Determining the Location of Runway Exits Using Airport Surface Detection Equipment

Christopher Bryan Clemmer
DETERMINING THE LOCATION OF RUNWAY EXITS
USING AIRPORT SURFACE DETECTION EQUIPMENT

By

Christopher Bryan Clemmer

A Thesis Submitted to the College of Engineering, Department of Civil Engineering
In Partial Fulfillment of the Requirements for the Degree of
Master of Science in Civil Engineering

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This thesis was prepared under the direction of the candidate’s Thesis Committee Chair, Dr. Christopher D. Grant, Vice Provost of Academic Support, Daytona Beach Campus, and Thesis Committee Members Dr. Hongyun Chen, Assistant Professor, Daytona Beach Campus, Dr. Scott A. Parr, Assistant Professor, Daytona Beach Campus, and Dr. Ashok H. Gurjar, Department Chair, Daytona Beach Campus, and has been approved by the Thesis Committee. It was submitted to the Department of Civil Engineering in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering.

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Abstract

Airport surface detection equipment, such as ASDE-X, is used by thirty-five commercially operated airports throughout the United States. ASDE-X is responsible for the safe monitoring of aircraft movements as well as ground support vehicle operating on the airfield. Like most radar-based technologies, ASDE-X can report the position of any aircraft within a one second time interval. This data not only contains the geographic position, but also reports speed, heading, altitude, and aircraft specific characteristics. Using a quantitative approach, this research will use the data reported by ASDE-X to analyze current runway exit locations and develop an improved method of determining the location of runway exits. Currently, the Federal Aviation Administration is using an out-of-date nonstandard categorization based on maximum takeoff weight to determine the location of runway exits. This research uses data from ASDE-X to determine the best categorization using the current Federal Aviation Administration’s airport design reference categorization. This study found the Airplane Design Group, or ADG, to be the best reference to locate runway exit locations. Reformed tables depicting the percent of capture of each ADG based on the location of a runway exit were created based on the quantitative analysis of operational data. These tables included the location of both high-speed runway exits as well as right-angled runway exits. This research recommends future studies at additional airports to determine the effect of airport elevation, geometric layouts, and geometric constraints. It is also recommended to study if a method of analyzing ASDE-X data can assist in determine runway length requirements.
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Chapter 1: Introduction

This research document seeks to build upon the prior knowledge and expanded scientific understanding for locating runway exits. Runway exits are taxiways that connect the runway to parallel or adjacent taxiways. Taxiways are the exclusive paved surfaces for aircraft movement on the airfield; connecting the airport terminal to the runway infrastructure. Runway exits are ideally located in logical areas to increase safety, logistical operation, and capacity. Runway exits can also perform a reverse roll as a runway entrance depending on the directional flow of air traffic.

1.1 Background

Aviation has changed the way people and cargo move, where companies conduct business, where communities build and grow, and has continued to be the preferred method of passenger transportation for long distance travel throughout the United States. Airports all over the world are critical when it comes to the safe, efficient, and economical transportation of passengers and cargo. According to the U.S Department of Transportation, U.S. civil aviation related economic activity generated $1.5 trillion and supported 11.8 million jobs with $459.4 billion in earnings. Civil aviation accounted for 5.4% of U.S. gross domestic product. (U.S. DOT, 2015). This economic activity is directly related to the operational efficiency of airports. According to the Federal Aviation Administration (FAA) there are 19,601 civilian airports in the United States, far more than any other country (FAA, 2018).
Most airports in the United States began as military naval and air bases during World War II and throughout the cold war. Finished construction in 1996, Denver International Airport is the newest major airport in the United States. For over two decades, commercial traffic is limited to the existing layout of commercial airports. Since 1996, the total number of passenger enplanements of the United States has increased by over 144% (Air Transport, Passengers Carried, 2018). Table 1.1 below shows the top 20 United States airports by passenger enplanements. The lack of additional airports requires current airports to increase capacity, not only in terms of passenger facilities, but also aircraft and airline operations. Most major airports in the United States are surrounded by the host city. After decades of population growth and land development, airports are “landlocked” and are unable to expand outside their current property. Adding passenger capacity isn’t as simple as adding another terminal. There is a complex chain of facilities that must coincide in order to increase an airports capacity.

Table 1.1: Top 20 United States Airports by Enplanements (Air Transport, 2018).

Source: Bureau of Transportation Statistics

<table>
<thead>
<tr>
<th>Rank</th>
<th>Airports</th>
<th>IATA Code</th>
<th>City</th>
<th>State</th>
<th>2017</th>
<th>2016</th>
<th>2015</th>
</tr>
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<tr>
<td>1</td>
<td>Hartsfield–Jackson Atlanta International Airport</td>
<td>ATL</td>
<td>Atlanta</td>
<td>GA</td>
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<td>50,501,858.00</td>
<td>49,340,732.00</td>
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<td>2</td>
<td>Los Angeles International Airport</td>
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<td>Los Angeles</td>
<td>CA</td>
<td>42,459,545.00</td>
<td>39,636,042.00</td>
<td>36,351,226.00</td>
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<td>3</td>
<td>O'Hare International Airport</td>
<td>ORD</td>
<td>Chicago</td>
<td>IL</td>
<td>38,593,028.00</td>
<td>37,589,899.00</td>
<td>36,305,668.00</td>
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<td>4</td>
<td>Dallas/Fort Worth International Airport</td>
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<td>Dallas/Fort Worth</td>
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<td>28,267,394.00</td>
<td>26,280,043.00</td>
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<td>7</td>
<td>San Francisco International Airport</td>
<td>SFO</td>
<td>San Francisco</td>
<td>CA</td>
<td>27,862,429.00</td>
<td>25,707,101.00</td>
<td>24,190,549.00</td>
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<td>8</td>
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<td>LAS</td>
<td>Las Vegas</td>
<td>NV</td>
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<td>22,833,267.00</td>
<td>21,824,231.00</td>
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<td>SEA</td>
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<td>WA</td>
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<td>11</td>
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<td>AZ</td>
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<td>13</td>
<td>Miami International Airport</td>
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<td>14</td>
<td>Newark Liberty International Airport</td>
<td>EWR</td>
<td>Newark/New York</td>
<td>NJ</td>
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<td>19,923,009.00</td>
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<td>15</td>
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<td>Houston</td>
<td>TX</td>
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<td>20,062,072.00</td>
<td>20,595,874.00</td>
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<td>16</td>
<td>Logan International Airport</td>
<td>BOS</td>
<td>Boston</td>
<td>MA</td>
<td>19,145,096.00</td>
<td>17,749,202.00</td>
<td>17,759,044.00</td>
</tr>
<tr>
<td>17</td>
<td>Minneapolis–Saint Paul International Airport</td>
<td>MSP</td>
<td>Minneapolis/St. Paul</td>
<td>MN</td>
<td>19,002,544.00</td>
<td>18,123,844.00</td>
<td>17,634,252.00</td>
</tr>
<tr>
<td>18</td>
<td>Detroit Metropolitan Airport</td>
<td>DTW</td>
<td>Detroit</td>
<td>MI</td>
<td>17,325,600.00</td>
<td>16,826,287.00</td>
<td>16,847,135.00</td>
</tr>
<tr>
<td>20</td>
<td>Philadelphia International Airport</td>
<td>PHL</td>
<td>Philadelphia</td>
<td>PA</td>
<td>14,760,585.00</td>
<td>14,564,419.00</td>
<td>15,101,318.00</td>
</tr>
</tbody>
</table>
Typically, airport capacity enhancement is achieved by increasing the total number of aircraft operation. Aircraft operations include the aircraft arriving to the airport and aircraft departing the airport. Increasing airport aircraft operational capacity will greatly increase the passenger capacity of the airport. The easiest way to increase aircraft operations at an airport is to build multiple runways in an efficient geometric layout. An example is multiple parallel runways. Refer to Figure 1.1 for the layout of typical parallel runways. Multiple runways will increase capacity but at great cost. Runways are expensive and requires vast amounts of land area, area that airports have limited access to or in some cases do not own the land necessary for build the runway. Adding additional runways is not an immediate solution to increase capacity, in most cases it takes many years to plan, design, and build a runway.

1.2 Statement of the Problem

The FAA uses existing standards for the location of runway exits that are quite dated and refers to a non-current classification system which references the maximum takeoff weight of aircraft. These outdated standards and classification technique utilized theoretical equations and small sample test from the 1980’s and 1990’s (FAA, 1983). Consistent design classification standards, in addition to the improvement of aircraft technologies, call for an update to the method of location of runway exits.
Figure 1.1: Airport Diagram of Hartsfield Jackson Atlanta International Airport depicting the use of parallel runways. Source: Federal Aviation Administration (FAA, 2018)
1.2 Background and Justification

Airport capacity is a major factor when it comes to the economic impact of that airport. Major airports around the United States serve a myriad of destinations either domestic or international. Consequently, there will be a “mix fleet”, meaning a large amount of varying aircraft types, sizes, and minimum approach speeds. This mix of aircraft types causes an inefficiency when it comes to aircraft landing operations. This inefficiency can cause chain reactions for every subsequent landing aircraft. As a slower aircraft lands ahead of a faster aircraft, the faster aircraft must compensate by slowing to match speed of the lead aircraft. However, this is a problem air traffic controllers are aware of and can take measures to make approach air traffic as efficient as possible. The same is not true for runway operations.

Aircraft cleared for landing or take off have the runway to themselves and no other aircraft or vehicle can use or cross that runway until the authorized aircraft has cleared the runway. The time an aircraft spends on the runway is known as Runway Occupancy Time (ROT). During an aircraft’s ROT, only the approved aircraft is allowed on the runway. For landing operations ROT is defined as the time cleared on final approach until completely exiting the runway and is no longer with in the Runway Safety Area (RSA). As soon as the aircraft is outside the RSA the next aircraft can then be cleared for an operation, either landing or takeoff. This cycle repeats for each aircraft.

Reducing ROT is a way to improve capacity for any runway and subsequently any airport. As ROT is decreased, the number of hourly operations can be increased. The way to improve ROT is to investigate the ideal location of runway exits. Runway exits are taxiways placed at strategic locations to vacate aircraft from the runway. Many runway exits are known as ‘high
speed taxiways’ or ‘rapid runway exits’ in which an aircraft can use this type of exit to expedite off the runway at a higher rate of speed, in return reducing ROT.

However, the current standards for the location of runway exits are quite dated and uses theoretical equations and small sample test from the 1980’s and 1990’s (FAA, 1983). Updates in design standards and improvement with aircraft technologies call for an update of the location of runway exits. This calls for a quantitative approach. The data is collected from Airport Surface Detection Equipment (ASDE-X) and will record every position of every landing aircraft from a select airport.

1.4 Purpose of the Study

The purpose of this study is to verify the current dated design standards for locating runway exits (or Rapid Exit Taxiways) provided by the Federal Aviation Administration’s Advisory Circulars (AC) and the International Civil Aviation Organization’s (ICAO) Aerodrome Design Manual can be modified and reflect the real-world characteristics by using ASDE-X reported data and data processing and analysis tools.

Rather than use outdated categorizations or categorizations with widespread intervals, such as aircraft weight, the use of an existing FAA design category will determine the minimum safe exit velocity for aircraft. Using this technique, the ultimate location of runway exits can be established. The distance from the end of the runway to the location aircraft tend to maintain a safe exit velocity or less will be sown as the real-world location for a runway exit. The intended audience for this research is aimed at those who would be affected and will benefit; current researchers within the aviation industry, airport operators, pilots, and aviation regulators.
1.4.1 Goal and Objectives

The goal is to locate runway exits using modern techniques and determine a modern classification to use for the method of locating runway exits. A quantitative analysis is used to determine an ideal location for all aircraft within a specific standardized category. After completion of the analysis, ASDE-X position data should be shown to have a statistically significant difference in runway exit locations than current FAA and ICAO standards. A standard FAA category will be shown as the best category to classify aircraft when it comes to locating runway exits and can be used to determine exit velocities of aircraft. The final objective is to analyze aircraft landing characteristics to determine future areas of research.
Chapter 2: Review of Relevant Literature

The aviation industry is the product of an incredible invention altering the modern means of transportation. Over one hundred years, the aircraft has evolved to become the most advanced and most vital technology to modern society. The airplane is by no means a new technology, but technological advancements have resulted in the safety and performance enhancements that were not possible during the early history of flight. Airports were created to allow the safe landing of aircraft and to be a terminal for transportation. An airport, as understood today, is a massive complex infrastructure allowing for hundreds of daily aircraft operations and millions of passenger enplanements annually. Part of this substantial infrastructure are the network of taxiways and most runways. Runways are essential for safe takeoff and landing operations. Just as important are the taxiways that allow aircraft to enter and exit the runway.

Locating, designing, and implementation of runway exits has been an evolutionary process. Henry Ford and Ford Motor Company are accredited with establishing the first modern airport in 1924. The airport was the first to use an improved surface runway made from concrete (The Henry Ford, 2018). Over time, more airports would begin to use improved surface runways using both concrete and asphalt. It was only a matter of time until the standard of improving all airfield surfaces, including taxiways, would be implemented. Structurally sufficient surfaces allowed for heavier and faster aircraft, eventually leading to the operational volumes that are seen at airports today. Airfield geometry and design would soon become standardized by the Federal Aviation Administration.

For the development of this research, several areas of literature were reviewed including airfield design manuals, Advisory Circulars, empirical studies on runway geometry, and studies of
implementing computerized software into designing procedures. The following sections of this chapter will discuss these elements in further detail.

2.1 Airfield Design Manuals and Advisory Circulars

Governmental organizations regulate aviation related activities under the jurisdiction of the governing body. Aviation regulations under government authority include pilot licensure, airworthiness of aircraft, air traffic management, airport management, and airport related operations. Regarding airport design and layout, these governmental agencies provide guidelines and policies that must be followed to be recognized under federal obligations. The International Civil Aviation Organization (ICAO) is a department under the control of the United Nations that provides international aviation standards the member nations of the United Nations. Many nations choose to adopt and conform to ICAO design standards when it comes to airport design. The FAA is governmental agency under the direction of the United States Federal Government. The FAA adopts many design standards from ICAO as many airports conduct international operations. The FAA also sets standards and it is expected that all federally obligated airports in the United States follow the design criteria set forth by the FAA.

2.1.1 International Civil Aviation Organization

ICAO publishes design standards through Doc 9157 Aerodrome Design Manual. The Aerodrome Design Manual is broken into parts where Part 1 is Runways, and Part 2 is Taxiways, Aprons, and Holding Bays. For this research only, Part 1 and Part 2 were reviewed. When it comes to determine the location of runway exits, the Aerodrome Design Manuals only specifies locating Rapid Taxiway Exits (RETS) which is another name for high-speed exits. ICAO defines RETS as:
A taxiway connected to a runway at an acute angle and designed to allow landing airplanes to turn off at higher speeds than those achieved on other exit taxiways, thereby minimizing runway occupancy time (ICAO, 2005).

According to ICAO, designing RETS is based on the anticipated air traffic. The main purpose of these taxiways is to minimize aircraft runway occupancy and increase aerodrome capacity (ICAO, 2005). The advantage for RETS becoming standardized, giving from ICAO, is that pilots become familiar with the configuration and can expect the same results when landing at any aerodrome (airport) with these facilities. ICAO has introduced design standards and uses the Three Segment Method as outlined below (ICAO, 2005):

Segment 1: Distance required from landing threshold to main gear touchdown ($S_1$).

Segment 2: Distance required for transition from main gear touchdown to establish stabilized braking configuration ($S_2$).

Segment 3: Distance required for deceleration in a normal braking mode to a nominal turnoff speed ($S_3$).

The total distance $S$ is the sum of three distinct segments which are computed separately.

Figure 2.1 below shows a graphical representation of the Three Segment method where:

$V_a$  Threshold speed based on 1.3 times the stall speed of assumed landing mass equal to 85 per cent of maximum landing mass. Speed is corrected for elevation and airport reference temperature.
\( V_{td} \) Assumed as \( V_{th} - 5 \text{ kts} \) (conservative). Speed decay considered representative for most types of aircraft.

\( V_{ba} \) Assumed brake application speed.

\( V_{th} \) 15 kts (wheel brakes and/or reverse thrust application).

\( V_{ex} \) Nominal turn-off speed: Code number 3 or 4: 30 kts or Code number 1 or 2: 15 kts

Figure 2.1: Figure 1-15 in Part 2 of the Aerodrome Manuel: The Three Segment Method based on the design standards for determining the location of runway exits (ICAO, 2005). Source: ICAO

In 1982, ICAO collected data on actual rapid exit taxiway usage. The data, provided information on the type of exit taxiway, distances from threshold to exits, exit angle and taxiway usage for each runway heading. An assumption was that an aircraft could have exited through a rapid exit taxiway, had there been a rapid exit taxiway on that location (ICAO, 2005). Figure 2.2 below shows accumulated rapid exit usage versus distance from thresholds as reported by ICAO.
2.1.2 Federal Aviation Administration

The FAA publishes airport design documentation using Advisory Circulars (ACs). The ACs are broken into many series. The series that documents airport design references is the 5300 series. This research will focus on two ACs, AC 150/5300-13A – Airport Design and AC150/5060-5 – Airport Capacity and Delay. When it comes to determining runway exit locations the FAA identifies high-speed exits as well as right-angles exit.

The FAA states that exit taxiways should be designed to permit free flow to the parallel taxiway or at least to a point where the aircraft is completely clear of the hold line (FAA, 2014). The FAA classifies runway exits as “right angle” or “acute angle” where right angle is a standard taxiway perpendicular (90°) to the runway and an acute angle is typically less than a 30° deviation from the approach end of the runway. Refer to the figure 2.3 below for an idea of what a high-speed exit would appear. The FAA states that the purpose of an acute or high-speed exit is to enhance airport capacity (FAA, 1983). The advantage of a right-angled exit is it can be used for landings in both directions and as a runway crossing point. As a financial prospective high-speed exits are more expensive than right-angled exits. According to the FAA the cost to construct high-speed exits is usually justified only on runways regularly serving aircraft in

<table>
<thead>
<tr>
<th>Aircraft category</th>
<th>50%</th>
<th>60%</th>
<th>70%</th>
<th>80%</th>
<th>90%</th>
<th>95%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1170</td>
<td>1320</td>
<td>1440</td>
<td>1600</td>
<td>1950</td>
<td>2200</td>
<td>2900</td>
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<tr>
<td>B</td>
<td>1370</td>
<td>1480</td>
<td>1590</td>
<td>1770</td>
<td>2070</td>
<td>2300</td>
<td>3000</td>
</tr>
<tr>
<td>C</td>
<td>1740</td>
<td>1850</td>
<td>1970</td>
<td>2150</td>
<td>2340</td>
<td>2670</td>
<td>3100</td>
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<td>D</td>
<td>2040</td>
<td>2190</td>
<td>2290</td>
<td>2480</td>
<td>2750</td>
<td>2950</td>
<td>4000</td>
</tr>
</tbody>
</table>

Figure 2.2: Table 1-12 from Part 2 of the Aerodrome Design Manual Accumulated rapid exit usage (ICAO, 2005). Source: ICAO
Many airports receive federal funding for taxiway construction projects and are required to follow FAA design criteria in order to maintain funding. This justification can hinder small operational airports ability to construct high-speed exits.

Figure 2.3: Figure 4-21 from AC150/5300-13A shows the proper layout of high-speed runway exits (FAA, 2014). Source: FAA

The FAA provides guidance on the effect of the taxiway location on runway capacity. The study was conducted in 1983. In general, each 100-foot reduction of the distance from the threshold to the exit taxiway reduces the runway occupancy time by approximately 0.75 second for each aircraft using the exit (FAA, 1983). When locating runway exits, the FAA considers wet and dry conditions, weight of aircraft, and type of exit. It is important to note that elevation was not a consideration in the FAA design standard. Refer to figure 2.4 below for the published design utilization percentages for runway exit locations.
2.2 Empirical Studies of Runway Exits

The existing background literature for the research, pertaining to aviation, seems to be focused on increasing airport capacity. The studies all have similar factors that are proposed as possible solutions to ultimately increase airport capacity in a nontraditional way. Two of the large factors that these studies investigate are the human elements associated with aircraft landing characteristics and the airport geometry or layout of the airfield. All the studies

Figure 2.4: Table 4-13 of AC150/5300-13A Exit taxiway cumulative utilization percentages (FAA, 2014). Source: FAA
researched were published in well acclaimed journals and the authors were all from well-known institutions. The following sections will summarize the related literature and analyze how these studies relates to this research.

2.2.1 Planning and the Human Factor

The human element in aviation is always questioned when designing and constructing airport facilities. The human factor is an integrated part of the aviation network which can cause great unknowns for the system but could not function without it. As related to aviation humans are pilots, air traffic controllers, airline management, and airport operators. Automation does exist within the aviation industry. Most notably, the autopilot system of most aircraft. Aircraft today fly with the most sophisticated technologies in the transportation field. However, the limitations of technology, even though small, makes it necessary to rely on humans to maintain control of most commercially operated aircraft.

The study titled “Airport Surface Trajectory Optimization Considering Runway Exit Selection,” considers a concept of Runway Exit Availability (REA), where REA measures the probability that a flight clears the runway from a specific runway exit (Cheng, Liu, & Zou, 2014). REA works in conjunction with finding the shortest taxi route from the runway to the airport terminal. Scheduling and Taxiway planning are the technique used by this study. Taxiway planning is the method of choosing the taxi path starting from a runway exit and ending at a terminal or parking position. This study performed a probabilistic distribution analysis to determine the probability that aircraft will use certain runway exits. When modeling taxiway scheduling the researcher assume the aircraft lands without performing a “go-around” procedure and assumes that only two phases of movement exist taxing at a constant speed and holding. The
researchers concluded that this strategy is results in a superior to other similar approaches. The
reported calculation time was noted to be acceptable (Cheng, Liu, & Zou, 2014).

This study does apply runway exit as a main variable to the research approach. However, this
study does not offer a geometrical solution to the research question. One such geometric solution
would be the relocating of runway exits if they fail to achieve a high REA. The study does apply
the principle that runway exit determination is a human factor issue and the results in a real word
scenario may be different. This study does utilize a runway exit probability distribution.

The case study titled “Statistical Modeling and Analysis of Landing Time Interval” proposes
that current literature does not take in the issue of airlines, pilots, and controllers when it comes
to the landing time interval between flights. The human element associated with these variables
are something other literature is avoiding or trying to propose other methods to eliminate the
human factor. When it comes to real world characteristics, data modeling becomes difficult, if
not impossible when you factor in the human element. This case study is determining a
mathematical model to help identify landing time intervals at Los Angeles International Airport.
The study analyses Performance Data Analysis and Reporting System (PDARS) and Aviation
System Performance Metrics (ASPM) databases and creates probability distributions to
determine landing time intervals. The study concluded that there was the dominant airline at
LAX behaved in a statistically significant way when comparing landing intervals (Rakas & Yin,
2005). This study used data sources relating position and other airline specific operational
characteristic. The scope of this study was to determine the intervals between arrivals of the
dominant air carrier at LAX. The study did not include aircraft characteristics, runway
performance, or runway exit characteristics.
2.2.2 Airfield Geometry

The layout of airports has been an evolving task for many decades. Airports have seen many changes in the aviation industry, the most important of which is the evolution of the airplane. The airplane is the singular factor that determines the geometry and layout of the airfield. Larger aircraft tend to require more room than smaller aircraft. Faster aircraft tend to need longer runways than slower aircraft. The size of an aircraft can also play a role in the airport capacity. A smaller aircraft needs require more frequent flights between cities in order to deliver the same amount of passenger as a larger aircraft flying the same route. Smaller planes at an airport typically equate to a high operational demand, in returns affects capacity. Runway geometry, more accurately, runway exit geometry is an important element to increase airport operational capacity. The following studies will show the importance of runway exits and the potential runway exits can provide to airport capacity.

The study “Microcomputer Model for Design and Location of Runway Exits” propose an interactive computer based program that uses kinematic equations to characterize aircraft landing dynamics and the use of polynomial-time dynamic programming algorithm to the determine the optimal location of high-speed runway exits (Hobeika, Trani, Sherali, & Kim, 1993). The study used terminal airspace procedures (TERP) categories to simulate a large variety of airport environments. The study notes during the data collection an analysis that one cannot overemphasize the importance of pilot behavior while exiting at high speeds, in other words a human factor exist. This study uses a kinematic model and is similar to the ICAO three segment method. The method factors in flare phase (distance an aircraft needs to stop producing lift), free roll phase I (the free rolling of the aircraft just after touchdown), breaking phase (braking distance), roll phase II (distance from where deceleration from braking isn’t required), and
finally runway clearance (Hobeika, Trani, Sherali, & Kim, 1993). The flare phase and braking phase are assumed to be a probabilistic event. Testing of the kinematic model was completed at the FAA Oklahoma City test facility and statistical analysis was completed at several airports. The study concludes that outputs from the runway exit design interactive model (REDIM) recommend optimal locations and geometric designs of high-speed exits.

This study shows the use of kinematic principles, which is the primary physics behind REDIM. This study did provide statistical data, but the collection method was not specified when verifying the results using real airports. This study was conducted by a well know institution in 1993 and the REDIM software is still available today. Due to the age of this study, the technology did not exist as what is proposed by this research thesis. The study failed to model right-angled exits and the optimal location for those exits.

2.5 Contribution of the Study

This document will address the shortcomings of the related literature and proved a modern method of determining the location of runway exits. The research will demonstration the need for a classification system unique to the current FAA standards when determining the location of all runway exits. This study will bring forth the method of using ASDE-X date in such a way as to exposed new research opportunities. The analysis of speed distributions will allow aviation planners, airport designers, pilots, and airlines to become aware of the actual performance of runway exits an allow them to use the analysis to their advantage. A review of the literature has shown that currently there is no research on using ASDE-X data to locate runway exits. There is a need for a uniform classification system and a modern method for determining the location of runway exits. This approach will address the deficiencies in the relevant literature as well as contribute to the aviation industry by unifying and modernizing current runway exit standards.
Chapter 3: Methodology

This chapter provides an outline of the research strategy and procedure used to answer the research question, the approach to the research, and an overview of the collected data. This chapter will also address the legitimacy and limitations of the data and the research in general. The overall aim of the research is to provide a modernized method to current FAA Advisory Circular Standards as related to the location of runway exits.

3.1 Quantitative Research Approach

Data collection technologies today are capable of recording, processing, and storing vast amounts of data gathered from anywhere in the world in an instant. Mass data collection is now feasible whereas in the late 1980’s data collection technologies didn’t exist, was not reliable, or too economically obsolete. Data collection was not easily accessible as the advent of the internet was just in the early stages of public use and data collection programs were not yet established for the world market. Primary radar systems have been well established throughout the United States since the 1960’s, followed by Secondary Surveillance Radar (SSR) and are still in use today. Refer to Figure 3.1 for an illustration of primary and secondary radar. These systems work well for detecting aircraft in the air, however, the lag time for a radar pulse is too great and the area coverage is too high of an altitude for accurately surveilling and reporting ground traffic. Monopulse Secondary Surveillance Radar (MSSR), developed in the 1990’s, addresses these issues and led to the technologies associated with ASDE-X, TCAS, and ADS-B (Stevens, 2016).
These technologies were not available during the initial Advisory Circulars completed by the FAA during the 1980’s. Since then, the standards for locating runway exits has not changed. Using a quantitative approach is deemed a good strategy due to the lack of quantitative analysis conducted by previous approaches and the access to quantitative data now exist. The quantitative approach consists of using raw positioning data received from an ASDE-X system. The ASDE-X systems displays and reports data as a text file (.txt) or comma delineated (.csv) file format. The system is able to report aircraft positions every one second. This short time interval can result in large data files that contain valuable data in regards to aircraft position, speed, and characteristics.

Figure 3.1: Primary and secondary radar tower. Typical of what is found at most airports (FAA, 2014). Source: FAA
3.2 Data Collection

The main motivation for the study was to use data showing all phases of flight for any given landing aircraft. The study required observing a multitude of aircraft during the final phase of flight, meaning for any statistical significance the number of observed operations would need to be more than several thousand. Observing thousands of landings in one setting is impractical if not impossible. Therefore the data needed to be collected by a surface radar system. Surface radar is usually only found at high commercial traffic airports. ASDE-X is found at 35 of the United States Airports. ASDE-X is a ground radar reporting system that collects the required data needed for the study.

The prime requirement for the collected data that it needed to contain the exact position of an aircraft. With this, the data also needed to contain the timestamp for the reported position, the airline callsign, a unique aircraft identifier in the data series, the unique FAA aircraft identifier, altitude, ground speed, and course (heading), and the FAA airport design reference codes.

3.2.1 Geographic Coordinate System

The position of the aircraft was reported using a geographic coordinate system, which is a system that allows any location on earth to be given a unique coordinate. The geographic coordinate position was reported using the coordinates of latitude and longitude. Latitude is the angle between the equatorial plane, i.e. equator, and parallel line on which the defining point lies. In terms of an x-y plane the latitude would be reported along the y-axis. Longitude is the angle between a reference meridian and a parallel meridian that passes through the defining point. In terms of an x-y plane the longitude would be reported along the x-axis.
The earth is not completely spherical. The equatorial plane protuberances making the radius of earth approximately 0.3% larger at the equator relative to the poles (Joint Glossary Committee, 1994). This causes the spherical lines of latitude and longitude to fit an ellipsoid rather than a sphere. Therefore, datums are used to convert between spherical and ellipsoidal coordinates. Global datums include the World Geodetic System of 1984 (WGS 84), the primary datum used in Global Positioning Systems and most systems using latitude and longitude as the coordinates (Joint Glossary Committee, 1994). The radar data from the ASDE-X system reports position by latitude and longitude using WGS 84.

When using WGS 84 data it is typically needed to be convert onto a Cartesian plane for some applications. A Cartesian plane is a rectilinear coordinate system that gives linear coordinates to data. Typically, smaller areas of land, such as states, are perceived as flat planes. This makes it easier to translate spherical coordinates to a series of x and y values that can be plotted like a grid. This process is called map projection, where the spherical coordinates are projected onto a Cartesian plane. Thus, simple geometry can be used to determine characteristics such as position, length, and area of a giving position on the earth’s surface.

3.2.2 FAA Aircraft Type Designator and Airline Designators

The FAA identifies all aircraft according to an Aircraft Type Designator (ATD), which is an abbreviated form of an aircraft type. The ATD is used mostly for air traffic management and the air traffic service automation systems. As an example, the Boeing 747-800 would be designated as B748. The ATD is necessary so that a unique identifier can identify a specific aircraft type as to avoid long aircraft names and so standardize a naming convention to uniformly work with air
traffic systems (FAA, 2018). ICAO is responsible for creating standard ATD’s for aircraft that commonly request air traffic service.

ICAO uses the following principles to assign an ATD:

a. Only one designator will be assigned per aircraft type.

b. A designator will be derived from the manufacturer’s model number or name, or from a common military type.

c. The designator will not be longer than four characters and will generally begin with a letter.

d. An assigned designator will not be changed for: license-built aircraft, when an aircraft model is sold to or manufactured by another company, when the manufacturer’s name changes, or when the aircraft type is derived or converted from another type.

e. A different designator for an alternate or subtype version of the aircraft will only be allocated when there is a significant difference in performance for ATS or no shared designator can be assigned.

f. “Homebuilt,” “amateur-built,” or “kit plane” aircraft that exist in operationally significant numbers will be assigned a designator; however, these aircraft will only be listed under the original designer or under the manufacturer that produces or produced the aircraft type in series.

g. In general, an aircraft type designator will be assigned to all aircraft heavier than micro-ultra-light. For the purpose of ICAO Document 8643: (1) Micro-/ultra-light are those aircraft types with a maximum certified take-off weight of 1,000 pounds or less and a stall speed not greater than 35 knots. (2) Micro-/ultra-light helicopters and gyrocopters are those helicopters or gyrocopters with a maximum certified take-off weight of 1,000 pounds or less.
h. Roman numerals used as part of aircraft model names or numbers will be replaced by Arabic numerals. (ICAO, 2018)

The airline designator is an abbreviated character string that contains the unique airline three letter identifier, designated by ICAO, and the aircrafts flight number. This identifier is used by the air traffic management systems and by air traffic controllers to identify the airline company of a specific aircraft, the destination, and also used as the radio communication identifier as air traffic control communicates vocally to the pilot. (FAA, 2016)

3.2.3 Altitude, Course, and Speed

When it comes to transportation, aviation is the only mode that requires the use of a third dimension. The height of an aircraft is called altitude and it is typically refers to the height above mean sea level (MSL) or true altitude. Mean sea level is the average surface level of all oceans (Adams, 1980). MSL is a geodetic reference point similar to a vertical datum. Altitudes in aviation is typically reported as an MSL value, however, many obstruction clearances are reported as above ground level (AGL). Air traffic management and pilots will use MSL as standard practice as to accurately report altitude. Since aircraft travel at high velocities, a ground-based reference elevation is impractical. MSL altitude can also help the pilot predict the performance of the aircraft. Aircraft performance is directly related to density altitude. Density altitude is the vertical distance above sea level in the standard atmosphere at which a given density is to be found. A decrease in air density means a high density altitude, increase in elevation will result in a decrease of air pressure. According to the FAA, The density of air has significant effects on the aircraft’s performance because as air becomes less dense, power is
reduced because the engine takes in less air, Thrust is reduced because a propeller is less efficient in thin air, and lift is reduced because the thin air exerts less force on the airfoils (FAA, 2016).

Knowing aircraft direction is important in determining the safety of other aircraft and also guiding aircraft to the intended destination. In aviation, direction is referred to as a course, or the cardinal direction in which the aircraft is traveling. Course is typically reported in degrees rather than the traditional cardinal directions. Magnetic heading is typically used as the reference direction in aircraft, however, true north is sometimes used as reference in regions close to Earth’s poles due to the sensitivity of magnetic compasses at the poles.

Aircraft, unlike ground vehicles, must maintain a speed appropriate to maintain lift during air operations. Aircraft use two speed references, airspeed and ground speed and both are reported in nautical miles per hour (Knots). Airspeed has many common conventions associated with the measurement, such as Indicated Airspeed (IAS) and True Airspeed (TAS). IAS is the value that is shown on an airspeed indicator, which uses ram air pressure and static air pressure to determine airspeed. TAS is the speed relative to the atmosphere and the aircraft velocity can be calculated when you involve course. True airspeed factors in wind speed which can cause an increase or decrease in airspeed but show a constant IAS. Ground speed is the aircrafts speed as measured by a ground track, GPS, or radar system. Ground speed is the speed relative to the ground.
3.2.4 FAA Airport Design Reference Codes

Planning and designing new facilities, such as runways, or improvements to existing airport facilities requires the use of one or more “design aircraft.” A design aircraft is the largest demanding aircraft, generally, having over 500 scheduled operations annually (FAA, 2014). Airports select a design aircraft for the purposes of planning and developing airport geometric design as an amalgamated aircraft representing a collection of aircraft classified by Aircraft Approach Category (AAC), Airplane Design Group (ADG), and Taxiway Design Group (TDG). The FAA uses these codes to classify aircraft so airport planners and designers and follow identical guideline for airport design at all federally obligated airports and airports that choose to follow FAA design standards (FAA, 2014).

3.2.4.1 Aircraft Approach Category

Aircraft approach category is an assemblage of aircraft based on a speed the approach speed of an aircraft. The approach speed is usually determined by the manufacture, however, the approach speed or $V_{REF}$ is generally defined as 1.3 times the aircrafts stall speed (FAA, 2014). The aircrafts stall speed is the minimum speed at which an aircraft can maintain lift at maximum certificated landing weight. Refer to Table 3.1 below for Approach Speed for each AAC.

Table 3.1: Aircraft Approach Category classification (FAA, 2014). Source: FAA

<table>
<thead>
<tr>
<th>AAC</th>
<th>$V_{REF}$/Approach Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Approach speed less than 91 knots</td>
</tr>
<tr>
<td>B</td>
<td>Approach speed 91 knots or more but less than 121 knots</td>
</tr>
<tr>
<td>C</td>
<td>Approach speed 121 knots or more but less than 141 knots</td>
</tr>
<tr>
<td>D</td>
<td>Approach speed 141 knots or more but less than 166 knots</td>
</tr>
<tr>
<td>E</td>
<td>Approach speed 166 knots or more</td>
</tr>
</tbody>
</table>
3.2.4.2 Airplane Design Group

The Airplane Design Group (ADG) is a physical characteristic category of identifying an aircraft. The ADG is defined as either the aircraft wingspan or tail height whichever is most restrictive or in other words the greatest length (FAA, 2014). The ADG is based on the largest aircraft expected to operate on the runway and adjacent taxiways. The classification lengths can be found in Table 3.2 below. The main objective of the ADG classification is to maintain adequate wingtip and safety area clearances to ensure aircraft on parallel or adjacent runways or taxiways will never be able to contact any part of the aircraft with another aircraft or object. The ADG is used to select the separation geometry, of taxiways and parallel taxiways or taxilanes and defines the geometry of safety areas such as Taxiway Safety Area (TSA) and Taxiway Object Free Area (TOFA). Refer to figure 3.2 for a reference of wingtip clearance between an aircraft and other airport objects as well as Figure 3.3 that defines the required separations and geometry of the safety areas.

Table 2.2: Airplane Design Group categorization based on tail height and wingspan (FAA, 2014).
Source: FAA
Figure 3.2: Figure 4-8 form AC150/5300-13A this illustrates the wingtip clearance that is provided by the safety areas (FAA, 2014). Source: FAA
3.2.4.3 Taxiway Design Group

Aircraft are classified by Taxiway Design Group (TDG) based on Main Gear Width (MGW) and Cockpit to Main Gear distance (CMG). TDG is the undercarriage dimensions of the aircraft. Refer to figure x below to show the relationship of MGW, CMD, and TDG. TDG is used to determine taxiway and taxilane width and radius of curvature, fillets, and, runway to taxiway and/or taxiway to taxilane separation requirements. Refer to Figure 3.4 and Figure 3.5 for TDG specific design standards. It is, however, common for taxiways to be built to different TDG based on the operational characteristics of the airports.
Figure 3.4: Figure 1-1 from AC150/5300-13A showing the classification of Taxiway Design Groups (FAA, 2014). Source FAA

Figure 3.5: Table 4-2 from AC150/5300-13A showing the TDG classification of taxiway geometry (FAA, 2014). Source: FAA
3.2.4.4 FAA and CFR Aircraft Weight Category

The FAA and Code of Federal Regulations specify aircraft weight as the Maximum Certified Takeoff Weight (MTOW). The MTOW is the maximum gross weight, including the weight of the aircraft and all cargo which an aircraft can safely achieve and maintain lift (FAA, 2014). The FAA defines the weight categories as followed:


b. H – Heavy. Aircraft capable of takeoff weights of 300,000 pounds or more whether or not they are operating at this weight during a particular phase of flight.

c. L – Large. Aircraft of more than 41,000 pounds, maximum certificated takeoff weight, up to but not including 300,000 pounds.

d. S – Small. Aircraft of 41,000 pounds or less maximum certificated takeoff weight. Aircraft weighing between 12,500 pounds and 41,000 pounds. For Class B airspace rules, these aircraft are “large, turbine-engine powered aircraft” Aircraft less than 12,500 pounds are able to be capable of single pilot operations (FAA, 2018).

3.3 Data Processing Implements

This project required to process the collected data for further analysis. All the data was stored as (.txt) or (.csv) computer files. Text and comma delineated files are basic data files that can be easily read using many computer applications or programs. The data contained in the files required to be reformatted for clarity or manipulation when analyzing the data and to also allow the addition or subtraction of other data entries or fields. The tools used in the data processing was spreadsheet application, geographic information system, and geospatial conversion application.
3.3.1 Microsoft Excel

Microsoft Excel is a spreadsheet application developed by Microsoft. A spreadsheet is an application that can store, manipulate, and analyze data in a tabular arrangement. Comma delineated files are easily accessible for spreadsheet application as comma delineated files use commas to designate a column and semicolons to represent rows. Spreadsheets are a combination of rows and columns to form a cell. Text or numerical values can be placed into cells. Microsoft Excel has the ability to open comma delineated data in a format easily visible and organized. Excel can manipulate cells by performing operations set by the user if the form of formulas that can be user created.

3.3.2 Esri ArcGIS ArcMap

ArcMap is a geographic information system developed by Esri. Geographic information systems can display, create, manipulate, and analyze geospatial or georeferenced data sets. ArcMap allows users to explore a data set, create visual maps, map layers, and shapefiles (.shp). Shapefiles are files containing a georeferenced dataset that can be used by other computer applications. ArcMap uses the latitude and longitude of each data point to displace the exact location on the specified map or globe. ArcMap can project a data sets coordinate system to a reference state plane. ArcMap can also add the rectilinear coordinated of the plane to the existing dataset using data management tools.
3.3.3 US Army Corps of Engineers CORPSCON v6.0

Corpscon is a Microsoft Windows application, developed by the US Army Corps of Engineers, which allows the user to convert coordinates between Geographic, State Plane, Universal Transverse Mercator (UTM) and US National Grid systems on the North American Datum of 1927 (NAD 27), the North American Datum of 1983 (NAD 83) and High Accuracy Reference Networks (HARNs). Corpscon was used to verify whether geospatial data processed by ArcGIS ArcMap application was indeed in the correct location. Corpscon was also used to project the location of all runway ends at JFK.

3.4 Procedure

This section proposes a method which uses data collected by ASDE-X to plot speed and distance dependent histograms containing cumulative distribution functions of Airplane Design Groups (ADG). Then, this section shows how these figures can be used to calculate and determine runway exit locations and is used to demonstrate an alternate approach to current FAA Advisory Circulars involving locating runway exits by using the evolution of surface radar technology and big data. In general, the research procedure was conducted in three tasks. The first task collected the necessary data and used processing tools to further refine the data into a format necessary for data analysis. The second task develops speed dependent histograms, to analyze aircraft exit velocities at runway exits, and distance dependent histograms, to determine the location of safe exit velocities. The third task then demonstrates how these plots can be used to calculate and determine runway exit locations. The following subsections describe these tasks in addition detail.
3.4.1 Data Collection and Processing

The first task for the study was determining the required data, finding a location, and a data source. First, it was determined that the required data consist of the geographic coordinates, timestamp for the reported position, the airline callsign, a unique aircraft identifier in the data series, the unique FAA aircraft identifier, altitude, ground speed, course (heading), and the FAA airport design reference codes. The location of the data collection was the next undertaking which required the use of airport statistics. John F Kennedy International (JFK) was chosen due to the diversity of aircraft types, airport configuration, and annual traffic volume (Air Transport, 2018). JFK is also one of the 35 airports in the United States equipped with ASDE-X.

The next task was to decide how to collect the data. The study required to have a significant number of landing aircraft. This would require a constant collection period of more than 250 days. The data for the study has already been recorded by the on airport ASDE-X. The contractors to the FAA data storage and research, Airborne Tactical Advantage Company (ATAC), is the supplier of all FAA ASDE-X data. The Next Generation ERAU Advanced Research (NEAR), located in Daytona Beach, Florida, was able to facilitate the acquisition of the necessary data for this research. The raw data required the use of mass storage devices such as an external drive in order to transport.

The next step was to process the data. ATAC was able to process the raw ASDE-X data into a usable CSV file. However, the data was not formatted for the proposed research. Refer to Appendix D for the ATAC metadata. The data contained two files, one for each runway. To refine the data to a usable form, Microsoft Excel was used. The data was opened using Microsoft Excel and then columns and rows were widened to get a graphical representation of the data. The data was sequenced like so: an aircraft header then the position data for that aircraft. The data
continued this pattern until the last aircraft. Refer to figure 3.6 below for a representation of the data layout as provided by ATAC.

Figure 3.6: Raw data as seen in a Microsoft Excel spread sheet. This data included an aircraft header and subsequent position data.

Using an Excel IF function the data was modified to have a complete column of aircraft designators in line with the corresponding position data of the aircraft. The IF statement is shown below.

=IF(AND(D3<>D2,ISTEXT(D3)=TRUE,D3<>"n",D3<>"?",D3<>"b"),D3,L2)

Using a similar IF statement as shown above, the approach runway end was also placed into a continuous column and corresponded with the correct positional data. The runway file
contained both directions of aircraft flow. It is necessary to identify which positional data corresponds to the direction of flow. Runways have two directions of flow exactly 180 degrees opposite of each other. After the runway approach end column is completed, the aircraft header can be removed. Selecting the column that displays longitudinal values as well as question marks (?). Filter out all (?), “blank”, and any airport identifier using the filter command in Excel. After the data is filtered out select the remaining cells, copy, and paste into a new Excel file and a CSV file. Name the new files in a convention to identify the airport, the data type, runway, etc. repeat this step for the remaining raw data.

Using Esri ArcMap add the new CSV data, as mentioned above, by using the Add Data tool in ArcMap. After adding the data, the data set name will be displayed in the table of contents window. Right-clicking on the file will give you the option to “Display Data”, click this option and follow the prompts. Be sure to correctly add the longitude to the X position and Latitude to the Y position and optional, add altitude to the Z position. The data will then need to be georeferenced. The positional data is using the WGS84, be sure to correctly reference this geographical reference system. The data will then be displayed as individual points. Using the “Add Data” tool again, add a basemap to verify the correct position of the data. Refer to figure 3.7.

After the data has been verified to be in the correct location, right-click the new layer in the table of contents and select “attributes table”. Using the select by attributed function within the attributes table, select all data points containing a runway end (there should only be two options). After the selection was made, right-click on the layer name in within the table of contents and choose “export data”. Continue to export the selected data as a shapefile (remember to use a logical file naming convention). Repeat the same sequence to save the other runway end as a
shapefile. This will ensure that the aircraft position data is unique to one direction of flow.

Repeat this step for all runways.

Figure 3.7: The data is displayed using Esri ArcGIS by geographical means.

The next step involves projecting the geographic coordinate system onto the state plane of the airport. Using the search feature in ArcMap, search for “Project (Data Management)”. Select the project tool and be sure the previously created shapefile containing the unique runway end is loaded. The project tool will ask to specify the file to be projected, and the projected geographic coordinate system. The state plane of New York, Long Island, using the NAD83 was selected as the reference for JFK Airport. After the dataset was projected, continue this process for all other
files. After projecting the data to the state plane, the X and Y value of the state plane needs to be added to the file. Again, using the search feature in ArcMap, search for “Add XY (Data Management)”. Select the Add XY tool and follow the prompts to add the XY data to the files. Continue this step for each file.

The next step is to isolate the aircraft that used a specific runway exit. Using ArcMap, open the file containing the XY projected data. Using the select by polygon figure, draw a polygon around the first runway exit, only select the data points within the runway exit. Export the selected features as a temporary shapefile. Using the join command join the XY projected file to the temporary shapefile by the unique key ID. After this join only data containing the aircraft using a specific runway exit will remain. Export this file and use a logical naming convention when saving the shape file. Remove the join from the XY projected file and repeat the process for each runway exit in the file. Repeat this step for each runway end.

The FAA has an Excel file containing aircraft’s unique identifier as well as the aircrafts airport design reference codes. Refer to Appendix B for an abbreviated list. Using Excel open the database file of the file containing the isolated runway exit data. In a new tab, paste the FAA Aircraft Reference Table. Using the VLOOKUP function in excel, add the AAC, ADG, TDG, and MTOW to the existing file by referencing the FAA Aircraft Reference Table. Create a new column and place the taxiway designator the data file represents. Repeat this step for all other files.

Using an FAA source, determine the exact coordinates of all runway ends. The coordinates must be converted into the airports state plane. Create a new column labeled as “Distance from Runway End”, and calculate the distance using the linear distance between two points formula. The runway end and the projected position should be used to determine the distance. Combine all
isolated taxiways into the safe file as the runway end. Refer to figure 3.8 below for the completed processing display of the data.

**Figure 3.8:** The completed data layout after processing as displayed on Microsoft Excel.

### 3.4.2 Speed and Distance Dependent Analysis

The next step was to determine the actual speed range of aircraft exiting runways. The approach for this is to determine the location of the runway exit. The exit location was determined by using distance measuring tools in ArcMap to measure the distance from the runway approach end to the beginning of the runway exit. Refer to Appendix C for the location of all runways and all runway exits used in this study. After the runway exits were located, the data could be filtered in excel to show only data points that where at the beginning of the runway.
exits. Using the filter between function, the distance from runway end column was filtered by a range of 100 feet around the exact location of the exit. This range is required since the data isn’t frequent enough to give an exact location of where the aircraft exited due to the one second delay from the radar.

After the data is filtered, the remaining data is copied and pasted into a new sheet. Using an IF function in excel a new column is made to identify and help filter out extraneous data. This happens when an aircraft has multiple positions within the filtered distance range. Using the Pivot table function in excel, a histogram of aircraft speed is produced. Refer to Appendix E for all exit velocity distributions.

The next step was to determine the distance where aircraft achieved the exit velocity. To determine this distance an analysis or the previous speed distributions is necessary. Using the actual exit speed range found from the histograms relating speed distribution, the excel file can be filtered. Using the filter between values, the speed column is filtered by the actual speed range found earlier. After filtering, the data is copied and pasted into a new sheet. The data is further processed leaving out extraneous aircraft position points and leaving only unique aircraft.

Using the Pivot table function, histograms and tables of the distance to the actual exit velocity, based on each FAA airport design reference, was made. Refer to Appendix F for all distance to safe exit velocity figures.
3.4.3 Runway Exit Location Analysis

The final step was to analyze the previous steps in order to determine runway exit locations. After determining the actual exit speed range for both, high speed exits and right-angled exits, the reference velocity range should be noted and recorded for later use. Using the distance to safe velocity figures, determine the most usable and well distributed FAA airport design classification. This classification should be depicted in logical arrangements within the figures and ultimately show the ADG classification is the well distributed and has the most logical arrangement, meaning the arrangements of the ADG in the figures were expected. After the speed range for high speed exits and right-angled exits are determined as well as the best aircraft classification, the next step is to combine the entire datasets into one large spreadsheet. Each complete runway should be merged together. After the large data set is complete, save the file as an Excel workbook, remembering to use an appropriate naming convention. Reopen the file and, using the actual speed range for a high-speed exit, filter the speed column using the filter between commands. Copy and save the results into a new sheet. Using the pivot table function create a table and related figure that shows the cumulative distribution of the classification determined earlier. The result will be the percent of capture for each ADG based on the distance from the end of the runway refer to figure x. Repeat for the right-angled exit speed distribution.
Chapter 4: Data Analysis and Results

This chapter will analyze the data used during the research and show the results of the study that relates to whether data collected by ASDE-X can be used to help determine a standardized classification system for determining the location of runway exits. This section will also address the legitimacy and limitations of the data and the research in general.

4.1 Runway Exit Velocity

Determining the speed at which aircraft proceeds to take runway exits is one of the main objectives of the study. A normal speed distribution will allow for a general idea of where aircraft will be capable to safely exit the runway. It is expected that a landing aircraft will continuously decelerate until achieving a safe speed to maneuver off the runway. The raw data seem to agree. As the aircraft approach the runway end, it is still at a velocity capable of producing lift. As the aircraft begins to touch down the speed decreases. From the data, the speed continues to decelerate until the aircraft uses a runway exit. It is assumed that the speed at which the aircraft takes the exit is in fact the safe speed for that specific aircraft.

To represent a normalized distribution of exit velocities, it was determined to use a histogram. The histogram would contain only one variable, speed, and would represent the distribution at each runway exit. The frequency of speeds at the exit were counted and displayed as bars on the histogram. Refer to Appendix E for all runway exit speed distributions. All figures displayed a normal distribution, followed a bell shape curve. A normal distribution is necessary for the data to accurately display data as found in the real world. Since each runway exit analyzed had hundreds of aircraft use it, it can be safe to rule out any error associated with a small sample size. The speed distribution range differed between a high-speed exit and a right-
angled exit. As expected, the distribution for a high-speed exit was normally distributed around a higher speed than a right-angled exit.

**4.3 Data Validity, Reliability, and Limitations**

The data was collected and distributed by a Federal Aviation Administration contractor ATAC. The data was reported by one of the most utilized systems in aviation for surface surveillance of aircraft. The accuracy is paramount for the ASDE-X system to be functioning properly. There were no indications of errors or flaws with in the data set or in the processing of the data. All parties involved with the handling and processing the raw data are well respected in the aviation industry. The limitations with the radar data include accurate altitude reporting. Although not necessary for the analysis of this project, the reliability of the altitude reporting may not be appropriate for any research based on altitude reporting. The altitude reporting for many radar-based systems has a tolerance for plus or minus 100 feet. The time interval of the data can limit the accuracy of the analysis. The current ASDE-X system reports positions every second. Aircraft travel at high speeds and decelerate quickly, a one second time interval can result in a position jump of hundreds of feet.

**4.4 Results**

The results of the research find that the average safe velocity for a right-angled runway exit is 25 knots. The safe velocity for a high-speed exit is determined to be 35 knots. Based on these observations the ADG is the best classification to determine the location of runway exits. To represent the location of runway exits Figure 4.1 and Table 4.1 shows potential design guides for locating right-angled runway exits and Figure 4.2 and Table 4.2 shows potential design guides for locating high-speed runway exits.
Figure 4.1: Graphical representation of distance to exit velocities for right-angled exits.

Table 3.1: Tabular representation of capture percentages from distance to exit velocities for right-angled exits

<table>
<thead>
<tr>
<th>Distance from Runway End (Feet)</th>
<th>ADG</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I</td>
</tr>
<tr>
<td>1000</td>
<td>1%</td>
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<tr>
<td>1500</td>
<td>2%</td>
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<tr>
<td>2000</td>
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</tr>
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<tr>
<td>7500</td>
<td>97%</td>
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<td>97%</td>
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</tr>
</tbody>
</table>
Figure 4.2: Graphical representation of distance to exit velocities for high-speed exits.

Table 4.2: Tabular representation of capture percentages from distance to exit velocities for high-speed exits.

<table>
<thead>
<tr>
<th>Distance from Runway End (Feet)</th>
<th>Percent of Capture – High-Speed Exit</th>
<th>ADG</th>
<th>Grand Total</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>I</td>
<td>II</td>
</tr>
<tr>
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<tr>
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</tbody>
</table>
It can be shown as tabular representation of the data used in this research to compare the current FAA AC regarding taxiway locations in Table 4.3 below. The table below used FAA defined categories used during the creation of table 4-13 in AC150/5300-13A to accurately depict a comparison between the AC. Please not that Table 4.3 assumes all weather conditions as opposed to the AC Table 4-13. Please refer to Figure 2.4 as the comparison.

Table 4.3: Tabular representant of the capture percentage by distance from runway threshold to compare to FAA AC150/5300-13A Table 4-13.

<table>
<thead>
<tr>
<th>Distance from Threshold to Exit</th>
<th>Right-Angled Exits</th>
<th>High-Speed Exits</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>S</td>
<td>T</td>
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<tr>
<td>1000 ft</td>
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<td>1500 ft</td>
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<tr>
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<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>
Chapter 5: Discussion

5.1 Determining Runway Exit Velocity

One of the largest unknowns during this research is the speed at which pilots use to take the runway exits. Deceleration rates and runway exiting speeds vary greatly among the myriad of aircraft types due to size, breaking technologies, and runway surface condition. Pilots can be a major culprit causing this unknown. Pilots have a comfort level and can feel the speed of the aircraft and control accordingly. This comfort speed is the optimum speed for the aircraft exiting the runway which varies amongst pilots.

In order to determine the optimal runway exit location the pilot’s comfort and limitation to the time intervals within the radar data a speed distribution must be found. This speed distribution was based on the known exits distance from the runway threshold. A 100 feet tolerance was placed around the exact location of the exit due to the amount of variation of distance within one second intervals. Using this method, it can be certain to obtain the data from every aircraft in the data set. The speed range will then be set by analyzing every runway exit. Refer to Appendix D for illustration of these figures.

5.2 Comparison of the Advisory Circular

The main objective of this research was to propose optimization of the FAA standards regarding runway exit location. It is important to compare the current standards to the actual real world. Table 4.3 attempts to compare the FAA AC150/5300-13A Table 4-13. The result is similar to the table using the older classification system. However, the table may not reflect the optimum exit location. 80% of aircraft at JFK are classified under the Large (L) category,
leaving 10% falling under Heavy (H) and 10% for Twin (T) and Small (S) combined. Knowing
the aircraft makeup of JFK it can be assumed that there is a lot of variation between the aircraft
in the L category. Although the table seems to be relevant to real world applications, the
variation between L category is limiting the optimum performance of the current exit locating
standards.

Weather conditions could not be compared due to the lack of weather information during the
data collection period. However, since the data collection period occurred over a long period of
time, it is assumed that performance, based on weather conditions, are inclusive and reflect well
with the data.

5.2 Meanings and Understandings

A quantitative analysis can be used to determine an ideal location for runway exits for all
aircraft within a specific standardized category based on Airplane Design Group. Since aircraft
can become very heavy, one might expect that the heavier an aircraft is the more distance is
needed in order to slow to a comfortable exit velocity. However, evidence from this research
suggest that basing aircraft deceleration rate on maximum takeoff weigh may not be the most
appropriate approach. The evidence indicates that the physical size of the aircraft is more likely
to determine the location where aircraft exited the runway rather than a weight classification.
This could be the result of a pilot “feeling” the size of an aircraft, like the driver of a car can
sense the size of a vehicle, a pilot generates a comfort level. This comfort lever may translate
into the decision of which runway exit to take.

Airport capacity is always a limiting factor at large commercial airports. Runway efficiency
is an important aspect in increasing capacity. Runway exits are the most likely enhancements to
achieve a better runway efficiency. The speed distributions found in this research help determine that the location of runway exits can be further optimized for the any specific aircraft size. Runway occupancy time can be a major judgment on the capacity of an airport. Measuring ROT with the optimal exit locations would theoretically determine the maximum capacity of the runway.

5.3 Implications of the Study

The significance of the findings can result in a change to the current guideline on locating runway exits. These results from this research can help any size airport obtain the optimum location of runway exits. The current standard set forth by the FAA gives little optimization to small airport for runway exits. The interval between aircraft classification is very significant and impractical for small airports. This study can allow pilots to better optimize the goal of slowing the aircraft safely to a safe exit velocity optimized for exiting the runway in as little time as possible. Airports can better plan for future runway and taxiway improvements to fall in line with optimizing the runway to obtain the maximum capacity possible.

The importance of this study to the aviation industry could be significant. The airport could significantly increase operational efficiency which leads to an increase in safety, operations, and decrease in fuel consumption. This all translate into saving money and more revenue for the airlines and airport as the added capacity results in larger number of passengers and aircraft.
5.4 Relevance of the Study for Future Research

This study leaves an open door for further research. Future research could be to expand on the results of this study to see the impact that airport elevation has on the runway exit distance. The data from this study was collected from JFK Airport in Long Island, New York where the airport elevation is only 13 feet MSL. The same study can be repeated for Denver International Airport where the airport elevation is above 5,000 feet MSL. High altitude is known to cause performance degradation of aircraft propulsion systems and lift generating capabilities. It is expected that this would increase the distances as shown from the results. Studying unique airfield geometry and geometric constraints and applying the method proposed in the research as another study that can be conducted. The results will give the optimum location of runway exits that can be further automated using computer software. Using the approach this study provides can help determine the optimum runway length. Runway are expensive infrastructures and building new runways leaves the large question of how long should it be? Using ASDE-X the optimum distance can be generated similar to the results of this paper.
Chapter 6: Conclusion and Recommendations

Current standards for the location of runway exits are quite dated and uses theoretical equations, small sample tests, and inconsistent aircraft characterizations. The importance of determining the optimal location of runway exits is to decrease the runway occupancy time which translate to safer operation, larger number of operations, fewer delays, and a reduction in fuel consumption. This all translate to an economical boost to the aviation industry. This problem is important to anyone who relies on the aviation industry as a means of transportation or occupation. This document addresses the shortcomings of the related literature and proved a modern method of determining the location of runway exits. The research demonstrated the need for a classification system unique to the current FAA standards when determining the location of all runway exits. The Airplane Design Group is found to be the best classification for locating runway exits.

The results of the research find that the average exit velocity for a right-angled runway exit is 25 knots and average exit velocity for a high-speed exit is determined to be 35 knots. Based on these observations the ADG is the best classification to determine the location of runway exits. An example of this was illustrated by creating a design figure to represent the probable location that an aircraft will exit the runway after landing. These finding were expected and consistent with prior research and experience which also indicate that there is a gap in researching the optimum runway exit locations. An example of this was shown when the current literature had no relevance to optimization of runway exits. This likely resulted from the lack of access to the data collection, the seemingly difficult task of changing FAA guidelines, and the relative age of the last study of runway exits.
Based on the findings of this research it is expected that the current design standards will be updated. Future researchers will be able to build upon this work by using the research approach and method as mentioned in this document. An area of particular significance is further investigation into factors that affect the outcome of runway exit locations. For example, airport elevation, geometric layout, and geographical constraints. From an application perspective it is suggested that these results can be used for optimizing runway efficiency for safety, allowing greater capacity at airports, and standardizing and implementing design procedure.
References


### Appendix A: Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAC</td>
<td>Aircraft Approach Category</td>
</tr>
<tr>
<td>AC</td>
<td>Advisory Circulars</td>
</tr>
<tr>
<td>ADG</td>
<td>Airplane Design Groups</td>
</tr>
<tr>
<td>ADS-B</td>
<td>Automatic Dependent Surveillance-Broadcast</td>
</tr>
<tr>
<td>AGL</td>
<td>Above Ground Level</td>
</tr>
<tr>
<td>ASDE-X</td>
<td>Airport Surface Detection Equipment</td>
</tr>
<tr>
<td>ASPM</td>
<td>Aviation System Performance Metrics</td>
</tr>
<tr>
<td>ATAC</td>
<td>Airborne Tactical Advantage Company</td>
</tr>
<tr>
<td>ATD</td>
<td>Aircraft Type Designator</td>
</tr>
<tr>
<td>CMG</td>
<td>Main Gear Outer Distance</td>
</tr>
<tr>
<td>FAA</td>
<td>Federal Aviation Administration</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>HARNs</td>
<td>High Accuracy Reference Networks</td>
</tr>
<tr>
<td>IAS</td>
<td>Indicated Airspeed</td>
</tr>
<tr>
<td>ICAO</td>
<td>International Civil Aviation Organization</td>
</tr>
<tr>
<td>JFK</td>
<td>John F Kennedy International Airport</td>
</tr>
<tr>
<td>MGW</td>
<td>Main Gear Width</td>
</tr>
<tr>
<td>MSL</td>
<td>Above Mean Sea Level</td>
</tr>
<tr>
<td>MSSR</td>
<td>Monopulse Secondary Surveillance Radar</td>
</tr>
<tr>
<td>MTOW</td>
<td>Maximum Certified Takeoff Weight</td>
</tr>
<tr>
<td>NAD83</td>
<td>North American Datum of 1983</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>NEAR</td>
<td>Next Generation ERAU Advanced Research</td>
</tr>
<tr>
<td>PDARS</td>
<td>Performance Data Analysis and Reporting System</td>
</tr>
<tr>
<td>REA</td>
<td>Runway Exit Availability</td>
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<tr>
<td>REDIM</td>
<td>Runway Exit Design Interactive Model</td>
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<td>Rapid Taxiway Exits</td>
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<td>Secondary Surveillance Radar</td>
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<td>True Airspeed</td>
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<tr>
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<td>Traffic Alert and Collision Avoidance System</td>
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<td>TDG</td>
<td>Taxiway Design Group</td>
</tr>
<tr>
<td>TERP</td>
<td>Terminal Airspace Procedure</td>
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<tr>
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<td>Taxiway Object Free Area</td>
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<td>TSA</td>
<td>Taxiway Safety Area</td>
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<td>UTM</td>
<td>Universal Transverse Mercator</td>
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<td>World Geodetic System of 1984</td>
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Figure B1: Airport diagram of John F/ Kennedy International Airport showing all runway and taxiway locations. Source: FAA
Figure B2: Traffic report for JFK for May 2018. This report shows the volume of passengers and operations at JFK. Source: The Port Authority of NY & NJ
Figure B2.1: Page 2 of the Traffic report for JFK for May 2018. This report shows the volume of passengers and operations at JFK. Source: The Port Authority of NY & NJ
Appendix C: Airport Surface Detection Equipment Model X

Airport Surface Detection System - Model X (ASDE-X) is a surveillance system using radar, multilateralization and satellite technology that allows air traffic controllers to track surface movement of aircraft and vehicles (FAA, 2014). ASDE-X will alert air traffic controllers of possible runway conflicts by surveillance of the movement of all vehicles on runways and taxiways. ASDE-X can track both transponder equipped and non-transponder equipped aircraft (on the ground and in the air) and ground support vehicles in the airport movement area (FAA, 2014). The FAA says that ASDE-X uses the following sources as data receivers (FAA, 2016):

- Surface surveillance radar located on top of the air traffic control tower and / or surface surveillance radar located on a remote tower
- Multilateralization sensors located around the airport
- Airport Surveillance Radars such as the ASR-9
- Automatic Dependent Surveillance — Broadcast (ADS-B) sensors
- Terminal automation system to obtain flight plan data.

The following is stated by the FAA: Controllers in the tower are presented this information on a color display depicting aircraft and vehicle positions as an icon overlaid on a map of the airport's runways/taxiways and airport approach corridors. The system continuously updates the map of the airport movement area that controllers can use to enhance their situational awareness. It's particularly beneficial at night or during inclement weather when visibility is poor. The ASDE-X system is also equipped with visual and aural alarms that will alert controllers of possible runway incursions (FAA, 2016). The following 35 major airports have received ASDE-X according to the FAA:
Baltimore Washington International Thurgood Marshall Airport (BWI)

Boston Logan International Airport (BOS)

Bradley International Airport (BDL)

Chicago Midway Airport (MDW)

Chicago O'Hare International Airport (ORD)

Charlotte Douglas International Airport (CLT)

Dallas Fort Worth International Airport (DFW)

Denver International Airport (DEN)

Detroit Metro Wayne County Airport (DTW)

Fort Lauderdale / Hollywood Airport (FLL)

General Mitchell International Airport (MKE)

George Bush Intercontinental Airport (IAH)

Hartsfield Jackson Atlanta International Airport (ATL)

Honolulu International Airport (HNL)

John F. Kennedy International Airport (JFK)

John Wayne — Orange County Airport (SNA)

LaGuardia Airport (LGA)

Lambert St. Louis International Airport (STL)
Las Vegas McCarran International Airport (LAS)

Los Angeles International Airport (LAX)

Louisville International Airport-Standiford Field (SDF)

Memphis International Airport (MEM)

Miami International Airport (MIA)

Minneapolis St. Paul International Airport (MSP)

Newark International Airport (EWK)

Orlando International Airport (MCO)

Philadelphia International Airport (PHL)

Phoenix Sky Harbor International Airport (PHX)

Ronald Reagan Washington National Airport (DCA)

San Diego International Airport (SAN)

Salt Lake City International Airport (SLC)

Seattle Tacoma International Airport (SEA)

Theodore Francis Green State Airport (PVD)

Washington Dulles International Airport (IAD)

William P. Hobby Airport (HOU)
Appendix D: Exit Velocity Distribution Figures

The following figures shows the exit velocity distribution of each indicated runway exit. These figures were derived from the data analyzed in this research document from John F. Kennedy International Airport (JFK). The figures are arranged in order of the associated approach runway. Please refer to Appendix B for the location of the runway exits depicted in these figures.

**D1 Runway 4L**

![Speed Distribution at Taxiway J Entrance](image)

**Figure D1.1: Speed distribution at Taxiway J from Runway 4L approach**
Figure D1.2: Speed distribution at Taxiway H from Runway 4L approach

Figure D1.3: Speed distribution at Taxiway GG from Runway 4L approach
Figure D1.4: Speed distribution at Taxiway G from Runway 4L approach

Figure D1.5: Speed distribution at Taxiway F from Runway 4L approach
Figure D1.6: Speed distribution at Taxiway YA from Runway 4L approach

D2 Runway 22R

Figure D2.1: Speed distribution at Taxiway H from Runway 22R approach
Figure D2.2: Speed distribution at Taxiway J from Runway 22R approach

Figure D2.3: Speed distribution at Runway 31L from Runway 22R approach
Figure D2.4: Speed distribution at Taxiway K4 from Runway 22R approach

Figure D2.5: Speed distribution at Taxiway K3 from Runway 22R approach
Figure D2.6: Speed distribution at Taxiway K2 from Runway 22R approach

Figure D2.7: Speed distribution at Taxiway K1 from Runway 22R approach
D3 Runway 31L

Figure D3.1: Speed distribution at Taxiway M from Runway 31L approach

Figure D3.2: Speed distribution at Taxiway MB from Runway 31L approach
Figure D3.3: Speed distribution at Taxiway MC from Runway 31L approach

Figure D3.4: Speed distribution at Taxiway MD from Runway 31L approach
Figure D3.5: Speed distribution at Taxiway PA from Runway 31L approach

Figure D3.6: Speed distribution at Taxiway PC from Runway 31L approach
Appendix E: Distance to Exit Velocity Figures

The following figures displays the distance to reach the runway exit velocity of each indicated runway exit. These figures were derived from the data analyzed in this research document from John F. Kennedy International Airport (JFK). The figures are arranged in order of the associated approach runway and contain comparisons between using the Aircraft Approach Code (AAC) and Airplane Design Group (ADG) classifications. Please refer to Appendix B for the location of the runway exits depicted in these figures.

E1 Runway 22R

![Graph](image)

Figure E1.1: Distance to achieving exit velocity at Taxiway H from Runway 22R approach
Figure E1.2: Distance to achieving exit velocity at Taxiway J from Runway 22R approach

Figure E1.3: Distance to achieving exit velocity at Runway 31L from Runway 22R approach
Figure E1.4: Distance to achieving exit velocity at Taxiway K4 from Runway 22R approach

Figure E1.5: Distance to achieving exit velocity at Taxiway K3 from Runway 22R approach
Figure E1.6: Distance to achieving exit velocity at Taxiway K2 from Runway 22R approach

Figure E1.7: Distance to achieving exit velocity at Taxiway K1 from Runway 22R approach
E.2 Runway 31L

Figure E2.1: Distance to exit velocity using AAC at Taxiway M from Runway 31L approach

Figure E2.2: Distance to exit velocity using ADG at Taxiway M from Runway 31L approach
Figure E2.3: Distance to exit velocity using AAC at Taxiway MB from Runway 31L approach

Figure E2.4: Distance to exit velocity using ADG at Taxiway MB from Runway 31L approach
Figure E2.5: Distance to exit velocity using AAC at Taxiway MD from Runway 31L approach

Figure E2.6: Distance to exit velocity using ADG at Taxiway MD from Runway 31L approach
Figure E2.7: Distance to exit velocity using AAC at Taxiway PA from Runway 31L approach

Figure E2.8: Distance to exit velocity using ADG at Taxiway PA from Runway 31L approach
Figure E2.9: Distance to exit velocity using AAC at Taxiway PC from Runway 31L approach

Figure E2.10: Distance to exit velocity using ADG at Taxiway PA from Runway 31L approach