight assumes 80%
load factor and configuration of 50 total seats on regional jet aircraft, so by their numbers, 1,000 passengers needed to be rebooked. Additionally, these passengers faced major headaches in the inconvenience of the cancellation – longer travel time, potentially more flight legs, etc.

Although the incident in Phoenix might be considered more of an isolated incident, it is important to study and understand in order to be better prepared for future incidents. According to Coffel, Thompson, and Horton, “global mean surface temperatures have increased approximately one degree Celsius above pre-industrial levels, with most of that change occurring after 1980.” As global temperatures rise, extreme weather becomes more frequent, and urban heat islands increase, the likelihood of an event similar to that day at PHX occurring is probable. McCarran International Airport (LAS) in Las Vegas, Nevada has experienced similar conditions to PHX and has had flights delay and cancel because of heat as well. In the past couple of years, heat records have been broken and/or tied in places such as California, Arizona, and Nevada. Meanwhile, regional jets are being used much more frequently than they were in the past, meaning more flights are susceptible to heat cancellations.
**A System that Encourages the Use of Regional Jets**

After passing in the Senate and House of Representatives, the Airline Deregulation Act was signed into law by President Jimmy Carter on October 24, 1978. The whole idea behind the ADA was “that unregulated airlines will operate more efficiently than regulated airlines.”

Prices were expected to be lower, in addition to higher load factors. Competition did heavily increase among airline carriers, and a number of carriers experienced bankruptcy. Some ceased to exist while others merged or were bought. There are five airlines left that are considered ‘legacy carriers’ – Alaska Airlines, American Airlines, Delta Air Lines, Hawaiian Airlines, and United Airlines (17 have become defunct). Since 1978, a number of ‘low-cost’ carriers have arisen such as Spirit Airlines. Southwest Airlines actually did operate before 1978, but they carried passengers solely via intrastate routes, as opposed to interstate, so they were not subject to the same federal government regulations as interstate carriers. A decent number of the legacy carriers that became defunct experienced bankruptcy because they did not have a well-established domestic route structure. For example, Pan American World Airways served mainly international destinations. Before deregulation, passengers wanting to travel overseas flew first on a domestic carrier and then transferred to an international carrier such as Pan Am. Domestic travel was obviously more common than international, so once the traditional domestic carriers were able to purchase international routes post-deregulation, the majority of their customer base remained loyal to that airline rather than transfer to a different one. This effect of deregulation led to the demise of airlines such as Pan Am.

Alongside the deregulation and subsequent consolidation of the airline industry was born a new method of travel: The Hub-and-Spoke (HS) System. Rather than flying from point-to-point, airlines shuttle passengers from their origin airport to a focused hub airport and then to their final destination. A mixture of aircraft feed the hub, with smaller, regional aircraft serving smaller destinations/airports in the hub-and-spoke system, and there was a significant increase in the number of smaller-city markets serviced after the passage of the ADA. Moore wrote an extensive article on the effects of US Airline Deregulation:

> “Many of the airlines have adopted a hub-spoke system with a large number of flights arriving at a hub during a short period of time followed by an equally large number of turnaround departures. For example, TWA [bought by American Airlines in 2001] has established a hub at St. Louis, United has hubs at Chicago and Denver, and Continental [which was acquired by United in 2010] has a hub at Denver. Thus, passengers can come from any one of the cities on the spoke and travel to any other; this saves aircraft and fuel for the airline but is less convenient than nonstop service for the customer. On the other hand, the hub system is more convenient for passengers than changing airlines, a phenomenon more common before deregulation” (p. 7).
The new HS system utilizes regional jets for many reasons. Although regional aircraft incur higher unit costs than larger aircraft (flight legs are much shorter), airlines can reach smaller markets to service their network, supplement routes already in existence, provide a higher flight frequency, and replace older turboprop planes. RJs became so popular because, as Brueckner and Pai note,

“Regional jets (RJs) offer a previously unavailable combination of attributes. They combine a relatively small passenger capacity, usually 70 seats or less, with a relatively long range (1500 miles), a high cruising speed comparable to that of mainline jets (over 500mph), and a level of passenger comfort close to that of mainline jets.”

“The evidence shows that RJs were used to provide service on a large number of new hub-and-spoke and point-to-point routes. In addition, they replaced discontinued jet and turboprop service on many HS routes, as well as supplementing continuing jet service on such routes. When replacement or supplementation occurred, passengers benefited from better service quality via higher flight frequencies” (p. 110).

Data from 1990 to 2005 shows the dramatic increase in the number of routes operated by regional aircraft:

<table>
<thead>
<tr>
<th>Year</th>
<th>Number of Routes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>6</td>
</tr>
<tr>
<td>1991</td>
<td>14</td>
</tr>
<tr>
<td>1992</td>
<td>55</td>
</tr>
<tr>
<td>1993</td>
<td>86</td>
</tr>
<tr>
<td>1994</td>
<td>99</td>
</tr>
<tr>
<td>1995</td>
<td>97</td>
</tr>
<tr>
<td>1996</td>
<td>74</td>
</tr>
<tr>
<td>1997</td>
<td>100</td>
</tr>
<tr>
<td>1998</td>
<td>158</td>
</tr>
<tr>
<td>1999</td>
<td>263</td>
</tr>
<tr>
<td>2000</td>
<td>460</td>
</tr>
<tr>
<td>2001</td>
<td>564</td>
</tr>
<tr>
<td>2002</td>
<td>707</td>
</tr>
<tr>
<td>2003</td>
<td>854</td>
</tr>
<tr>
<td>2004</td>
<td>925</td>
</tr>
<tr>
<td>2005</td>
<td>1091</td>
</tr>
</tbody>
</table>

Regional jets allow airlines to serve airports and markets that would not be economical to serve with larger jets. From 1997-2005, 244 hub-and-spoke routes and 91 point-to-point routes (routes where a hub is not involved) began being serviced by RJs with no other type of aircraft on the route. Many of these routes could not be serviced by turboprops (TP) because of the long
distance. Furthermore, the more effective RJs began replacing TPs (Some airlines do still operate a small number of TPs, such as American Airlines and Alaska Airlines). Because RJs have significantly fewer seats than larger aircraft, they can service destinations with a higher frequency and maintain a load factor that makes financial sense for the airline to continue servicing the city. Without RJs, airlines might only be able to offer one daily flight to/from a location, which is not ideal. Now, airlines can offer customers a higher service level with multiple flight options a day (without sacrificing empty seats). This logic also applies to supplementing a market already serviced by a Boeing or Airbus aircraft.¹⁴

This graph from 2005 is a good visual representation of the distribution of regional jets as opposed to larger jets (i.e. Boeing, Airbus, McDonnell Douglas) corresponding to the route distance on point-to-point routes:

![Graph showing regional vs larger jet distribution](image)

(Source: Brueckner and Pai)¹⁴

While regional aircraft may be more expensive to operate per seat mile, fares on flights operated by RJs may be higher, and the crew salaries are much less than those working for the mainline carrier. The graph on the next page shows the progression of a pilot’s salary as an employee of a regional carrier (in this example, Envoy) to joining the mainline. The lower salaries are one of the many reasons RJ flights are operated as a subsidiary of an airline or under contract with the airline.
American Eagle is comprised of three subsidiaries of the American Airlines Group (Envoy Air Inc., Piedmont Airlines Inc., and PSA Airlines Inc.) as well as seven contracted carriers: Air Wisconsin (contract ends March 2018; not being renewed), Compass, ExpressJet, Mesa, Republic, SkyWest, and Trans States. To give an example of the scope of these regional carriers, the three subsidiaries of American Airlines Group combine to operate 1,900 daily flights. Delta Connection is comprised of ExpressJet, Compass, GoJet Airlines, Endeavor Air, Republic Airline, and SkyWest while Air Wisconsin, Cape Air, CA CommutAir, ExpressJet, GoJet Airlines, Mesa, Republic Airlines, SkyWest, and Trans States make up United Express.

To give an example of how airlines service smaller markets through their hub-and-spoke system, let us examine daily flights at McGhee Tyson Airport (TYS), which served a record 1,988,019 people in 2017, in Knoxville, Tennessee. It is important to note that Allegiant Air and Frontier Airlines operate a select few flights (infrequent days and some seasonal) through TYS, but we will focus on the only other airlines to service TYS. American, Delta, and United are in the top four airlines for enplanement (passengers boarded onto an aircraft). Searching for flights departing TYS on Friday, January 26, 2018, almost all flights are operated on regional aircraft. One of United’s flights to Newark is operated on an A319, and four of Delta’s flights to Atlanta are operated on a B717. While the A319 is a larger aircraft, the Boeing 717 is closer in size to regional aircraft, with approximately 100 seats.
While the Federal Aviation Administration forecasts the regional carrier fleet to decline from 2,156 aircraft in 2016 to 2,027 in 2037, this reduction is mainly due to the removal of smaller 50-seat regional jets as well as outdated turboprop and piston aircraft. However, even though overall numbers decline, the number of jets in regional carrier fleets is expected to be up from 1,637 in 2016 to 1,828 in 2037. It is important to note these numbers do not include Embraer planes (another type of regional aircraft) at JetBlue, which is not a regional carrier. The numbers also do not include Embraer planes that are operated by American Airlines as mainline carrier service. The number of these regional planes will grow in the future, as part of an industry-wide projected increase of 37 narrow body planes per year until 2037.18

As the number of regional aircraft, such as the CRJ, grows in the future and as they are utilized more frequently, it is important to be aware of the events that happened in Phoenix. While still infrequent at this time, a similar occurrence could likely happen again soon in the future, so both the aerospace and the airline industry need to consider how extreme heat affects this type of aircraft and develop mitigation plans for these occurrences.
Not Just Regional – How Heat Significantly Affects Large Aircraft: Part I

While the discussion so far has focused on regional aircraft, it is important to understand that heat also significantly impacts non-regional aircraft. Understanding why and how is vital, especially since non-regional jets make up the majority percentage of the US carrier fleet and are expected to increase in the future. Larger, narrow-body and wide-body aircraft, consisting of Airbus, Boeing, and McDonnell Douglas, have higher operating temperatures, so they are probably not going to be cancelled due to temperatures exceeding their overall temperature limitation. However, thousands, if not tens-of-thousands, of flights each year are subjected to weight restrictions resulting from high temperatures. Every plane has a maximum takeoff weight, but very frequently, they are subject to additional weight restrictions for a variety of reasons such as the length of runways (the shorter, the worse), the altitude of the airport (the higher, the worse), and temperatures (the hotter, the worse). Sometimes the weight of an aircraft before takeoff (sufficient fuel, high passenger load factor, cargo, etc.) exceeds effective weight restriction, and the aircraft must be made lighter before it is allowed to fly. The majority of the time, passengers and their luggage must be removed from the aircraft. Airline operations and strategy must account for these weight restrictions and frequently have to deal with them same-day. Weight restrictions can lead to generating less revenue for the airline, having to deny a certain number of customers from boarding, having to rebook passengers, departure delays, and the inability to ship as much cargo.

As temperatures heat up, air becomes less dense, and the airport’s effective density altitude increases, which decreases aircraft performance because air molecules are spread further apart in hot weather. The Aircraft Owners and Pilots Association describes how higher temperatures, and thus a higher density altitude, affect flight:
“The aircraft will accelerate more slowly down the runway, will need to move faster to attain the same lift, and will climb more slowly. The less dense the air, the less lift, the more lackluster the climb, and the longer the distance needed for takeoff and landing. Fewer air molecules in a given volume of air also result in reduced propeller efficiency and therefore reduced net thrust.”

Even though PHX is 1,134.6 feet above sea level, on June 20, 2017 at 15:51, planes departing Phoenix took off as though they were already at an elevation of approximately 5,707.96 feet (an increase of 4,233.36 feet; see Appendix C for calculation). This increase means the effective maximum takeoff weight of the aircraft is decreased. Just because it is affected does not necessarily mean that an effective weight restriction always results in the removal of passengers, but it certainly is possible. Density altitude can be more of an issue at airports with already much higher elevations, such as Denver International Airport (DEN), which is located at 5,433.8 feet above sea level.
Phoenix Case Study Continued

Let us take another look at Phoenix Sky Harbor International Airport the day of June 20, 2017. We have thoroughly analyzed the regional jet flights that were cancelled, but now, let’s analyze flights that were subject to weight restrictions due to the heat constraint. According to information from Boeing, Boeing 737s at PHX are subject to a 1,000 lb (454kg) weight reduction at 38°C (100.4°F) and a 10,000 lb (4536kg) weight reduction at 47°C (116.6°F). Cross-referencing temperature data from Weather Underground and flight data from the Bureau of Transportation, we can see the number of flights scheduled to operate with the B737 that had a weight restriction implemented. The number could actually be higher, however, because there were 14 flights that day where the type of aircraft information was not available, so some of these planes could potentially be B737s.

<table>
<thead>
<tr>
<th>Time</th>
<th>Temperature °F</th>
<th>1,000 lb reductions</th>
<th>10,000 lb reductions</th>
</tr>
</thead>
<tbody>
<tr>
<td>09:51</td>
<td>104.0</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>10:51</td>
<td>108.0</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>11:51</td>
<td>108.0</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>12:51</td>
<td>111.9</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>13:51</td>
<td>116.1</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>14:51</td>
<td>118.0</td>
<td></td>
<td>11</td>
</tr>
<tr>
<td>15:51</td>
<td>118.9</td>
<td></td>
<td>7</td>
</tr>
<tr>
<td>16:51</td>
<td>118.0</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>17:51</td>
<td>118.0</td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>18:51</td>
<td>117.0</td>
<td></td>
<td>19</td>
</tr>
<tr>
<td><strong>20:51</strong></td>
<td>109.0</td>
<td><strong>17</strong></td>
<td></td>
</tr>
<tr>
<td><strong>21:51</strong></td>
<td>105.1</td>
<td><strong>4</strong></td>
<td></td>
</tr>
<tr>
<td><strong>22:51</strong></td>
<td>102.9</td>
<td><strong>2</strong></td>
<td></td>
</tr>
</tbody>
</table>

(Sources: Weather Underground² & Bureau of Transportation³)

A total of 122 Boeing 737 flights departing PHX that day were subjected to weight restrictions. Most of these flights affected were on Southwest since the airline solely operates this type of plane, but Alaska Airlines, Delta Air Lines, and United Airlines also had flights affected. Some of the planes might not have been realistically affected for a variety of reasons. The plane might not have had a high load factor, or the flight route could have been relatively short, meaning the aircraft was not near max capacity of fuel. However, it is safe to assume that
some of the aircraft were realistically affected. Load factors on other planes might have been very high (this data is not publically available) and/or the route could be long, and subsequently, a larger amount of fuel onboard. On June 20, 2016, the longest route on a B737 was a distance of 2,153 miles – a flight from PHX to JFK.

Of the 122 weight restricted flights, 52 (see Appendix B for full list) were at least 15 minutes late in their departure (flights that had a late aircraft delay that was the same as departure delay were factored out of this calculation). Flights are still considered “on-time” if they depart within 15 minutes of the time in the airline’s computerized reservation system (CRS). Flight delays can be attributed to a wide variety of factors, and unfortunately, there is no way to know the specific reason behind the delay. However, one way a flight is delayed is if the airline must deal with a larger number of passengers than the plane can effectively depart with. I am not suggesting we should assume all 52 delays were caused because of heat, but I believe it is highly likely that a decent number of the aircraft were delayed because the weight restrictions resulted in the airline being unable to seat all of their passengers and dealing with the subsequent obstacle of handling the over-capacity passenger situation.

Assuming some of the delays were due to heat weight restrictions, the effects of the high temperatures that day cost the airlines money. When an airline is unable to seat all of their passengers, they usually accommodate them on a different flight (sometimes even on a different airline), and sometimes “buy off” passengers, which both cost money. Sometimes airlines have a structured priority list of who they have the right to refuse seating (i.e. last people to ‘check-in’ for their flight, people who purchased ‘basic economy’ fares with a large number of restrictions), but other times, airlines will offer travel vouchers, which can vary in amount, to passengers who agree to give up their seat and wait for a later flight.

Regardless of the cause of the delay, delays cost money. According to Airlines for America, the direct aircraft operating cost per block minute was $62.55 in 2016, so each minute a plane is delayed, the cost quickly adds up.21

<table>
<thead>
<tr>
<th>Crew - Pilots/Flight</th>
<th>Fuel</th>
<th>Maintenance</th>
<th>Aircraft Ownership</th>
<th>Other</th>
<th>Total Direct Operating Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>$21.24</td>
<td>$18.44</td>
<td>$12.01</td>
<td>$8.06</td>
<td>$2.80</td>
<td>$62.55</td>
</tr>
</tbody>
</table>

(Source: Airlines for America)21

The total delayed minutes of these 52 flights adds up to a sum of 2,008 minutes, so according to Airlines for America’s 2016 numbers, the cost of these delayed flights tallies up to $125,600.40. This figure is obviously significant and concerning, and it only represents one day at one airport with one type of aircraft. Furthermore, delays occur every day. While obviously not all of this cost is attributable to the effects of extreme heat, some of it is, and incidents of weight restrictions due to heat are only expected to grow in the future.
**How Heat Significantly Affects Large Aircraft: Part II**

A few different studies have begun to analyze the current effects and to predict the future of how climate change will affect aircraft operations. As mean temperatures continue to rise, so will the number of aircraft subject to weight restrictions. Each airport will be affected differently, and some airports that are at a high elevation, such as DEN, or that have shorter runways, such as LGA, might see greater affects since their geography and layout already present a restriction itself. Coffel and Horton describe:

“For a given runway length, airport elevation, and aircraft type, there is a temperature threshold above which the airplane cannot take off at its maximum weight and thus must be weight restricted. The number of summer days necessitating weight restriction has increased since 1980 along with the observed increase in surface temperature… These changes will negatively affect aircraft performance, leading to increased weight restrictions, especially at airports with short runways and little room to expand. For a Boeing 737-800 aircraft, it was found that the number of weight-restriction days between May and September will increase by 50%-200% at four major airports in the United States by 2050-70 under the RCP8.5 emissions scenario.” (p. 94)

Coffel and Horton analyze B737-800 (426,789 B737-800 flights in 2013) temperature thresholds at PHX because of its high summer temperatures, DEN because of its high elevation, in addition to both LGA and DCA, which have shorter runways, little-to-no room for expansion, and a large amount of traffic. The temperature modeling they use projects “significant increases in temperature by midcentury.” After accounting for the weight of the aircraft, there are 82,900 lbs available for fuel, passengers, and cargo on the B737-8. For a cross-country route on this aircraft, fuel will be near capacity, weighing in at 46,000 lbs. “A 15,000 lb weight restriction represents approximately 30% of the payload capacity of the aircraft,” which translates into 79 less passengers (52 less for 10,000 lb and 5 less for 1,000 lb, based on their calculations).

It is important to note, however, that the weight restriction might not necessarily equate to this number of passengers being removed from the aircraft. One other factor to consider is what is in the cargo hold. Just because a weight restriction exists does not necessarily mean that the plane is over the weight limit (low load factor, little cargo other than passenger’s bags, shorter route meaning less fuel, etc.) Furthermore, when a “payload is reduced, less fuel is required to carry that payload, and less still is required to carry that reduced fuel load.”

According to Coffel and Horton, the “mean partitioning of a weight restriction for a Boeing 737-800 [is] 83% payload and 17% fuel.”
Looking at the daily temperature maximums for June, July, and August of 2017, we can see how many instances of weight restrictions (and their severity) occurred at the four airports from Coffel and Horton’s study. Since we are looking at daily maximums, planes were not necessarily weight restricted the entire day, but at some point in time during the day, weight restrictions were implemented.

Appendix D contains a copy of Coffel and Horton’s weight restriction projection graphs. As shown by their research, the number of days where weight restrictions will be implemented on B737s at these four airports will significantly increase (as much as 100-300%), and in turn, significantly affect aircraft operations and airline revenues.

The Boeing 737 is a very popular aircraft type because of its medium size and efficiency (even more efficient with the new Boeing 737 MAX). In fact, according to Boeing, the B737 is “the best-selling commercial jetliner in history” and now holds a Guinness World Record for being the “most produced commercial jet aircraft model.” Thus, it is reasonable to assume that the 737 is not going anywhere, so as we look to the future, it is important to understand how heat affects the 737. However, heat affects more than just the 737, and Coffel and Horton, along with Thompson, expanded upon their research to analyze the effects on other aircraft types and at more

---

### B737-800 Temperature Thresholds

<table>
<thead>
<tr>
<th>Airport</th>
<th>2013 Flight #s</th>
<th>1,000-lb reduction</th>
<th>10,000-lb reduction</th>
<th>15,000-lb reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHX</td>
<td>180,044</td>
<td>100.4</td>
<td>116.6</td>
<td>127.4</td>
</tr>
<tr>
<td>DEN</td>
<td>267,649</td>
<td>Always</td>
<td>86</td>
<td>98.6</td>
</tr>
<tr>
<td>LGA</td>
<td>163,883</td>
<td>Always</td>
<td>87.8</td>
<td>91.4</td>
</tr>
<tr>
<td>DCA</td>
<td>137,262</td>
<td>Always</td>
<td>87.8</td>
<td>91.4</td>
</tr>
</tbody>
</table>

*Temperatures in Fahrenheit

(Source: Coffel and Horton)

---

### Number of Days of B737 Weight Restriction

<table>
<thead>
<tr>
<th>Airport</th>
<th>2017</th>
<th>1,000 lb</th>
<th>10,000 lb</th>
<th>15,000 lb</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHX</td>
<td>June</td>
<td>27</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>PHX</td>
<td>July</td>
<td>28</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>PHX</td>
<td>August</td>
<td>29</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DEN</td>
<td>June</td>
<td>Always</td>
<td>13</td>
<td>1</td>
</tr>
<tr>
<td>DEN</td>
<td>July</td>
<td>Always</td>
<td>26</td>
<td>3</td>
</tr>
<tr>
<td>DEN</td>
<td>August</td>
<td>Always</td>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>LGA</td>
<td>June</td>
<td>Always</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>LGA</td>
<td>July</td>
<td>Always</td>
<td>12</td>
<td>4</td>
</tr>
<tr>
<td>LGA</td>
<td>August</td>
<td>Always</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>DCA</td>
<td>June</td>
<td>Always</td>
<td>15</td>
<td>5</td>
</tr>
<tr>
<td>DCA</td>
<td>July</td>
<td>Always</td>
<td>22</td>
<td>13</td>
</tr>
<tr>
<td>DCA</td>
<td>August</td>
<td>Always</td>
<td>11</td>
<td>1</td>
</tr>
</tbody>
</table>

---

22
23
airports (see Appendix D for a copy of their notable projection graphs). They predict the Boeing 777-300 and Boeing 787-8 will feel the effects of weight restriction the most (fuel and payload reduction of 3-5% and 30-40% of flights experiencing a restriction).  

Number of Days of Weight Restrictions

**B737-800 at LaGuardia Airport (LGA)**

**B787-8 at Denver International Airport (DEN)**

**Boeing 777-300 at Dubai International Airport (DXB)**

(Source: Coffel, Thompson, and Horton)
**Additional Effects of Heat on Aviation**

In addition to weight restrictions, heat also affects aviation through increasing turbulence, changing the length of flight times, and even threatening the operations of airports near the sea. The International Civil Aviation Organization (ICAO), which is part of the United Nations, identifies many of the impacts associated with climate change:

<table>
<thead>
<tr>
<th>Climate risk</th>
<th>Impact</th>
</tr>
</thead>
</table>
| Precipitation change | - disruption to operations e.g. airfield flooding, ground subsidence  
- reduction in airport throughput  
- inadequate drainage system capacity  
- inundation of underground infrastructure (e.g. electrical)  
- inundation of ground transport access (passengers and staff)  
- loss of local utilities provision (e.g. power). |
| Temperature change | - changes in aircraft performance  
- changes in noise impact due to changes in aircraft performance  
- heat damage to airport surface (runway, taxiway)  
- increased heating and cooling requirements  
- increased pressure on local utilities e.g. water and power (for cooling). |
| Sea-level rise | - loss of airport capacity  
- impacts on en-route capacity due to lack of ground capacity  
- loss of airport infrastructure  
- loss of ground transport access  
- convective weather: disruption to operations  
- convective weather: route extensions  
- jet stream: potential increase in en-route turbulence  
- local wind patterns: potential disruption to operations and changes to distribution of noise impact  
- disruption to operations, route extensions  
- disruption to ground transport access  
- disruption to supply of utilities |

(Graphic from ICAO)²⁴

Williams completed research that suggests climate change increases the prevalence of transatlantic wintertime clear-air turbulence. Estimates show that there are over 63,000 encounters with moderate turbulence and 5,000 encounters with severe turbulence. The effects
(passenger/crew injuries, aircraft damage, inspections, investigations, delays, etc.) from this turbulence can tally up to **$200 million per year**. Furthermore, “flight paths could become more convoluted, lengthening journey times and increasing fuel consumption and emissions” because pilots often try to avoid turbulence.25

Williams also completed another study examining transatlantic flight times (between Heathrow Airport (LHR) in London and John F. Kennedy International Airport (JFK) in New York) and their relationship with climate change. The results of his study indicate that jet-stream winds will increase, meaning eastbound flight-times will shorten while westbound flight times will increase; however, the shortening of eastbound flights does not mitigate the longer westbound flights, so the round-trip time will actually increase.26 This extra time means:

> “Even assuming no future growth in aviation, the extrapolation of our results to all transatlantic traffic suggests that aircraft will collectively be airborne for **an extra 2000 h** each year, burning an **extra 7.2 million gallons of jet fuel at a cost of US$ 22 million, and emitting an extra 70 million kg of carbon dioxide.**” (p. 7)26

Karnauskas and others also examined flight times and climate and noted the interdependence of climate change and flight time:

> “In particular, radiatively forced changes in circulation have the potential to influence the rate of consumption of fossil fuels by the airline industry (initially by up to a few percent), thus feeding back onto the global radiative forcing and resultant changes in circulation. Central to this feedback is the residual dependence of total flying time on flight-level winds, the dynamics of which warrant further investigation.” (p. 1072)27

The ICAO has discussed how heat and the subsequent rise of the average global sea level will affect airports. They also provide a case study examining how the Brisbane Airport (BNE) in Australia accounted for and did their best to mitigate climate change affects in its airport planning and construction. The airport location is near the coast, is subject to flooding, and experiences a subtropical climate, and airport planners took these factors into account when designing and constructing a new runway.

> “The rise in globally averaged sea level, through increased melting of ice sheets and glaciers and also thermal expansion of the oceans, is well understood and documented. Coupled with rising sea levels, storm surges linked to more intense extra-tropical cyclones may threaten the viability of low-lying airports at coastal locations unless protective measures are taken. These effects are likely to be exacerbated through very intense precipitation episodes linked to these storms, which can lead to excess flooding where run-off collides head-on with storm tides.” (p. 205)24
Whether it be the Canadair Regional Jet or the Boeing 737, the Phoenix International Airport or LaGuardia Airport, or one of the other effects we have discussed, it is clear that heat has a number of wide-ranging effects on aircraft, airports, and airlines. As temperatures, as well as air traffic, are expected to increase in the future, it is important to understand how heat affects aviation and how to best mitigate the negative effects. There are a number of potential solutions that will help alleviate the issues of heat, but these solutions also include challenges that might make their implementation very difficult, or even near-impossible.

The following solutions that will be discussed include increasing runway lengths, adjusting airport routing, swapping aircraft on routes, adjusting departure times, improving aircraft design, and decreasing on-board weight.
Potential Solution: Increasing Runway Lengths

As previously noted, each airport has their own weight restriction thresholds due to their specific elevation and runway lengths. In places such as LGA and DCA, where runway lengths are shorter, some weight restrictions are always in place because the plane does not have sufficient time to reach takeoff speed. In other locations, such as DEN, weight restrictions are in place because of the higher altitude. Trani concludes that a Boeing 737-800 needs an additional 94% more runway at airports that are 8,000 feet above sea level than airports located at sea level with a typical weight of 155,000 lb. Furthermore, the same aircraft needs 18% more runway at sea-level airports when the temperature increases 25 °C.\(^{28}\) We focus on takeoff length requirements as opposed to landing length requirements because less length is needed for a plane to land. Looking at Boeing’s takeoff runway length requirements on a standard day (59 °F at sea level) vs. a day that is 27 °F warmer, we can see how a plane needs more runway in order to take off. For example, using Boeing’s charts\(^{29}\) (see Appendix E), on a day that is 27 °F warmer than the standard day, a Boeing 737-400 (an older version, but its graphics are better for visualization) with a weight of 130,000 pounds and departing an airport at 4,000 feet would require approximately 350 more feet of runway (~7,800 feet vs. ~8,150 feet). The FAA also provides examples on calculating runway lengths and mentions factors to consider in runway length design such as wind, runway surface conditions, difference in centerline elevation, temperature, operating weights, airport elevation, and airplane type.\(^{30}\)

Using data from the Air Cyber Alliance,\(^{31}\) we can examine the distribution of airports’ maximum runway length (note: unsure of date of data; potentially outdated). The longest runway is DEN at 16,000 feet, and the shortest is Compton/Woodley Airport (CPM) at 3,322 feet.
In some locations, current runways may be able to be extended or longer runways constructed. For example, the ICAO completed a case study of the Brisbane Airport, which noted that:

“Consideration of temperature increases in future decades was automatically accounted for in the ultimate length planning for both the existing runway and for the new runway, each of which has significant additional lengths available to be added in the future.” (p. 215)\(^{24}\)

McGhee Tyson Airport in Knoxville, Tennessee is currently undergoing a $108 million project to extend its 9,005 foot runway another 1,000 feet, among other projects such as updating and modernizing the airport and its taxiways/runways. The goal of the runway expansion is to attract more long-distance flights,\(^ {32}\) but the expansion will simultaneously alleviate the issue of some possible weight restrictions since the runway will be longer. As we can see via the map, TYS has room to expand its runways.

(Source: Google Maps)

It is not necessarily easy to simply expand a runway because there are many potential challenges and obstacles. First, expansions and construction cost money. Grants can be available; TYS received a $27.9 million grant from the FAA for its projects.\(^ {32}\) Second, regulations exist and government approvals may be needed. There might exist noise regulations, no-fly zone regulations, and safety regulations. Furthermore, if the airport doesn’t already own the land
where it could potentially expand, it must first purchase and acquire the land. Runways also must include a runway safety area (RSA) to mitigate against an “undershoot, overshoot, or excursion from the runway” of an airplane. The RSA ranges from 240 to 1,000 feet in length. The Brisbane Airport expansion project was “subject to numerous legislated planning conditions and approvals; involve[d] detailed stakeholder engagement; and, pose[d] a range of construction and operational challenges.” It was finally approved in 2007 after submitting and receiving approval on a “comprehensive” Environmental Impact Statement and Major Development Plan. Another example of a regulation challenge is the case where plans to expand the Wellington International Airport (WLG) in 2017 were blocked by the New Zealand Supreme Court over safety concerns.

In addition to these challenges, airports need to actually have room to expand. Airports very close to big cities and/or near water can be very limited when it comes to space. LaGuardia Airport (LGA) has utilized all of its runway space, as can be seen by the map to the left below.

Ronald Reagan Washington National Airport (DCA) also appears to have no more room for runway expansion. They actually did maneuver through costs and challenges to expand one of their runways in 2013, although the length ultimately remained the same because they had to remove some of the runway on the opposite end. Because Runway 15-33 failed FAA safety standards, the project had to be completed, and 24 alternatives were considered before deciding on this project. Some 4.51 acres of the Potomac River were filled to pave over in order to make up for removing part of the opposite end of the runway, which was part of the $7.16 million project. Part of that land was transferred from the National Park Service to the FAA for the project, which was going to “adversely impact approximately 1.94 acres of NPS-managed...
riverine tidal wetlands.” In response, the airport had to pay another $2.5 million to fund a restoration project.35

DCA Runway Project

(Source: Washington Business Journal)35

Even if there were room for runway expansion does not necessarily mean it would mitigate weight restrictions. According to Coffel and Horton, the Denver International Airport runways are “sufficiently long [16,000 feet], but the required takeoff speed would exceed the maximum tire speed of 225 mph (Boeing 2013).”20 Tire speed is just one more limitation to take into consideration.

Phoenix Sky Harbor International Airport (PHX), which has been a focus airport throughout this paper is land-locked by the city and river and thus is unable to expand.

(Source: from Google Maps)
Potential Solution: Changing Flight Route Structure

In addition to increasing runway lengths, a few potential solutions are to adjust flight paths, temporarily change the type of plane that flies out of a certain airport, or adjust flight departure times. However, these three options face their own significant obstacles.

Adjusting Airport Routing

In many cities, especially larger ones, there are multiple airports in relatively close proximity to one another. Ronald Reagan Washington National Airport (DCA) and Dulles International Airport (IAD) are only a driving distance of 29.1 miles from each other, according to Google maps. IAD has a runway that is much longer than DCA (11,500 feet vs. 7,169 feet). LaGuardia Airport (LGA) and John F. Kennedy International Airport (JFK) are only a driving distance of 9.6 miles, according to Google, and both of these airports are only a little over 30 miles away from Newark Liberty International Airport (EWR) in New Jersey. JFK has a runway length of 14,511 feet and EWR has a runway length of 11,000 feet, compared to LGA’s 7,003 feet. Therefore, one option could be for airlines to alter their departures during hotter months to favor airports with the longer runways.

However, airlines have a very well developed structure at their current airports, with facilities, contracts, fees, personnel, etc., and passengers also might only want to leave from a specific airport. Other cities don’t have another airport option, and even with cities that do, the other option might not be any better: runways might not be as long, capacity might already be full, infrastructure might not allow for mass influx of capacity, etc. For example, Phoenix-Mesa Gateway Airport (AZA) is a little over 30 miles from PHX, but its runways are not as long as PHX, and the only airlines currently serving AZA are Allegiant alongside a seasonal service from WestJet. DEN’s runways are sufficiently long but plane tire speeds would exceed their max speed, as discussed earlier.

Most airports, especially in big cities, are already operating near or at capacity and would not be able to handle an influx of more flights. JFK is a perfect example of an airport already at capacity. It serves as a focus city for JetBlue and is a hub for both American Airlines and Delta Air Lines, in addition to multiple cargo airlines. It sees hundreds of flights per day, and according to a capacity analysis completed by the FAA in 2014, it is right at its max capacity. JFK felt the effects of operating near max capacity during the Bomb Cyclone, the winter storm that hit the Northeast in January of 2018. Many planes had to sit on the Tarmac full of passengers for hours because all of the gates were full. For example, An AirChina flight was “stranded” on the tarmac for seven hours.

While the option of altering flight routes exists, it would be extremely difficult. Not only are several airports near capacity, trying to simultaneously alter airport contracts, personnel, operations, ticketing, etc. would be extremely difficult, if not impossible, therefore making this potential solution not viable.
Swapping Aircraft

A different option that is much simpler and easier than changing airport destinations/departures is altering the type of aircraft that is flown on a particular route. However, to do this well requires some advanced planning. Last minute swaps are still possible, but forecasting methods should be used to determine plane swaps in advance.

Different planes have different characteristics – for example, some planes and their particular engines can generate more thrust and lift than other types of aircraft. Coffel and Horton note that “airlines may need to allocate summertime cross-country flights to aircraft with better takeoff performance, such as the 757 today or perhaps a new aircraft in the future.”

According to Patrick Smith, a Boeing 757 pilot, “the 737 falls way short of the 757 in terms of runway performance. The 737 requires a much higher takeoff speed and much more runway to get off the ground.”

After interviewing Vasu Raja, American Airlines Vice President of Planning, for an article about American Airlines and long-haul routes, Brian Sumers discusses:

“American may also use the ‘wrong’ airplane if it needs better performance characteristics. The Airbus A319 and Boeing 757 have more power than the rest of the fleet, and they can take off at hot and high airports with full payloads. You might see American fly an A319 to some Rocky Mountain destinations, even if the smaller Embraer 175 is a better fit by seat count.”

According to Raja, “American’s schedule is mostly locked 120 days before departure. If you buy an American ticket within 120 days of departure, your flight probably won’t change at all. It will depart at the same time, and on the same plane, as American promised when you bought your ticket… But beyond 120 days, all bets are off. If you buy a ticket for seven or 10 months from now, you’re buying an estimate – a flight American intends to fly, but isn’t locked into.”

(Source: FAA)
*Note: These quotations did not make the final cut of the article because the article was about long-haul flights, but this excerpt was included in an email with additional sentences from Sumer’s discussion with Raja.

When deciding on aircraft route swaps in anticipation of higher heat, airlines must consider the specific limitations and restrictions of the aircraft (range, capacity, performance, etc.), the number of that type of plane in the fleet and its availability, how the swap affects other route structures, difference in class types and number of seats, etc. There’s a common saying: the only way planes make money is if they are in the air. Flight routing is very similar to a “puzzle,” and all the pieces need to fit together as efficiently and effectively as possible. The further in advance airlines can plan for an alteration, the easier it will be to implement.

United Airlines states on their website that flight schedules are published “up to 11 months in advance,” but “may make some adjustments to accommodate changes to aircraft and routes.” One of the adjustment reasons is “changes to type of aircraft.”

One reason it is easier to alter aircraft routes earlier rather than later is to not have to rebook or downgrade first class passengers. The further out from the flight date, the less likely the flight is to be nearing capacity. Even if one route is upgraded to a larger plane, the smaller plane that was originally on this route will likely be used on a different route. We can see seating differences between the American Airlines Boeing 737 vs. 757 and Embraer 175 vs. Airbus A319 in the following tables.

<table>
<thead>
<tr>
<th>AA Boeing 737-800 V1</th>
<th>AA Boeing 757-200 Domestic</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Class</strong></td>
<td><strong>Pitch</strong></td>
</tr>
<tr>
<td>First</td>
<td>40</td>
</tr>
<tr>
<td>Main Cabin Extra</td>
<td>35-37</td>
</tr>
<tr>
<td>Economy</td>
<td>31</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>AA Embraer ERJ-175 V1</th>
<th>AA Airbus A319 V1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Class</strong></td>
<td><strong>Pitch</strong></td>
</tr>
<tr>
<td>First</td>
<td>37</td>
</tr>
<tr>
<td>Main Cabin Extra</td>
<td>34</td>
</tr>
<tr>
<td>Economy</td>
<td>30</td>
</tr>
</tbody>
</table>

(Source: Seat Guru)

One additional obstacle to consider with aircraft route restructuring is fleet availability. According to PlaneSpotters.net, American only has 34 B757s compared to 309 B737s. Delta has 127 B757s compared to 178 B737s. United has 77 B757s compared to 329 B737s. Southwest is unable to switch from a 737 to a 757 because their fleet is comprised exclusively of B737s.
Adjusting Departure Times

In addition to adjusting aircraft route structures, airlines can alter departure times. At busier airports such as JFK, which we examined earlier, adjusting flight times is more difficult because the airport is near or at capacity, and the maximum number of planes are already taking off and landing most of the day. Also, at a hub airport, an airline is going to have several flights departing most hours of the day, and they need that frequency. Another issue to be aware of is the issue with flight frequency. Flights are offered at different times of the day for customer convenience and to allow for consumer choice. Moving flight times from certain parts of the day due to heat restricts some of this consumer choice and can cause more of an inconvenience for the passenger. Furthermore, restricting flight times can make it harder for the ‘puzzle’ pieces to come together to maximize flying (and subsequently, revenue-earning) time of an airline’s aircraft.

One airline that flies in and out of McCarran International Airport in Las Vegas chose this flight departure time solution, and another cancelled their flights altogether this past summer. Chinese airline, Hainan Airlines, moved their departure for Beijing from 2:10pm to 1:10am. They were forced to leave cargo in Las Vegas (they chose this option as opposed to removing passengers) in order to take off in the afternoon, “resulting in hefty financial penalties.” Hainan resumed the afternoon departure time in October, when daily temperatures did not reach as high as the hotter summer months. In the summer, airport officials worked to keep some employees, especially those fluent in Chinese, there later and concessions open longer to accommodate this late-night/early-morning departure. Because of frequent “hourslong delays” due to heat, Norwegian Air Shuttle suspended their service between Europe and Las Vegas at the end of March and resumed “seasonal service” in November.42
Potential Solution: Changes and Improvements in Plane Structure and Technology

Over the years, many technological innovations have vastly improved the performance of aircraft. As we look towards the future, further innovation and improvements can help mitigate the effects of higher temperatures. While newer planes might include advancements that increase their performance in hotter weather, commercial planes remain in service for multiple decades. For example, the MD-80, whose production ended in 1999, is still in service by American and Delta. Therefore, older planes will take a long time to phase out and will still be an issue in times of high heat. However, some modifications can be made during retrofitting of aircraft to improve their performance immediately, such as installing winglets on older B737s.

Improving Aircraft Design

Engines can be designed to generate more thrust. However, as Coffel and Horton note, engines and planes are designed for one another, so “a new generation of engines cannot be installed on existing aircraft without significant effort.” Business Insider writes:

“Since its introduction in the 1960s, Boeing has been installing larger and larger engines on the 737 as the size of the plane grew. Unfortunately, the amount of room underneath the wing hasn’t changed. Thus, Boeing has all but maxed out on the size of the engines it can mount on the 737 without completely redesigning the plane’s under carriage.”

Advancements can be made to increase the maximum takeoff speed of airplane tires. As we saw earlier, at some airports, planes have sufficient runway length to achieve a higher speed for takeoff, but this higher speed would exceed the maximum tire speed.

Engineers could create new wing designs to generate better lift. For example, maybe improvements exist in flaps and ailerons. Another example of an actual new wing design in practice is the Boeing 777X. This aircraft has not been delivered for commercial service yet but is expected to be within the next couple of years. As Boeing describes, “the 777X will be the largest and most efficient twin-engine jet in the world, unmatched in every aspect of performance.” This new aircraft has long composite wings, which are lighter, more efficient, better aerodynamically, and require less fuel. The wings are actually so long, that the 777X would not be able to operate at some of the same airports that the 777 can because of gate limitations. Boeing wanted to maintain its airport compatibility, so their engineers developed a safe way for the wingtips to be folded up while on the ground at the gate and to be fully down during flight.

Lighter planes could potentially mitigate the effects of heat in the future. The Boeing 787 is mainly composed of composite fiber materials, making it much lighter than other aircraft. However, as we saw from the Coffel and Horton study earlier, the B787 is projected to have
some of the most weight restrictions in the future. Unfortunately, the heat-lift problem may still exist even with wing, engine, and structural improvements because Coffel and Horton describe:

“The wings of commercial aircraft are designed to be most efficient at high speeds, since the vast majority of flight time is spent in cruise. There is a trade-off between high speed efficiency and low speed lift generation, and both cannot generally be increased together.”

“Changes in technology will no doubt revolutionize the aviation industry in the next 50 years. Carbon fiber structures will make aircraft lighter and new engines will produce more thrust with less fuel. However, these changes do not inherently result in better takeoff performance – aircraft manufacturers may need to prioritize this in the future.” (p. 99)\(^{20}\)

**Boeing 777X wing length**

![Boeing 777X wing length](image)

(Source: Boeing)\(^{35}\)

**Decreasing On-Board Weight**

What can airlines do right now to help prevent weight restrictions from causing them and their passengers headaches? American, Delta, United, and other airlines are all changing their strategy in regard to how they offer in-flight entertainment options. Many planes nowadays are wired with screens/monitors on the back of each seat to keep passengers entertained during flight. However, so many passengers bring their own devices such as phones and tablets on board, that these on-board devices seem unnecessary. The system of screens and wiring costs money, requires maintenance, and takes up a fairly significant amount of weight. Now that in-flight internet connectivity has significantly improved, airlines are strategically offering this
better internet service instead of focusing on on-board screens. Passengers can access a library of movies, TV shows, music, games, etc. offered by the airline via their own smart device, in addition to browsing the internet.

American Airlines estimates 90% of its passengers bring their own devices on board. These seatback screens will begin disappearing with their 100 new Boeing 737 Max planes. The company contends, “It makes sense for American to focus on giving customers the best entertainment and fast connection options rather than installing seatback monitors that will be obsolete within a few years.” United is also going to phase-out seatback screens in their single-aisle jets. It is likely the airlines will keep seatback screens on their long-haul jets, however.46 WestJet Airlines is also eliminating seatback screens, in an effort to eliminate an estimated 1,200 pounds from their aircraft’s weight.47 The seatback screens not only take up weight and become “technologically obsolete” relatively quickly, but they also can cost approximately $10,000 per seat, according to one transportation consulting firm.48 With regards to the weight aspect, the less weight taken up by IFE (inflight entertainment) devices, the more ‘wiggle-room’ an airline has to keep more passengers on board during a weight restriction. The Points Guy, a popular airline travel blog, describes one instance of how weight and fuel is saved by eliminating IFE devices:

“Airlines benefit from getting rid of built-in screens, too: Passing the device obligation from the carrier to the passenger decreases airline overhead and aircraft downtime. When Lufthansa began offering its wireless IFE solution, BoardConnect, the airline discovered it could reduce weight by decreasing the amount of equipment carried aboard. For the four-engine Airbus A340-600 carrying up to 380 passengers, the reduction in weight allowed the aircraft to save 47 metric tons (that is, roughly 103,617 pounds) of fuel per year. The technical wing of the German carrier noted the reduced weight came from removing screens from aircraft, which also reduced maintenance… With so much money saved in fuel and maintenance, it’s no wonder airlines are pushing toward streaming IFE.”49

Delta is not quite yet ready to eliminate onboard IFE devices altogether, but they are still responding to the changing landscape, just in a different way. They are rolling out their new idea on 75 new Bombardier aircraft. “Rather than a wired, custom-designed screen, Delta would install standardized Android tablets at each seat that would wirelessly stream content from an onboard server.” This new idea would still reduce the weight from what a traditional IFE seatback system would look like.50 While structural design changes of airplanes would take a very long time to fully integrate and mitigate the effects of extreme heat, solutions such as removing IFE seatback screens is a very viable and relatively simple option that airlines can do to save weight and in effect, reduce the effect of weight restrictions. Airlines can choose this no-screen idea on their new planes, as well as retrofit older planes by briefly taking the plane out of service to remove them.
Potential Solutions Matrix

<table>
<thead>
<tr>
<th>FEASIBILITY</th>
<th>COST</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOW</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

**KEY**

1. Increasing Runway Lengths
2. Adjusting Airport Routing
3. Swapping Aircraft
4. Adjusting Departure Times
5. Improving Aircraft Design
6. Decreasing On-Board Weight
Conclusion

“This fact is true of all climate impacts: even if they can be adapted to, they still have a cost. A variety of climate impacts on the aviation industry are likely to occur in the coming decades, and the sooner climate change is incorporated into mid- and long-range plans, the more effective adaption efforts can be.”

As we have seen, heat can significantly affect the aviation industry. From cancellations of regional jets to weight restrictions of larger jets, the effect of heat is far-reaching and costs airlines millions per year, in addition to creating many headaches for passengers. As both temperatures and enplanements are expected to increase in the future, it is vital that all parties in the aerospace and airline industry realize and understand the negative effects of heat and do their best to mitigate these effects. The more aware we are of the impacts of heat on aviation, the more well-suited we are in terms of seeking feasible, cost effective solutions.

(Source: FAA)

There are a number of potential solutions available – some more viable than others, but none of the solutions are lacking challenges. The sooner airplane manufacturers and airline operators begin implementing solutions, the better. The sooner we begin coming up with ideas and solutions, the sooner we will be prepared to deal with and minimize the negative effects of heat on the aviation industry.
Appendix: A: Data Collection Example

Brief Overview of How I Collected Data to combine Flight Information and Weather Data

1. Visit this link from The Bureau of Transportation (BOT) Statistics:
   https://www.transtats.bts.gov/DL_SelectFields.asp?Table_ID=236
2. Select the desired field names and download the file.
3. Sort and filter field names as necessary.
4. Download detailed aircraft information from:
5. Reference the relevant information from this data into BOT data via a VLOOKUP function by aircraft tail number.
6. Some aircraft from the BOT data did not have information in the Aircraft Information link, but when necessary, I hard-coded WN (International Air Transport Association code for Southwest) aircraft types as 737s because Southwest only operates this type of aircraft.
8. Sort BOT data by time.
9. Sum BOT data in hour segments that correspond with Weather Underground data.
### Appendix: B: PHX B737 Flights Delayed > 15 minutes on June 20, 2017

<table>
<thead>
<tr>
<th>CARRIER</th>
<th>TAIL NUM</th>
<th>Type</th>
<th>ORIGIN</th>
<th>DEST</th>
<th>CNS</th>
<th>DEP TIME</th>
<th>DEP TIME</th>
<th>DELAY</th>
</tr>
</thead>
<tbody>
<tr>
<td>WN</td>
<td>N400WN</td>
<td>PHX</td>
<td>PHX</td>
<td>ABQ</td>
<td>935</td>
<td>953</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>WN</td>
<td>N281WN</td>
<td>PHX</td>
<td>PHX</td>
<td>SJC</td>
<td>930</td>
<td>1016</td>
<td>46</td>
<td></td>
</tr>
<tr>
<td>UA</td>
<td>N6880J</td>
<td>PHX</td>
<td>PHX</td>
<td>IAH</td>
<td>955</td>
<td>1033</td>
<td>38</td>
<td></td>
</tr>
<tr>
<td>WN</td>
<td>N904WN</td>
<td>PHX</td>
<td>PHX</td>
<td>AUS</td>
<td>1025</td>
<td>1047</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>AS</td>
<td>N323AS</td>
<td>PHX</td>
<td>PHX</td>
<td>SEA</td>
<td>950</td>
<td>1050</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>WN</td>
<td>N254WN</td>
<td>PHX</td>
<td>PHX</td>
<td>DEN</td>
<td>1120</td>
<td>1136</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>DL</td>
<td>N3741S</td>
<td>PHX</td>
<td>PHX</td>
<td>MSP</td>
<td>1130</td>
<td>1150</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>WN</td>
<td>N931WN</td>
<td>PHX</td>
<td>PHX</td>
<td>SEA</td>
<td>1135</td>
<td>1205</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>WN</td>
<td>N284WN</td>
<td>PHX</td>
<td>PHX</td>
<td>HOU</td>
<td>1155</td>
<td>1231</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>WN</td>
<td>N728S</td>
<td>PHX</td>
<td>PHX</td>
<td>BUR</td>
<td>1200</td>
<td>1252</td>
<td>52</td>
<td></td>
</tr>
<tr>
<td>WN</td>
<td>N852U</td>
<td>PHX</td>
<td>PHX</td>
<td>SFO</td>
<td>1225</td>
<td>1301</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>WN</td>
<td>N400WN</td>
<td>PHX</td>
<td>PHX</td>
<td>ABQ</td>
<td>1305</td>
<td>1332</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td>WN</td>
<td>N208WN</td>
<td>PHX</td>
<td>PHX</td>
<td>LAS</td>
<td>1315</td>
<td>1339</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>WN</td>
<td>N444WN</td>
<td>PHX</td>
<td>PHX</td>
<td>BUR</td>
<td>1325</td>
<td>1350</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>WN</td>
<td>N412WN</td>
<td>PHX</td>
<td>PHX</td>
<td>BOI</td>
<td>1415</td>
<td>1449</td>
<td>34</td>
<td></td>
</tr>
<tr>
<td>UA</td>
<td>N35430</td>
<td>PHX</td>
<td>PHX</td>
<td>ORD</td>
<td>1415</td>
<td>1510</td>
<td>55</td>
<td></td>
</tr>
<tr>
<td>WN</td>
<td>N8629A</td>
<td>PHX</td>
<td>ATL</td>
<td>1500</td>
<td>1521</td>
<td>21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WN</td>
<td>N961WN</td>
<td>PHX</td>
<td>CNT</td>
<td>1500</td>
<td>1524</td>
<td>23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WN</td>
<td>N7873A</td>
<td>PHX</td>
<td>ELP</td>
<td>1450</td>
<td>1530</td>
<td>40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WN</td>
<td>N774WN</td>
<td>PHX</td>
<td>MDW</td>
<td>1510</td>
<td>1543</td>
<td>33</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WN</td>
<td>N767WS</td>
<td>PHX</td>
<td>SLC</td>
<td>1515</td>
<td>1557</td>
<td>42</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WN</td>
<td>N753SA</td>
<td>PHX</td>
<td>LAS</td>
<td>1600</td>
<td>1622</td>
<td>22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>UA</td>
<td>N1371S</td>
<td>PHX</td>
<td>IAH</td>
<td>1557</td>
<td>1627</td>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WN</td>
<td>N7840A</td>
<td>PHX</td>
<td>NCI</td>
<td>1600</td>
<td>1631</td>
<td>31</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WN</td>
<td>N7882B</td>
<td>PHX</td>
<td>PHL</td>
<td>1710</td>
<td>1727</td>
<td>17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WN</td>
<td>N481WN</td>
<td>PHX</td>
<td>TPA</td>
<td>1710</td>
<td>1825</td>
<td>75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WN</td>
<td>N771LV</td>
<td>PHX</td>
<td>SMF</td>
<td>1810</td>
<td>1831</td>
<td>21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WN</td>
<td>N961WN</td>
<td>PHX</td>
<td>ALB</td>
<td>1830</td>
<td>1847</td>
<td>17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WN</td>
<td>N728WS</td>
<td>PHX</td>
<td>NCI</td>
<td>1830</td>
<td>1853</td>
<td>23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WN</td>
<td>N8526S</td>
<td>PHX</td>
<td>NKE</td>
<td>1835</td>
<td>1853</td>
<td>18</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WN</td>
<td>N8315H</td>
<td>PHX</td>
<td>OMA</td>
<td>1835</td>
<td>1854</td>
<td>19</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WN</td>
<td>N7604S</td>
<td>PHX</td>
<td>SFO</td>
<td>1815</td>
<td>1857</td>
<td>42</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WN</td>
<td>N8303R</td>
<td>PHX</td>
<td>BNA</td>
<td>1845</td>
<td>1904</td>
<td>19</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DL</td>
<td>N3750A</td>
<td>PHX</td>
<td>SLC</td>
<td>1848</td>
<td>1909</td>
<td>21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WN</td>
<td>N4764A</td>
<td>PHX</td>
<td>ABQ</td>
<td>1745</td>
<td>1909</td>
<td>84</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WN</td>
<td>N550A</td>
<td>PHX</td>
<td>OAK</td>
<td>1805</td>
<td>1911</td>
<td>66</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WN</td>
<td>N8632B</td>
<td>PHX</td>
<td>MDW</td>
<td>1830</td>
<td>1941</td>
<td>71</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WN</td>
<td>N644S</td>
<td>PHX</td>
<td>BUR</td>
<td>1915</td>
<td>1944</td>
<td>29</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WN</td>
<td>N918A</td>
<td>PHX</td>
<td>SJC</td>
<td>1945</td>
<td>2012</td>
<td>27</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WN</td>
<td>N940A</td>
<td>PHX</td>
<td>CNT</td>
<td>1935</td>
<td>2043</td>
<td>68</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WN</td>
<td>N751S</td>
<td>PHX</td>
<td>LAS</td>
<td>2040</td>
<td>2057</td>
<td>17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WN</td>
<td>N759S</td>
<td>PHX</td>
<td>BUR</td>
<td>2035</td>
<td>2114</td>
<td>39</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WN</td>
<td>N450A</td>
<td>PHX</td>
<td>MDW</td>
<td>1940</td>
<td>2120</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WN</td>
<td>N7742B</td>
<td>PHX</td>
<td>ABQ</td>
<td>2055</td>
<td>2122</td>
<td>27</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WN</td>
<td>N8318F</td>
<td>PHX</td>
<td>SFO</td>
<td>2050</td>
<td>2124</td>
<td>34</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WN</td>
<td>N438WN</td>
<td>PHX</td>
<td>LAX</td>
<td>2050</td>
<td>2133</td>
<td>43</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WN</td>
<td>N8640D</td>
<td>PHX</td>
<td>RNO</td>
<td>2050</td>
<td>2134</td>
<td>44</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WN</td>
<td>N273WN</td>
<td>PHX</td>
<td>SJC</td>
<td>2055</td>
<td>2135</td>
<td>40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WN</td>
<td>N425LV</td>
<td>PHX</td>
<td>SEA</td>
<td>2050</td>
<td>2137</td>
<td>47</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WN</td>
<td>N7545S</td>
<td>PHX</td>
<td>POX</td>
<td>2050</td>
<td>2139</td>
<td>49</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WN</td>
<td>N448WN</td>
<td>PHX</td>
<td>HOU</td>
<td>1925</td>
<td>2145</td>
<td>140</td>
<td></td>
<td></td>
</tr>
<tr>
<td>UA</td>
<td>N3845S</td>
<td>PHX</td>
<td>EWR</td>
<td>2230</td>
<td>2300</td>
<td>30</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(Source: Bureau of Transportation\(^3\) and Lakew\(^4\))

*Note: WN Flights with no “Type” info were listed as 737 since Southwest only operates B737s.

**AS = Alaska    **DL = Delta    **UA = United    **WN = Southwest
Appendix: C: Density Altitude Calculation

Density altitude in feet is calculated by:
Pressure Altitude in Feet + (120 * (Outside Air Temperature – Standard temperature))
Note: Temperatures in this calculation must be in degrees Celsius
Note: Standard temperature at sea level is 15°C, but it decreases ~2°C per 1,000 feet above sea level

Pressure Altitude in Feet is calculated by:
(Standard Pressure – Current Pressure Setting) * 1,000 + Field Elevation
Note: Standard Pressure = 29.92

For example, let us calculate the density altitude at PHX on June 20, 2017 at 15:51.

Temperature = 48.278°C  Pressure = 29.58in  Elevation = 1,134.6 feet

Pressure Altitude in Feet = (29.92 – 29.58) * 1,000 + 1,134.6 = 1,474.6
Density Altitude in Feet = 1,474.6 + (120* (48.278 – 13)) = 5,707.96
Note: For simplicity’s sake, we will assume standard temperature is 13°C since PHX is ~ 1,000 feet above sea level and standard temperature decreases ~2°C from 15°C every 1,000 feet.
Appendix D: Coffel and Horton Weight Restriction Projection Graphs\textsuperscript{10}

Fig. 3. Number of weight-restriction days per year in the past and future. (a),(b) PHX; (c),(d) DEN; (e),(f) LGA; and (g),(h) DCA for (left) 10,000-lb restriction and (right) 15,000-lb restriction. The black line is calculated from observations and the red line is the observed trend. The gray error bars represent the standard deviation of the number of weight-restriction days per year between the 17 CMIP5 models. Note that the historical CMIP5 data end in 2005.
Appendix: D: Coffel and Horton Weight Restriction Projection Graphs

“Weight Restriction as a function of TOW in the historical period (blue, 1985-2005) and the future (red, 2060-2080) under RCP 8.5. Weight is restriction calculated at the time of highest daily air temperature at each of the 19 selected airports and then averaged. The left column shows the percentage of flights with some weight restriction, and the right column shows the restriction as a percentage of total fuel and payload capacity. The shaded region shows +/- 1 standard deviation across 27 GCMs.”
Appendix: E: Boeing Chart – Standard Day

NOTES:
* NO ENGINE AIRBLEED FOR AIR CONDITIONING
* ZERO WIND, ZERO RUNWAY GRADIENT
* CONSULT USING AIRLINE FOR SPECIFIC OPERATING PROCEDURE PRIOR TO FACILITY DESIGN
* CFM 56–382 ENGINES RATED AT 22,000 LB SLST

3.3.15 F.A.R. TAKEOFF RUNWAY LENGTH REQUIREMENTS
STANDARD DAY
MODEL 737-400 (CFM56-38-2 ENGINES AT 22,000 LB SLST)
Appendix: E: Boeing Chart - Standard Day +27°F

NOTES:
- No engine air bleed for air conditioning
- Zero wind, zero runway gradient
- Consult using airline for specific operating procedure prior to facility design
- CFM 56-3B2 engines rated at 22,000 lb SLST

3.3.16 F.A.R. Takeoff Runway Length Requirements
Standard Day +27°F (STD + 15°C)
MODEL 737-400 (CFM56-3B2 Engines at 22,000 LB SLST)
### Effects of Extreme Heat on Aviation

**Regional Aircraft**
- Maximum operating temperature of Canadair Regional Jet: 118 °F
- 25 Cancellations due to “Weather” or “NAS”
- Cost of cancellations: $26,250
- 1,000 passengers needed to be rebooked
  - Similar experiences at McCarran International Airport in Las Vegas
- Why Use Regional Jets?
  - Higher flight frequency: ~ 3.7 flights/day
- Hub-and-Spoke system
- Service smaller markets
- Cheaper crew salaries
- Regional Jet Routes: 6 in 1990 vs. 1,091 in 2002
- Number of regional jets expected to increase ~ 12% by 2037

**Amplified Effects in the Future?**
- Will temperatures continue to increase?
  - Global mean surface temperatures have increased ~ 1.3°C above pre-industrial levels, with most of that change after 1980.
- Enplanements expected to increase ~ 40% from 2017 to 2037.

**Additional Effects of Heat:**
- Increased turbulence (can reach up to ~ $200 million/year);
- Change in jet-stream winds leading to longer flight times (putting planes airborne for another 2,000 hours, burning 7.2 million more gallons of fuel, costing $22 million and emitting 70 million more kg of carbon dioxide);
- Rising sea level threatening coastal airports.

### Appendix: E. Thesis Poster Summary

#### Number of Affected Flights at PHX Airport on 6/20/2017

<table>
<thead>
<tr>
<th>Time</th>
<th>Temperature</th>
<th>CRI Aircraft</th>
<th>Boeing 737 Aircraft</th>
</tr>
</thead>
<tbody>
<tr>
<td>09:51</td>
<td>104.0 °F</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>16:51</td>
<td>108.0 °F</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>12:51</td>
<td>113.0 °F</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>13:51</td>
<td>116.0 °F</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>14:51</td>
<td>118.0 °F</td>
<td>5</td>
<td>11</td>
</tr>
<tr>
<td>15:51</td>
<td>118.0 °F</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>16:51</td>
<td>118.0 °F</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>17:51</td>
<td>118.0 °F</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>18:51</td>
<td>117.0 °F</td>
<td>5</td>
<td>12</td>
</tr>
</tbody>
</table>

**No Temperature Data for 19:51**

#### Additional Effects of Heat:
- Increased turbulence (can reach up to ~ $200 million/year);
- Change in jet-stream winds leading to longer flight times (putting planes airborne for another 2,000 hours, burning 7.2 million more gallons of fuel, costing $22 million and emitting 70 million more kg of carbon dioxide);
- Rising sea level threatening coastal airports.

#### Higher Feasibility
- Adjust Departure Times
  - Depart at cooler parts of the day
- Challenges: decreased consumer/flight experience;
- Adjust Departure Times
  - Depart cooler parts of the day
- Challenges: decreased consumer/flight experience;
- Swap Aircraft on Routes
  - Some planes can generate more lift/hour; common solution
- Challenges: availability; different characteristics; need advanced planning, like a “twist”
- Examples: Swapping 737 for 877
- Examples: Swapping 877 for 837
- Examples: Swapping 837 for 817
- Examples: Swapping 817 for 837

#### Potential Solutions
- Adjust Airport Routing
  - Big cities with multiple airports
- Challenges: well-developed structures at current airports; different in size and runway lengths; most at already near max capacity
- Examples: None... Not viable
- Aircraft Design Improvements
  - Improve performance of aircraft
  - Challenges: planes in service for decades; cost; R&D limitations such as tire speed & engine size
- Examples: B737 windgap; more effective engines; composite 877/877x folding wingtip
- Increase Runway Lengths
  - B737 needs 18% more runway than 25 °C increase at sea-level
- Challenges: limited/no room, cost, regulations, RSA
- Examples: BNE (accounted for higher temp); 170,000 feet; DCA (~270 feet; 29.66 million)
- Adjust Departure Times
  - Depart at cooler parts of the day
  - Challenges: decreased consumer/flight experience;
- Swap Aircraft on Routes
  - Some planes can generate more lift/hour; common solution
- Challenges: availability; different characteristics; need advanced planning, like a “twist”
- Examples: Swapping 737 for 877
- Examples: Swapping 877 for 837
- Examples: Swapping 837 for 817
- Examples: Swapping 817 for 837

#### Decrease On-Board Weight
- Less effects of weight restriction
- Challenges: Designs already tried to minimize weight
- Examples: Many phasing out IFE systems & enhancing Wi-Fi

#### Lower Feasibility
- Adjust Airport Routing
  - Big cities with multiple airports
- Challenges: well-developed structures at current airports; different in size and runway lengths; most at already near max capacity
- Examples: None... Not viable
- Aircraft Design Improvements
  - Improve performance of aircraft
  - Challenges: planes in service for decades; cost; R&D limitations such as tire speed & engine size
- Examples: B737 windgap; more effective engines; composite 877/877x folding wingtip
- Increase Runway Lengths
  - B737 needs 18% more runway than 25 °C increase at sea-level
- Challenges: limited/no room, cost, regulations, RSA
- Examples: BNE (accounted for higher temp); 170,000 feet; DCA (~270 feet; 29.66 million)
- Adjust Departure Times
  - Depart at cooler parts of the day
  - Challenges: decreased consumer/flight experience;
- Swap Aircraft on Routes
  - Some planes can generate more lift/hour; common solution
- Challenges: availability; different characteristics; need advanced planning, like a “twist”
- Examples: Swapping 737 for 877
- Examples: Swapping 877 for 837
- Examples: Swapping 837 for 817
- Examples: Swapping 817 for 837

#### Potential Solutions
- Adjust Airport Routing
  - Big cities with multiple airports
- Challenges: well-developed structures at current airports; different in size and runway lengths; most at already near max capacity
- Examples: None... Not viable
- Aircraft Design Improvements
  - Improve performance of aircraft
  - Challenges: planes in service for decades; cost; R&D limitations such as tire speed & engine size
- Examples: B737 windgap; more effective engines; composite 877/877x folding wingtip
- Increase Runway Lengths
  - B737 needs 18% more runway than 25 °C increase at sea-level
- Challenges: limited/no room, cost, regulations, RSA
- Examples: BNE (accounted for higher temp); 170,000 feet; DCA (~270 feet; 29.66 million)
- Adjust Departure Times
  - Depart at cooler parts of the day
  - Challenges: decreased consumer/flight experience;
- Swap Aircraft on Routes
  - Some planes can generate more lift/hour; common solution
- Challenges: availability; different characteristics; need advanced planning, like a “twist”
- Examples: Swapping 737 for 877
- Examples: Swapping 877 for 837
- Examples: Swapping 837 for 817
- Examples: Swapping 817 for 837

#### Decrease On-Board Weight
- Less effects of weight restriction
- Challenges: Designs already tried to minimize weight
- Examples: Many phasing out IFE systems & enhancing Wi-Fi

---

**References**
Bibliography


38. Sumers, Brian. “More from American Airlines: Here are some tidbits from my chat with American’s Vasu Raja that did not make the story we published.” Skift Airline Innovation Report, 14 February 2018, http://info.skift.com/airline-innovation-report-how-american-airlines-chooses-which/routes/to-fly?ecid=ACsprvvxPfuEBCPb7ZfMmMue5t9mdzT_15C24NpwifjFH6-lqFIPfFW1V8_1N17dvoxswXvshq13&utm_campaign=Skift%20Airline%20Innovation%20Report&utm_source=hs_email&utm_medium=email&utm_content=60664523&hs_enc=p2ANqtz-9_hZ4B5BuX1RIQcDzW136j6PsNXCYUZMeGsSELfYa1y1rsmceVpeZB8ZILEhMw5U-DLhJvnLG5VWUdKCwJ09L4etVcQ&_hsml=60664523.


Cover Art:
Thermometer Picture: http://sweetclipart.com/multisite/sweetclipart/files/medical_red_thermometer_1.png

Recommended Citation: