The Influence of Runway Occupancy Time and Wake Vortex Separation Requirements on Runway Throughput

By

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B.S. Aerospace Engineering
University of Florida, 2011

SUBMITTED TO THE DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE IN AEROSPACE ENGINEERING
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

September 2013

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Submitted to the Department of Aeronautics and Astronautics
on August 9, 2013, in partial fulfillment of the
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Master of Science

Abstract

Air traffic growth in the U.S. has led to runway capacity constraints in the air transportation network. There has been limited new construction of runways due to land availability. One approach to increase capacity of existing runways is to reduce inter-arrival separations during the final approach phase of flight. This study evaluates two major elements influencing runway capacity; runway occupancy and wake vortex separation, and under what conditions each becomes a constraint to runway capacity. A detailed analysis of runway occupancy time measurements and wake vortex separation measurements is performed for Boston, Philadelphia, New York La Guardia, and Newark airports based on Airport Surface Detection Equipment Model-X (ASDE-X) aircraft surveillance data. The findings of this study indicate that runway occupancy does not necessary scale with aircraft size. Small aircraft often occupy the runway as long as large aircraft, which limits the potential for reduced separations behind small aircraft. The results also indicate that high-speed runway exits can make a significant difference in runway occupancy. Runways equipped with high-speed exits have lower runway occupancy times than runways equipped with standard 90-degree exits. Comparison of runway occupancy times in Visual Meteorological Conditions (VMC) and Instrument Meteorological Conditions (IMC) suggest no significant difference between the two weather conditions. Wake vortex separation measurements show that aircraft pairs with small lead aircraft receive longer separation buffers than other aircraft pairs, and airports with more runways implement longer separation buffers. The comparison of landing time intervals and runway occupancy illustrates that wake vortex separation requirements limit runway capacity when heavy or Boeing 757 is the lead aircraft. Lastly, this study evaluates the runway capacity benefits of reduced wake separation requirements for the aircraft re-categorization (RECAT) program. The results estimate an 8.2-8.3% increase in runway capacity at Philadelphia and at Newark, a 7.8% increase at Boston, and a 5.1% increase at La Guardia. The magnitude of benefits strongly depends on how the local traffic mix looks like.

Acknowledgements

First and foremost I would like to thank my adviser, Professor John Hansman, for his continuous support and guidance throughout this study. His wisdom and constructive criticism not only helped to improve my quality of work, but also cultivated my critical thinking skills when doing research. I would also like to thank Professor Antonio Trani, Professor John Shortle, Ed Johnson and Tom Proeschel for their help and assistance with this project.

A special acknowledgement goes to Alexander and Vishnu for their incredible support and friendship since the very first day we arrived to MIT. You have been a great inspiration and a source of energy ever since. I hope our travel and bike adventures will continue soon! I would also like to thank Heiko who has been supportive in every way. From sharing a desk to taking study breaks on the Charles, we have become great friends and amazing research partners.

A group from ICAT has not been mentioned yet. I would like to thank the Skylounge crew for creating a fantastic work environment. From discussing news, gossip, and research to organizing lunch outings, you have made the lab a fun place to be. I also thank D2 for encouraging me to begin my journey at MIT.

Last, but not least, I would like to thank my family! Their support has been unconditional throughout the past years, and without them this work would not have been possible.

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Chapter 1

1 Introduction

1.1 Motivation

Airport and airspace capacity have become a major concern in today's air transportation environment, as the industry is growing globally approximately at a rate of 5% annually [1]. The revenue passenger kilometer (RPK) growth between 1996 and 2012 is shown below in Figure 1-1. This growth has led to increased congestion and longer delays since the current airspace system that cannot handle such a large increase in traffic.

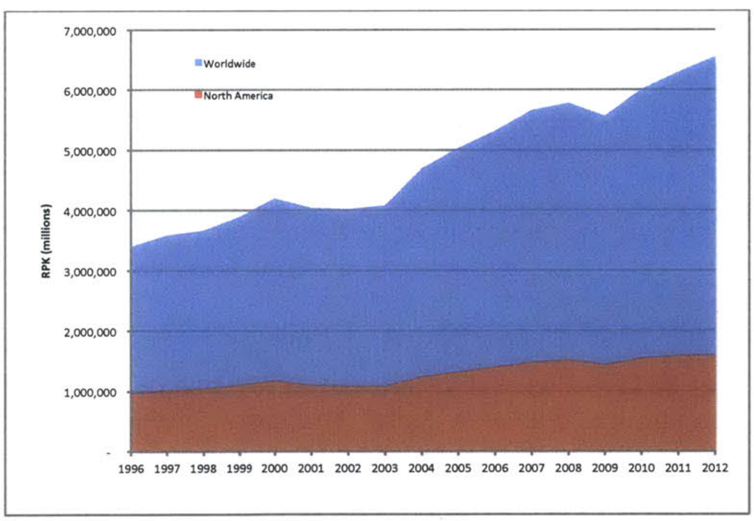


Figure 1-1. Revenue Passenger Kilometers (RPK) in North American and worldwide (Source: IATA, BTS [2])

Capacity constraints can increase costs both for airlines and to passengers, and longer delays can create passenger inconvenience. One bottleneck for growth is terminal area capacity. The terminal area is a controlled airspace in the proximity of major airports with high volumes of traffic. Since arriving and departing flights share the same airspace, holding patterns and delays can build up due to the limited number of runways at an airport. One approach to increase throughput is to expand airports with additional runways. However, the construction of new runways and opening of new airports does not only require large capital investment, but it is also limited by land availability, and it is subject to noise and environmental regulations. The lack of airport expansion projects is clearly reflected in the number of commercially serviced airports in the United States, which has been decreasing in the past 10-15 years, as shown in Figure 1-2 [3].

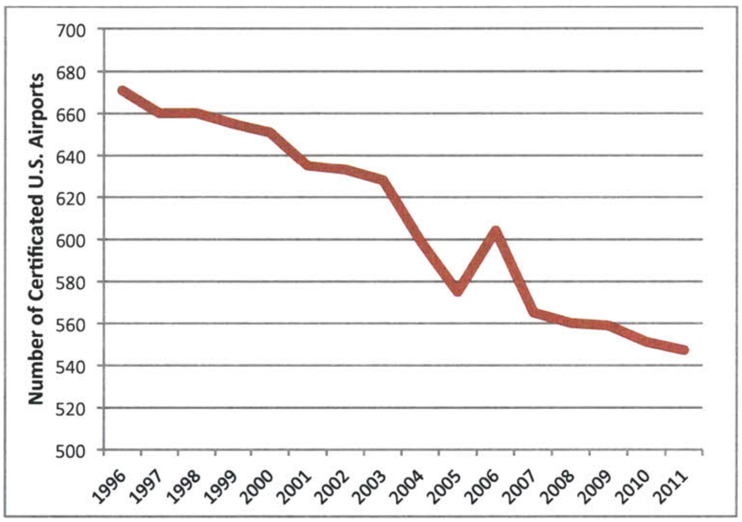


Figure 1-2. U.S. Airports with commercial service (DOT)

Since the construction of new airports and new runways is limited, another approach is needed to accommodate air traffic growth. This approach looks at the factors that limit runway throughput. The first factor is runway occupancy. In the United States and in several other countries, simultaneous runway occupancy is not allowed. This means that only one landing aircraft is allowed to be on the runway at a given time to minimize the risk of runway collisions. The following arrival can only take place once the runway is clear of the preceding aircraft. If the preceding aircraft has not cleared the runway, the following aircraft has to initiate a go-around, which hinders runway throughput. Consequently, short runway occupancy is beneficial to increase runway throughput.

The second major element that limits runway throughput is wake vortex separation. Inter-arrival spacing is based on prescribed requirements that aircraft must follow. In bad weather conditions, it is the air traffic controllers' responsibility to maintain required separations between arrivals. On good weather days, however, this responsibility is transferred to the pilots, who then decide on the appropriate spacing. This shift of responsibility to the pilots often leads to increased runway throughput due to smaller inter-arrival spacing, which shows that separation requirements could potentially be reduced when bad weather conditions prevail. If wake vortex separation standards can be reduced without compromising safety, the reduced spacing is likely to have a positive impact on airport capacity. There are a number of US and international proposals for reduced wake separation requirements, one of which includes the re-categorization of aircraft and reduced separations between certain aircraft pairs (discussed in Chapter 2). Other proposals include crosswind enabled reduced separations, time-based separation requirements, and dual runway threshold systems.

The objective of this study is to understand when runway occupancy becomes a constraint and when wake separation becomes a constraint to runway throughput. With the introduction of the Airport Surface Detection Equipment Model X (ASDE-X), a new source of data is available that allows for direct measure of this paramter. ASDE-X collects information from surface radars, Automatic Dependent Surveillance-Broadcast (ADS-B) sensors, terminal radars, and aircraft transponders to determine the position of aircraft both on the surface and in the air within close proximity of the terminal area [4]. Analyzing aircraft position data with high accuracy can provide a realistic picture of today's typical runway occupancy times and inter-arrival separations. This new data source can also help to quantify the potential runway throughput benefits of reduced wake separation concepts.

1.2 Research Objectives

The objectives of this study are summarized as:

1. Measure runway occupancy times and wake vortex separations by investigating ASDE-X aircraft surveillance data.
2. Determine under what conditions runway occupancy becomes the limiting factor for runway throughput.
3. Evaluate inter-arrival separations and identify potential opportunities for reduced minimum separations.
4. Quantify runway capacity benefits of reduced wake separation concepts.

The focus of this study is to provide high fidelity measurements of runway occupancy times and inter-arrival separations for various aircraft categories by using aircraft surveillance data. These measurements will help to identify whether runway occupancy is restricting the possibility of reduced separations between certain aircraft pairs. The results of this study will show the limitations and benefits of reduced separation concepts, and will provide decision makers with realistic capacity impact estimates.

1.3 Thesis Outline

The thesis begins with an overview of previous research work on runway occupancy measurements and wake separation concepts. Chapter 2 explains the concept of wake vortex turbulence and explains the wake separation standards applied in the present airspace system. Several reduced separation proposals are discussed in details with a focus on re-categorization of aircraft into new aircraft wake categories. Chapter 2 also introduces the Airport Surface Detection Equipment Model – X (ASDE-X) aircraft surveillance system, which provides high accuracy aircraft position data for runway occupancy and wake separation measurements. This chapter also discusses the runway capacity model that is used to estimate the potential benefits of re-categorization. The runway capacity model requires a detailed data analysis of runway occupancy and wake separations, both of which are explained in the following chapters.

Chapter 3 is a detailed study on runway occupancy. This chapter looks at runway occupancy times for each of the aircraft wake groups by analyzing aircraft position data. The results are evaluated across multiple runways at several airports and the runway occupancy influencing factors are explained in details.

Chapter 4 evaluates the inter-arrival separations applied in today's environment; it compares observed separations to the minimum separation standards, and to runway occupancy times. The results of this wake separation study can provide information about the additional spacing controllers use and it can identify opportunities for reduced separation minimums between certain aircraft categories.

Chapter 5 presents the capacity benefits of re-categorization by applying the results of the runway occupancy and wake separation analysis.

Chapter 6 summarizes the findings of the study and makes recommendations for future research.

Chapter 2

2 Background and Literature Review

Chapter 2 introduces two key limitations to runway capacity growth: wake turbulence separation and runway occupancy. This chapter begins with the concept of wake turbulence and introduces current wake separation requirements. The traffic mix, the sequencing of departure and arrival movements, and weather conditions all influence wake separation requirements. Furthermore, the number of runway exits, their location, and the availability of high-speed exits influence runway occupancy. Long runway occupancy times can be a limiting factor in runway throughput. When runway occupancy is short, wake vortex separation becomes the restraining factor. A number of proposals have been established to mitigate wake vortices and to enable reduced separations. This study focuses on re-categorization of aircraft as one of the reduced inter-arrival separation concepts, which can lead to increased runway throughput.

2.1 Wake Vortex Separation

Wake vortex turbulence research has been of great interest since the early introduction of commercial jet aircraft. Wake vortex is an unavoidable side product of aerodynamic lift. The low-pressure air above the wing surface unites with the high-pressure air under the wing surface at the wing tip. The pressure differential leaves a swirling mass of airflow behind, as shown in Figure 2-1. The strength of the wake vortex is largely a function of the weight of the aircraft, the speed at which it flies, and the profile of the wing. Consequently, large aircraft generate stronger wake vortices than small aircraft. A Wake Vortex Encounter (WVE) can occur when a small aircraft follows a large aircraft too closely. This is a potential hazard for small aircraft since it can lead to a complete loss of control in the aircraft.

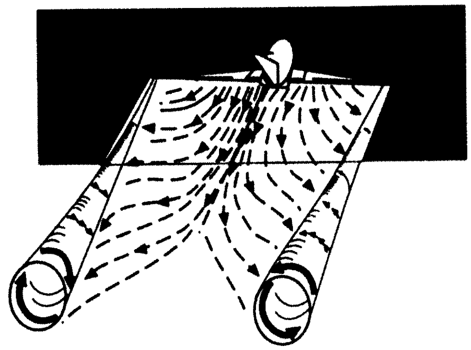


Figure 2-1. Illustration of a wake vortex generator aircraft in flight [1]

In order to minimize the risk and to avoid WVE, the International Civil Aviation Organization (ICAO) and the Federal Aviation Administration (FAA) in the United States have established minimum wake separation requirements that are applied in all stages of flight [5]. In the United States aircraft are put into wake groups, such as Super (A380), Heavy (B747, B777), Large (A320, B737), and small (SF340, E120), based on their maximum takeoff weight (MTOW). The FAA weight criterion is shown in Table 2-1. As an aside, the Boeing 757 is assigned to its own wake category, because there are no other aircraft of similar weight and size, and because it generates stronger wake vortices than large aircraft.

Table 2-1. Aircraft wake categories based on MTOW

	Heavy	Large	Small
MTOW (lbs)	MTOW ≥ 300,000	41,000 < MTOW < 300,000	MTOW ≤ 41,000

Minimum separations between aircraft vary upon what type of aircraft is leading and what type is following. Each of the wake group lead-follow pairs has a required minimum separation distance assigned, which is given in nautical miles. The final approach separation minimums, as defined by the FAA, are summarized in Table 2-2.

Table 2-2. Final approach separation minimums in the United States (IFR)

Leader \ Follower (NM)	Super	Heavy	B757	Large	Small
Super	2.5/3	6	7	7	8
Heavy	2.5/3	4	5	5	6
B757	2.5/3	4	4	4	5
Large	2.5/3	2.5/3	2.5/3	2.5/3	4
Small	2.5/3	2.5/3	2.5/3	2.5/3	2.5/3

The table describes leader aircraft on the left column, and the follower aircraft on the top row. For instance, a heavy aircraft followed by a large aircraft requires a minimum of 5 NM separation, and a large aircraft followed by a small aircraft requires a minimum of 4 NM spacing. For some aircraft pairs, the separation is shown as 2.5 or 3 NM. These values are based on the Minimum Radar Separation (MRS), which is the authorized separation between aircraft established on the final approach course within 10 NM of the runway. The MRS is 3 NM when radar capabilities at a given location permit. A reduced separation of 2.5 NM may be applied when the average runway occupancy time of landing aircraft is statistically proven, by means such as data collection and statistical analysis, not to exceed 50 seconds, braking action is reported as good, and the runway turnoff points are visible from the control tower [5], [6]. For aircraft pairs, where the MRS dictates the separation minimum, runway occupancy is very likely to be the limiting factor for runway throughput. For all other aircraft pairs, the separation minimum is driven by wake turbulence, which is likely to be the limiting factor for runway throughput.

These final approach separation rules are only applicable in Instrumental Meteorological Conditions (IMC), i.e. flying in clouds and in poor weather. Under IMC, pilots fly under Instrument Flight Rules (IFR) and it is the air traffic controllers' responsibility to ensure that the minimum separation standards are maintained at all times.

In visual meteorological conditions (VMC), pilots can fly under visual flight rules (VFR) and the "see and avoid" rule applies for separations. If the pilot of the trailing aircraft confirms the preceding aircraft in sight, it is the pilot's responsibility to maintain an appropriate safe separation. The required minimum separation for instrumental approaches does not apply in this case. This shift of responsibility from the controller to the pilot to maintain a sufficient separation can lead to an increased arrival rate and higher arrival capacity at the airport due to reduced separations.

The separation requirements are different for departures than for arrivals. For departures, instrument and visual separation rules are the same, as they are independent of the weather conditions. For example, the required separation behind Heavy jets and B757 aircraft is two minutes when aircraft depart from the same runway. Separation requirements are more complex when crossing runways or closely spaced parallel runways are used, but for the purpose of this study only single runway arrival separations are considered.

2.2 Runway Occupancy

This study focuses on Runway Occupancy Time (ROT) measurements for arrivals and defines ROT as the time interval from threshold crossing to crossing the runway exit holding point marker. Since the number of exits and the location of runway exits influence runway occupancy times, runway exits are likely to have a strong impact on runway throughput.

A number of studies have been conducted on predicting and measuring runway occupancy times. In earlier studies, observational data sometimes is not enough to achieve statistically significant conclusions, and the measurements are subject to large uncertainty. Weiss (1985) collected runway occupancy information at four airports (Los Angeles, San Francisco, Atlanta, and Dallas-Fort Worth) to determine whether a reduced longitudinal separation is feasible [7]. Haynie (2002) also measured runway occupancy times at Atlanta Hartsfield airport by observing operations from a nearby hotel [8]. The data collection is limited to timing runway threshold and runway exit crossings for arriving aircraft. In some cases the landing time intervals are below the runway occupancy times, which might have been due to simultaneous runway occupancy. Since this study is purely observational, there is considerable uncertainty with the measurements.

Lee et al. (1999) also studied runway occupancy times at Atlanta using the NASA Dynamic Runway Occupancy Measurement System (DROMS) [9]. DROMS is an automated tool that collected runway occupancy times for over 3000 arriving aircraft, also including the type and operator of the aircraft, as well as the runway exit used by the aircraft. DROMS calculated aircraft position by measuring the difference in distance to two or more stations at known locations every second. The data excluded runway occupancy times below 25 seconds or above 65 seconds, assuming the data is incorrect or the aircraft taxied to a specific location at the end of the runway. The study concluded that runway occupancy times are dependent on aircraft weight and speed, and there is no significant difference between carriers or headwind/tailwind conditions. The overall average runway occupancy time is 45 seconds, which is below the 50-second runway occupancy requirement for the 2.5 NM inter-arrival separation between certain aircraft pairs. Although DROMS measurements have improved accuracy over visual observations, they require special equipment at each airport for any detailed runway occupancy studies.

2.3 Runway Capacity

The arrival capacity of a single runway is defined as the maximum number of landings that can be performed in a given period of time while maintaining all separation requirements under continuous demand [10]. Runway capacity may vary if there are departures sequenced in between arrivals, since inter-arrival spacing has to be increased. Runway throughput is defined as the number of aircraft that use the runway per unit time. Throughput is usually less than runway capacity due to longer than necessary inter-arrival spacing, low demand hours, and changing traffic mix during the day.

In the case of a multiple runway system, a Pareto capacity envelope, such as the one shown in Figure 2-2, can illustrate maximum runway capacity. The Pareto envelope defines the maximum number or arrivals and departures that can be performed until the frontier, when any additional increase in arrivals (or departures) is only plausible by reducing the departure (or arrival) rate. Each additional arrival is traded off for an addition departure and vice versa. For instance, in Figure 2-2, 13 departures can be achieved with up to 9 arrivals per quarter hour. Increasing the arrival rate further, however, requires decreasing the departure rate. In order to reach the maximum arrival rate, only 10 departures can be performed.

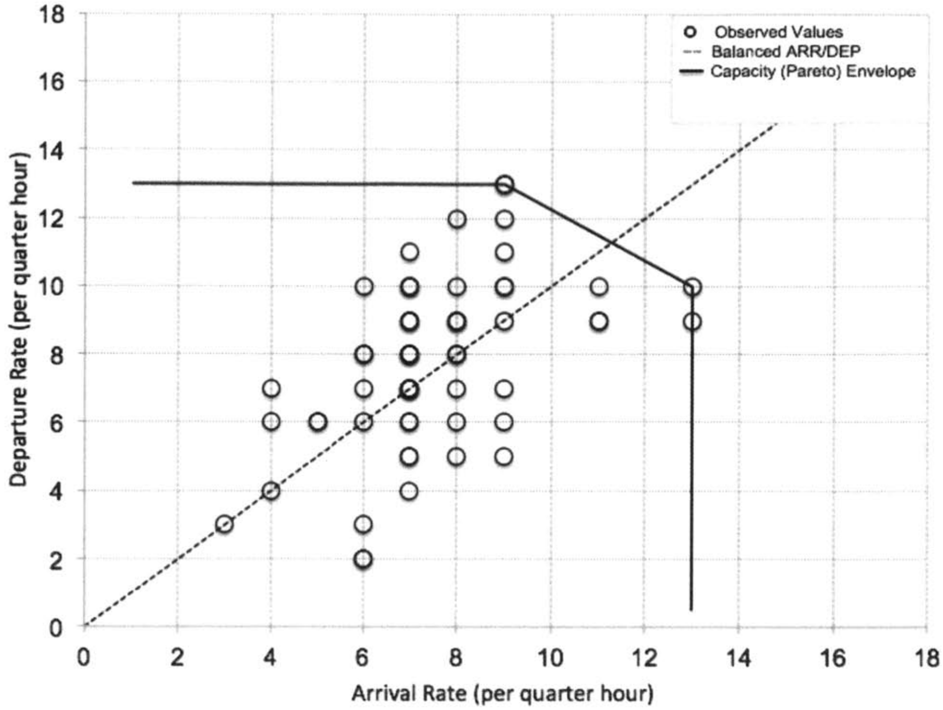


Figure 2-2. Example Pareto capacity envelope for BOS

The circles in Figure 2-2 are observed runway throughput values at Boston from a typical day of operations. The observed values all fall within the capacity envelope of the runway system. In order to accommodate air traffic growth, the maximum capacity envelope needs to expand. As the air transportation industry continues to grow, runway capacity is already reaching its limits. Some of the busiest airports in the Unites States, such as New York's Kennedy, LaGuardia, or Washington's Reagan National have already been forced to implement a slot control system to prevent further delays and congestion in the airspace [11].

Expanding runway capacity by physically expanding airport infrastructure requires long term planning, negotiation and approval processes, large capital investment, and it is often restricted by land availability or environmental regulations. London Heathrow, for instance, is actively seeking an opportunity for an additional runway in order to increase capacity and to stay competitive with other major European hub airports. Likewise, in Boston, it took several decades to plan and construct an additional unidirectional runway to handle growing demand [12]. For this reason, a better approach to increase capacity is to reduce wake separation requirements, and to understand what other factors influence runway capacity.

2.3.1 Factors Influencing Runway Capacity

For simplicity, this study considers single runway operations. The arrival process begins far out from the destination airport. Air traffic controllers start sequencing arriving flights long before they reach the terminal area. Once aircraft turn on final approach, the previously introduced wake separation requirements are enforced. When aircraft land, runway occupancy plays a role in determining when the next landing can take place. The capacity of a runway is also influenced by many other factors, which are summarized in Figure 2-3 below.

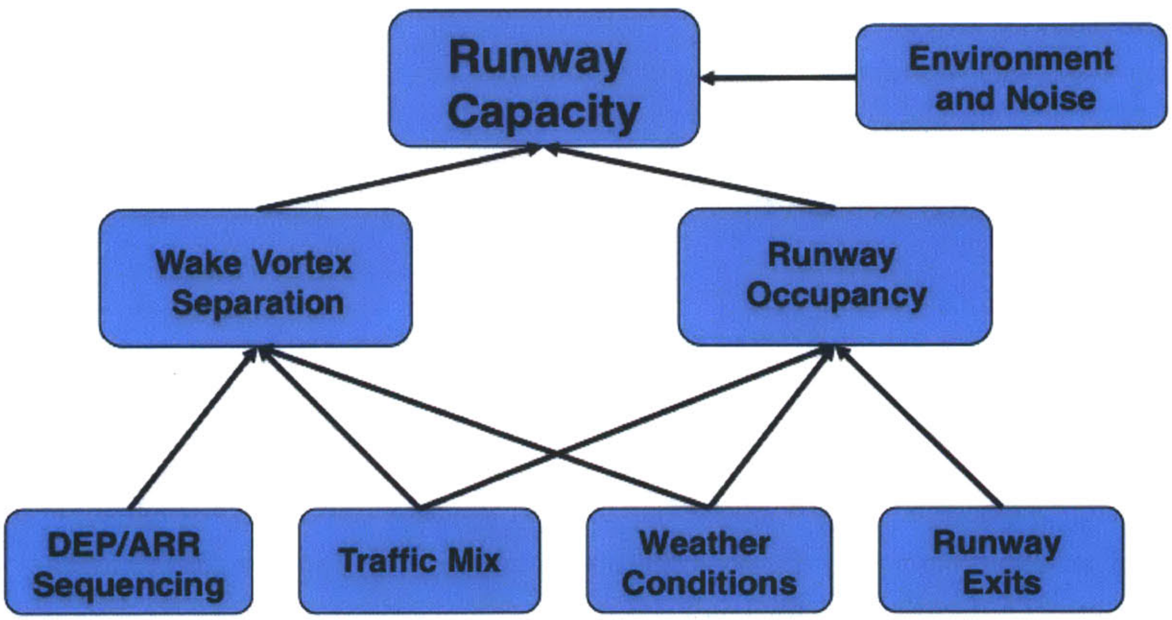


Figure 2-3. Factors influencing runway capacity

The two major elements limiting capacity of a single runway are wake vortex separation requirements and runway occupancy. These two elements, however, are influenced by many other variables. Wake vortex separation requirement depend on the sequencing of departure and arrival movements and the types of aircraft operating at the airport. Weather conditions influence both separation requirements and runway occupancy and runway exits also have an effect on ROT.

Runway capacity can vary significantly based on the sequencing of arrival and departure movements, which determines the appropriate wake separation requirements. As mentioned earlier, wake separation requirements are established on final approach for arriving aircraft, but departing aircraft also generate wake vortices. The capacity of a runway is higher when it is used mostly for departures than when it is used mostly for arrivals due to the less restrictive separation requirements. When a departure is scheduled between two consecutive arrivals, the arrival separation is usually longer to permit the line up and take off roll. Accordingly, strategic sequencing of movements can increase runway capacity.

The mix of aircraft operating at an airport can influence average separations and hence, runway capacity. Aircraft pairs in which the lead aircraft is heavy or large require a longer separation due to the stronger wake turbulence they generate, than aircraft pairs with a smaller lead aircraft. The larger the required separation is, the lower the runway capacity. Airports with a high share of international or cargo traffic see larger separation requirements, and consequently lower capacity, than airports with mostly regional jet operations. A relatively homogeneous aircraft mix usually leads to higher capacity than a nonhomogeneous mix.

Runway capacity can vary throughout the day with changing traffic density and dynamic weather conditions. Visibility and cloud ceiling determine separation requirements for airport operation (instrument or visual). In inclement weather, the separation requirements are higher than in good weather conditions, which reduces the runway's hourly capacity. Heavy rain, snow, and ice also increase ROT, as they can reduce braking performance for landing aircraft.

Figure 2-4 shows the runway capacity of Boston Logan for a one-day period on June 3, 2013. Instrument weather conditions occured in the morning (highlighted with grey boxes), which led to lower runway capacity until early afternoon.

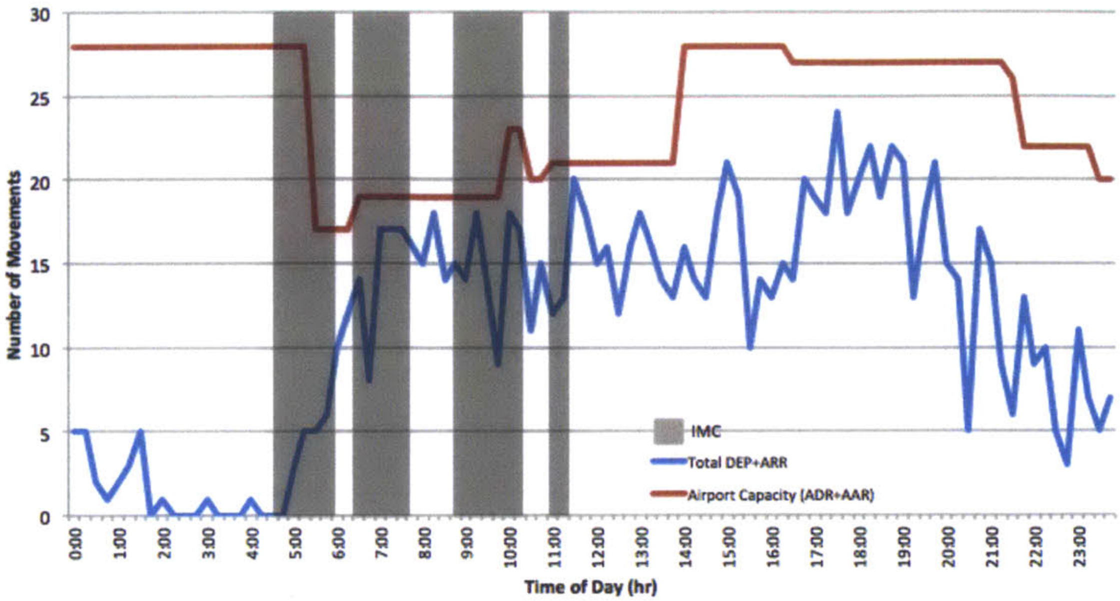


Figure 2-4. Demand and capacity fluctuates throughout the day at Bostonon June 3, 2013. The airport operates at lower capacity in IMC between 5AM and 11AM, highlighted by the grey time intervals (Source: FAA Operations & Performance Data).

The type of runway exits and their locations strongly influence runway occupancy, and runway capacity. The location of the runway exits influences how long the runway is occupied before the next landing or departure can take place on the same runway. High-speed turn offs can also reduce runway occupancy by letting aircraft exit the runway at a faster speed than standard 90-degree exits. An example of a standard exit and a high-speed exit can be seen in Figure 2-5.

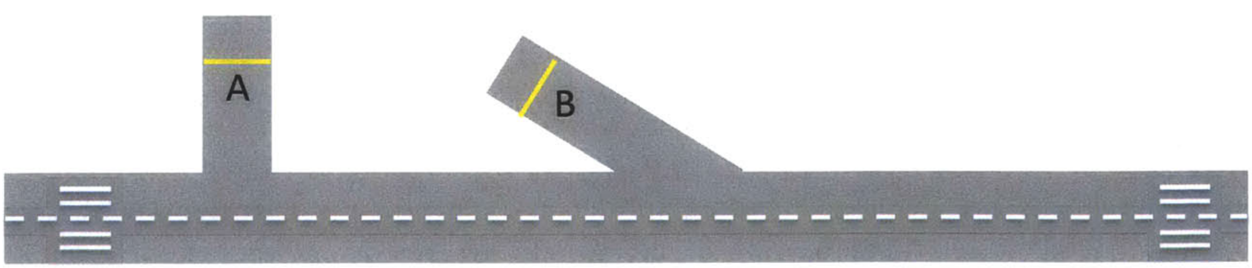


Figure 2-5. Standard (A) and high-speed (B) runway exits

High-speed exits are designed to get an aircraft (that is decelerating) off the runway as fast as possible. Faster exits reduce runway occupancy by clearing the runway quickly for the next aircraft. On the flip side, standard runway exits require the aircraft to slow down further, which results in higher runway occupancy times and lower runway throughput. The construction of high-speed exits is higher than the cost of conventional exits, but the additional cost may be justified if lower runway occupancy allows for reduced separations and increased runway throughput.

Environmental regulations also have an impact on capacity. Noise quotas at many airports limit operations late night operations, and runway configurations throughout the day may change to mitigate the air traffic impact on neighborhoods and communities around the airport.

2.3.2 Modeling Runway Capacity

Measuring runway capacity is necessary for long term planning to anticipate any plausible capacity changes for which controllers can prepare. Runway capacity measurements are essential to predict capacity changes in the long-term. In case of reduced capacity, various flow control methods can be implemented to minimize airborne delays and to maintain operational performance.

A variety of mathematical and computer simulation models have been developed to calculate runway capacity. In this study, a probabilistic queuing model is used as the basis for estimating capacity of a single runway. This model is developed by Blumstein (1959) to estimate capacity when a runway is used solely for arrivals [13]. Odoni and de Neufville extended this model to include departures and mixed movements [10].

The arrival capacity model assumes that arriving aircraft share a common final approach path with a known final approach fix. The length of the final approach is denoted by r. The leading aircraft's weight group is denoted with the letter i, and the following aircraft's group with the letter j. The inter-arrival minimum separation requirements are defined according to the FAA standards under IFR, and they are maintained at all times on approach. S_{ij} indicates the minimum required separation between the leading aircraft type and the following aircraft type. Similarly, T_{ij} is the minimum time interval between successive arrivals for the aircraft i and j. The final approach velocities are denoted by v_i and v_j, respectively.

The minimum time interval between successive arrivals is dependent on whether the lead aircraft or trailing aircraft is flying the final approach faster. When the leading aircraft is flying faster, the separation between the pair is at its minimum when the leading aircraft begins the final approach at the final approach fix, as shown in Figure 2-6 below. This is called an opening case.

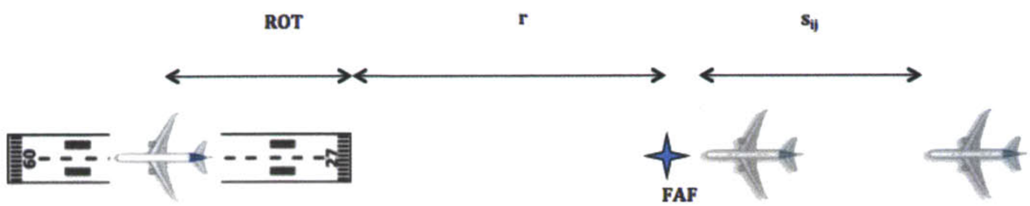


Figure 2-6. Representation of an opening case used for the runway capacity model

The minimum time separation then can be calculated from Equation 1 below.

$$\boldsymbol{T_{ij} = max\left[\frac{r+s_{ij}}{v_j} - \frac{r}{v_i}, ROT_i\right] \; when \; v_i > v_j} \qquad (1)$$

In the closing case, the trailing aircraft is faster than the leading aircraft and the minimum separation between them occurs when the leading aircraft crosses the runway threshold, as shown in Figure 2-7. Representation of a closing case used for the runway capacity model.

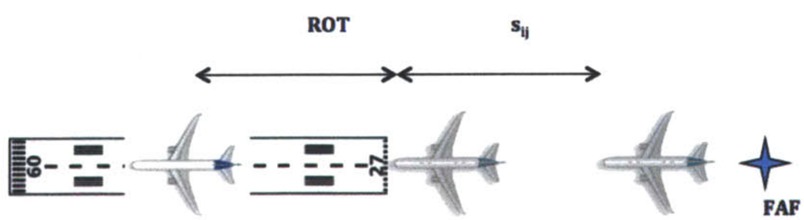


Figure 2-7. Representation of a closing case used for the runway capacity model

Therefore, the minimum time interval for the closing case can be calculated as illustrated in Equation 2.

$$T_{ij} = max\left[\frac{s_{ij}}{v_j}, ROT_i\right] \; when \; v_i \leq v_j \qquad (2)$$

In both the opening and closing case, however, the minimum time interval between successive arrivals is also influenced by the runway occupancy time of the leading aircraft. Since simultaneous runway occupancy is not allowed, the leading aircraft needs to exit the runway before the trailing aircraft is allowed to land. The queuing model accounts for this requirement by evaluating both the minimum separation and the runway occupancy, and takes the larger of the two as the minimum landing time interval.

The probability of a given pair of aircraft weight categories can be evaluated based on a given traffic mix. The expected time an aircraft pair takes to land can be calculated from Equation 3 below, where b indicates a buffer time added to the system. The buffer is an increased safety margin.

$$E(t) = \Sigma P_{ij}(T_{ij} + b) \qquad (3)$$

Once the expected time between consecutive landings has been calculated, the arrival capacity of the runway is the inverse of the expected time as presented in Equation 4.

$$\mu = \frac{1}{E(t)} \qquad (4)$$

2.3.3 Prior Studies on Wake Separation and Runway Occupancy

A number of wake separation and runway occupancy studies have been conducted based on visual observations of operations. Haynie's (2002) inter-arrival time measurements indicated frequent loss of wake vortex separation standards at Atlanta [8]. The data collection included only three days of operations under VMC, which resulted in a small sample size and a high uncertainty in the measurements, especially when simultaneous approaches occurred. Venkatakrishnan et al. (1993) developed a succinct landing time interval model based on air traffic control practices at Boston [14].

Their study, similar to Haynie's work, also analyzed manually collected observational flight position data.

Due to the advent of modern surveillance systems, visual observation of airport operations and manual data collection are no longer needed. These new systems have a broad range of features to collect, analyze, and report air traffic data with higher accuracy than stopwatch measurements. The vast majority of aircraft surveillance is carried out by ground based secondary radars system in the United States. Ballin and Erzberger (1996) studied traffic flows at Dallas/Forth Worth International Airport (DFW) over a 6-month period with the help of these radar systems [15]. Radar tracks are recorded with terminal radar to identify arrival rush periods and to measure landing separations. The results showed that there is a large potential for improving accuracy and consistency of spacing between arrivals on final approach.

Multilateration is another technique to accurately locate aircraft, which employs a number of ground stations, implements a time difference of arrival method. Ground stations receive replies from transponder-equipped aircraft, including radar and Automatic Dependent Surveillance-Broadcast (ADS-B) avionics, and determine aircraft position based on the time difference of arrival of the replies. Multilateration systems have been installed at several airports in previous years.

Jeddie et al. (2009) processed multilateration data at Detroit Metropolitan Wayne County airport (DTW) to extract time and position recordings of flights [16]. This data is analyzed to provide probability distributions of inter-arrival times, landing time intervals, runway occupancy and simultaneous runway occupancy. The study found that runway occupancy is best represented by a beta distribution, but not with a normal distribution. Runway occupancy is observed to be very similar in VMC and IMC conditions. Levy et al. (2004) also analyzed multilateration data for over 100,000 arrivals at Memphis International Airport (MEM) under VMC to obtain probability distributions of inter-arrival distance and time separations [17].

2.3.4 Modern Airport Surface Surveillance

It is also possible to combine surveillance reports from multiple sensors, including traditional ground based radars, ADS-B and multilateration ground stations into single flight tracks. Fused flight tracks provide improved aircraft position data for controllers. One such joined system is the Airport Surface Detection Equipment, Model-X (ASDE-X) that can be used for tracking arriving or departing flights. ASDE-X is an automated, high-resolution surveillance radar system that provides aircraft position data and aircraft identification in the terminal area with a one second update rate [18]. The position information is a combination of surface radar, aircraft transponder, and ADS-B data. The collected fields include flight track numbers, aircraft types, callsigns, altitude, latitude, and longitude. An example of ASDE-X recorded flight tracks is shown in Figure 2-8 for La Guardia Airport (LGA). The red data points indicate arrival flight tracks to runway 4. The aircraft positions are also shown on the airport surface.

Figure 2-8. Sample ASDE-X flight tracks of arriving aircraft to La Guardia (LGA)

Kumar et al. (2009) extracted and analyzed runway occupancy from ASDE-X surface track data at DFW [19]. The study found that runway occupancy times of small aircraft are very similar to large aircraft, and identical runways exhibit statistically significant runway occupancy differences. ASDE-X data, however, is unable to capture weather effects, such as the impact of rain or wind on runway occupancy.

Aircraft position data can be used to evaluate typical runway occupancy times, inter-arrival separations, and average separation buffers. These parameters can then be applied in the runway capacity model to examine impacts of reduced wake separation concepts on runway throughput.

2.4 Current and Emerging Wake Procedures

There are a number of international efforts to develop new procedures that allow shorter wake vortex separations, which are summarized in Table 2-3.

Table 2-3. Reduced wake separation concepts for single and closely spaced parallel runways

	Name	Method	Applicability
Single Runway	Current FAA Final Approach Separations	Distance - based	Arrivals
	Current FAA Departure Separations	Time – based	Departures
	Time-based Separation	Time - based	Arrivals
	CREDOS (Crosswind – Reduced Separations for Departure Operations)	Crosswind - based	Departures
	RECAT	Re - categorization	Arrivals/Departures
CSPR (Closely Spaced Parallel Runway)	WTMA (Wake Turbulence Mitigation for Arrivals)	Crosswind - based	Arrivals
	WTMD (Wake Turbulence Mitigation for Departures)	Crosswind - based	Departures
	7110.308	Reduced diagonal separation	Arrivals
	Dual Threshold	Shifted threshold	Arrivals

Single runway studies include the current separation requirements, crosswind enabled reduced inter-arrival separations, re-categorization of aircraft wake groups, and time based separation methods. The current FAA prescribed separation requirements have been explained in Table 2-2. Arrival aircraft are separated by a distance based separation criteria, and departing aircraft are separated by a time-based rule.

A new concept to improve single runway capacity is time-based separations for arrivals, which is a tool to prevent loss of runway capacity in strong headwind conditions. If existing distance-based separation rules are replaced with time equivalent separations, arrival throughput could increase in strong headwind conditions without sacrificing safety standards. In strong headwind conditions the ground speed of aircraft is reduced, which results in longer times to cover the separation distance, and as a results leads to a loss in runway capacity (when distance based separation rules are applied). Runway capacity is constant and independent from final approach speeds when time based separation rules are applied. Initial benefits of time-based separation rules at London Heathrow showed a landing improvement of two to three additional aircraft per hour compared to current arrival rates. According to Janic, a time based separation rule has several benefits over the more traditional distance-based separation; however, it is difficult to implement for air traffic controllers [20]. Since controllers separate aircraft based on radar screen observations, the distance between aircraft pairs is easier to determine than the time separation, which results in reduced workload.

CREDOS, Crosswind-Reduced Separation for Departure Operations, is proposed by the European Commission to replace static wake turbulence separation minima with lower ones when crosswind conditions are present [21]. When crosswind requirements are met, the wind carries the wake laterally out of the path of the trailing aircraft, permitting lower separations and increasing runway throughput.

The joint FAA and Eurocontrol initiated re-categorization (RECAT) program aims to review and re-evaluate the existing wake categories and the corresponding minimum wake separation requirements for single runway arrival operations. The RECAT program is discussed in details in the next section of this chapter.

New procedures are also studied for Closely Spaced Parallel Runways (CSPR). CSPR geometry refers to parallel runways, where the centerlines of the two runways are closer than 2500 feet apart. These new CSPR procedures consider crosswind enabled reduced separations. For instance, WTMD, Wake Turbulence Mitigation for Departures, and WTMA, Wake Turbulence Mitigation for Arrivals, both explore the circumstances under which reduced separations can be extended when weather conditions meet crosswind requirements. In presence of a favorable crosswind, reduced separations can be applied between departures from the parallel runways. Alternatively, if the crosswind carries the leading aircraft's wake away from the path of the trailing aircraft, reduced diagonal separations can be implemented.

There is also a procedure for CSPR approaches to conduct 1.5 NM diagonal separations, which is usually referred to as Order 7110.308. This order allows the use of the parallel dependent instrument approaches for specific airport parallel runways for reduced diagonal spacing.

Steeper glide slopes and dual threshold systems can also be used for CSPR configurations. These systems permit aircraft to fly a higher-than-normal final approach glideslope [22]. Since wake vortices spread sideways and sink, with these new procedure the trailing aircraft can stay above the wake of the leading aircraft's path at all times by flying a steeper approach. Dual threshold systems, however, can increase operational complexity for controllers. Furthermore, dual threshold systems are limited by runway length. Since the threshold is shifted, the available landing distance becomes shorter. This means that smaller airports with short runways would be unable to implement such systems.

2.5 Aircraft Re-categorization (RECAT)

To further achieve capacity growth, the reduction of wake minimum separations is also possible by defining new aircraft wake categories. The current aircraft wake groups are established several decades ago, and only minor changes and adjustments have been made. However, with the introduction of new aircraft types, such as the extension of categories with a new super heavy category for the Airbus A380, this introduces new separation requirements.

With the technological evolution of wake vortex measurement capabilities, the understanding of wake behavior has been more accurately defined. This has allowed a new way to categorize aircraft into wake groups, which address not only the maximum takeoff weight, but also the wingspan of the aircraft, the final approach speeds and aircraft dynamics parameters. As an example, consider a Boeing 747 and a Boeing 767 aircraft pair, as shown in Figure 2-9. Given the current aircraft wake categories both of these aircraft belong to the Heavy category. The minimum required wake separation between two Heavies on final approach is 4 NM. Recent flight tests and historical observations have shown that the 4 NM-separation is safe when the B767 is following the B747 and vice versa. However, when the B747 is following the B767, the 4 NM could be too conservative. The two aircraft have very different wake characteristics since the B767 produces less severe wake turbulence than the B747 due to its lighter weight. Therefore it is possible to separate these aircraft into different wake categories and assign different minimum wake separation requirements between them depending on the type of the leading aircraft.

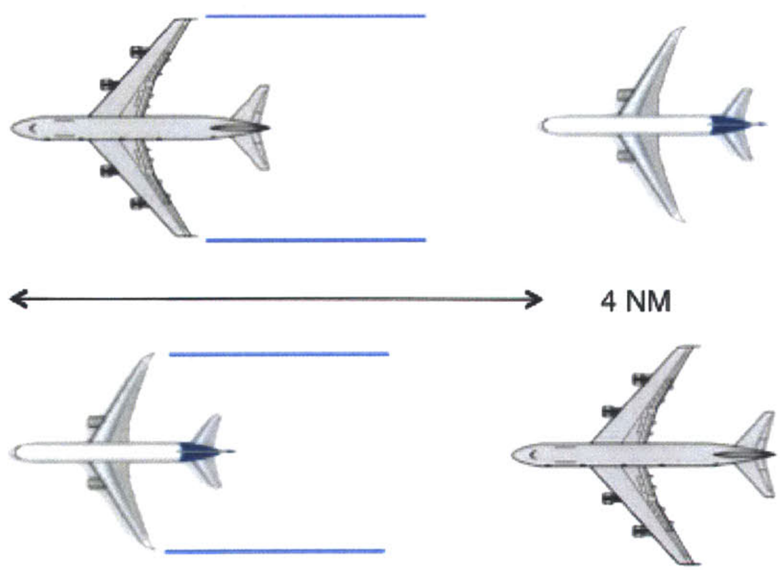


Figure 2-9. Changing wake separation standards with re-categorization. The current 4-NM Heavy-Heavy separation is safe when the B747 is followed by the B767, but it could be too conservative when the B767 is followed by the B747.

In RECAT, aircraft are categorized into six groups, which range from A to F. Group A contains the largest commercially operated aircraft generating the most severe wake turbulence (the A380 and the AN-225), and group F contains small business jets and turboprops generating weaker wake vortices. Group B and C are Heavy aircraft that are divided into two categories; group C includes smaller wingspan Heavies, such as the

MD11, the B767, and the A300. Large aircraft are divided into two categories, group D and E. Group D contains the most common narrow-body aircraft, such as the B737, A320, and other the regional jets. Group E includes larger turboprops and some business jets.

Table 2-4. RECAT wake separation standards

		Follower (NM)					
		A	B	C	D	E	F
Leader	A	2.5/3	5	6	7	7	8
	B	2.5/3	3	4	5	5	7
	C	2.5/3	2.5/3	2.5/3	3.5	3.5	6
	D	2.5/3	2.5/3	2.5/3	2.5/3	2.5/3	5
	E	2.5/3	2.5/3	2.5/3	2.5/3	2.5/3	4
	F	2.5/3	2.5/3	2.5/3	2.5/3	2.5/3	2.5/3

According to the new RECAT wake separation standards, shown in Table 2-4, separation is increased for some of A-F, B-F, C-F, D-F, and E-F lead-follow pairs [23]. On the other hand, separation is reduced for all A-B, B-B, C-B, C-C, C-D, and C-E lead-follow pairs. Separation is also reduced for some of E-F, and F-F pairs. The greatest reduction in separation standards occurred for pairs with a group C lead aircraft.

It is also worth mentioning that there are more complicated versions of the RECAT program, which are outside the scope of this study. These programs include more complex static and dynamic pair-wise separation systems.

Chapter 3

3 Runway Occupancy

Chapter 3 measures typical runway occupancy times and evaluates what the influencing factors are by comparing multiple runways at different airports. Runway occupancy times are analyzed for all aircraft groups under both visual and instrument meteorological conditions using aircraft surveillance data. The results indicate that runway occupancy usually scales with aircraft size, but small aircraft can spend as much time on runways as large aircraft. The study shows that runway occupancy strongly depends on the location of runway exits and the number of high-speed taxiways, which permit aircraft to turn off the runway at faster speeds. The analysis also suggests that visual and instrument meteorological conditions have no significant impact on runway occupancy times.

3.1 Runway Occupancy Study Objective

In order to determine under what conditions runway occupancy is limiting runway capacity, it is essential to measure what typical ROT values look like in today's operational environment. Since even a few-second difference in ROT can have a significant impact on runway capacity, runway occupancy needs to be measured with high accuracy, which is one of the research objectives of this study.

As explained in Chapter 2, traffic mix, weather conditions, and runway exit locations can all influence ROT. Chapter 3 aims to quantify the impacts of these variables across multiple airports and multiple runways. This information can serve as the basis for reduced wake separation considerations and it is one of the key input parameters for evaluating runway capacity.

Runway occupancy varies with aircraft type, as the kinetic energy of an aircraft increases with the square of its speed. The heavier the aircraft weighs, the longer runway it requires for landing in order to dissipate the higher amount of energy.

Airports with dominant regional jet traffic can observe very different performance than large international airports with mostly heavy aircraft operations.

Runway geometry can influence runway occupancy times; therefore differences may be seen within the same airport. Runway exits, aircraft and pilot performance all play an important role in controlling runway occupancy. According to Pavlin et al. (2006), pilots can improve runway occupancy performance by aiming for an exit which can be made comfortably, rather than aiming for an earlier exit, and rolling slowly to the next if they miss it [24]. Pilots may increase ROT if they roll down on the runway longer to vacate at an exit that is more convenient to their parking gate.

Minimizing the time an aircraft spends on a runway can increase runway capacity. A small reduction in ROT can enable reduced inter-arrival separations and it can represent a significant capacity change. Since simultaneous runway occupancy (more than one aircraft on the runway at the same time) is not allowed, ROT limits how much separation can be reduced. In VMC operations at busy airports, inter-arrival separations and ROT values are not very far apart and go-arounds occur frequently. In the case of mixed arrival and departure operations on the same runway, ROT also determines how early a departing aircraft can be released after an arrival.

Analyzing aircraft position data can help to understand current airport surface operations and can provide a baseline measurement against which new technologies and procedures can be compared to.

3.2 Runway Occupancy Time – Study Method

For the purpose of this study, runway occupancy time for arriving aircraft is defined as the time interval between the aircraft crossing the runway threshold, and the instant when the same aircraft crosses the holding position marker at any of the runway exits. This definition is consistent with the FAA's description of when the runway is clear, which states that taxiing aircraft are clear of the runway when they cross the hold line, and landing aircraft are clear of the runway when the entire airframe has crossed the applicable holding position marking [25].

Although this study measures runway occupancy times based on the FAA definition when the runway is clear, it should be noted that several other definitions can also be considered. Eurocontrol defines arrival runway occupancy as the time interval between the aircraft crossing the threshold and its tail vacating the runway [26]. Kumar et al. slightly modified this definition by measuring ROT until the instant the aircraft is 25 feet clear of the runway boundary [19]. The 25 feet buffer is selected to ensure that all parts of the aircraft are clear of the runway. This approximation, however, could be an underestimate for wide body aircraft with long fuselage and wide wingspan. For such an aircraft, the tail would still occupy the runway 25 feet from the edge of the runway. Since the runway holding position markers adopted in this study are placed further out from the runway than 25 feet, the measured ROT values are expected to be higher than in former runway studies, which implemented the Eurocontrol definition of ROT.

A few-second reduction in runway occupancy per landing can lead to significant runway throughput improvements. For this reason, an aircraft position data source with a high update rate is desirable. The previously introduced ASDE-X surveillance and data collection system in Chapter 2 is used to track aircraft not only in the air, but on the runways and on the taxiways as well. ASDE-X data is available at several American airports. As of March 2011, 35 majors airports had received or are in the process of deploying ASDE-X. The list of these airports is shown below in Table 3-1. Based on ASDE-X data availability, four airports are selected for the runway occupancy study: Boston Logan (BOS), New York La Guardia (LGA), Newark (EWR), and Philadelphia (PHL). These airports are chosen because they have very different runway configurations and traffic mixes.

Table 3-1. List of ASDE-X equipped airports in the United States [27]. The four selected airports for this study are shown in the boxes.

- Baltimore-Washington International Thurgood Marshall Airport (Baltimore, MD)
- Boston Logan International Airport (Boston, MA)*
- Bradley International Airport (Windsor Locks, CT)*
- Chicago Midway Airport (Chicago, IL)*
- Chicago O'Hare International Airport (Chicago, IL)*
- Charlotte Douglas International Airport (Charlotte, NC)*
- Dallas-Ft. Worth International Airport (Dallas, TX)*
- Denver International Airport (Denver, CO)*
- Detroit Metro Wayne County Airport (Detroit, MI)*
- Ft. Lauderdale/Hollywood Airport (Ft. Lauderdale, FL)*
- General Mitchell International Airport (Milwaukee, WI)*
- George Bush Intercontinental Airport (Houston, TX)*
- Hartsfield-Jackson Atlanta International Airport (Atlanta, GA)*
- Honolulu International –Hickam Air Force Base Airport (Honolulu, HI)*
- John F. Kennedy International Airport (Jamaica, NY)*
- John Wayne-Orange County Airport (Santa Ana, CA)*
- LaGuardia Airport, (Flushing, NY)
- Lambert-St. Louis International Airport (St. Louis, MO)*
- Las Vegas McCarran International Airport (Las Vegas, NV)
- Los Angeles International Airport (Los Angeles, CA)*
- Louisville International Airport-Standiford Field (Louisville, KY)*
- Memphis International Airport (Memphis, TN)
- Miami International Airport (Miami, FL)*
- Minneapolis St. Paul International Airport (Minneapolis, MN)*
- Newark International Airport (Newark, NJ)*
- Orlando International Airport (Orlando, FL)*
- Philadelphia International Airport (Philadelphia, PA)*
- Phoenix Sky Harbor International Airport (Phoenix, AZ)*
- Ronald Reagan Washington National Airport (Washington, DC)
- San Diego International Airport (San Diego, CA)*
- Salt Lake City International Airport (Salt Lake City, UT)*
- Seattle-Tacoma International Airport (Seattle, WA)*
- Theodore Francis Green State Airport (Providence, RI)*
- Washington Dulles International Airport (Chantilly, VA)*
- William P. Hobby Airport (Houston, TX)*

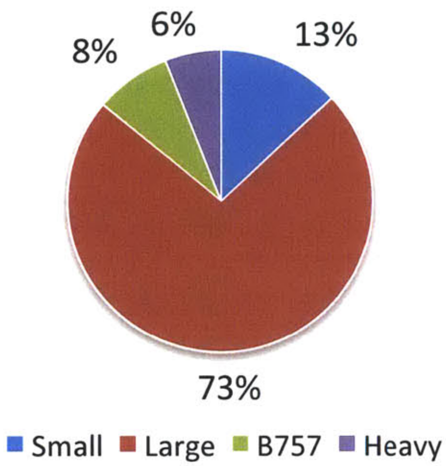
3.2.1 Airport Selection

The primary factors for selecting these airports are the high demand and busy traffic at these locations, the different traffic mix at the airports, and the different runway geometries. All four of these airports rank in the top 25 world's busiest airports by number of movements (landings and takeoffs) [28]. Philadelphia ranked 14th, Newark ranked 20th, Boston 24th, and La Guardia 25th.

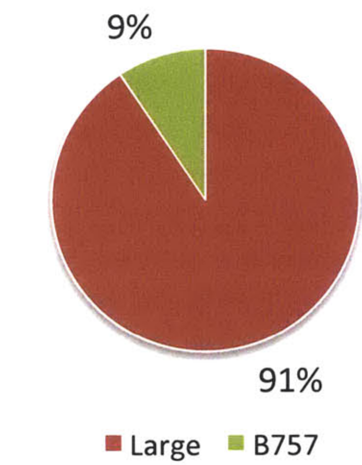
As seen from the traffic mix in Table 3-2, all four aircraft categories operate at Boston. Large aircraft dominate the traffic mix with 73% of all traffic, followed by small aircraft with 13%. Most of these small aircraft operations at Boston are small propeller aircraft serving the New England area. The small percentage of heavy aircraft is international arrivals from Europe and domestic cargo flights. The traffic mix at Philadelphia and at Newark includes a larger percentage of heavies. Philadelphia also has a large percentage of small aircraft, as opposed to Newark, where there are no small aircraft operating. La Guardia's traffic is very homogeneous with 91% large aircraft and the remaining Boeing 757s.

Table 3-2. Traffic mix at the selected airports

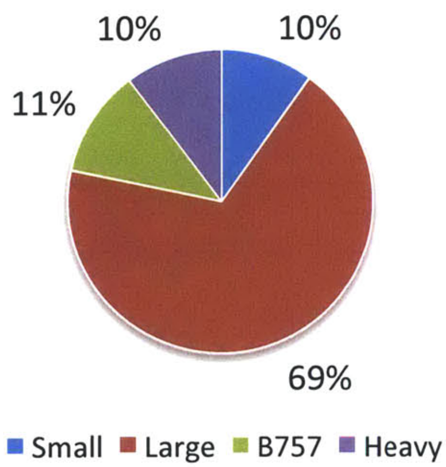
BOS



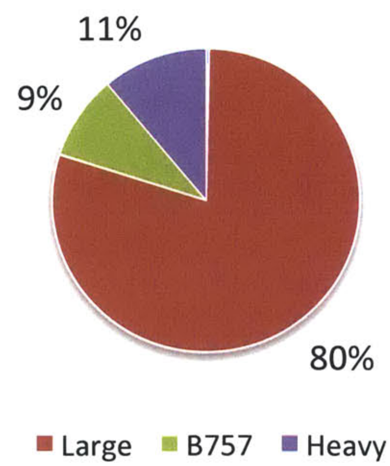
LGA



PHL



EWR



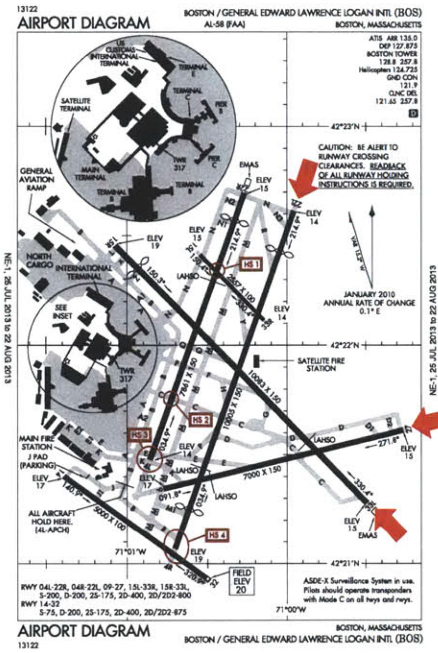
Boston is equipped with six runways, with lengths ranging from 2,557 feet to 10,083 feet. The airport is a good example of an evolved runway configuration, as it has both parallel and crossing runways. A runway configuration defines which runways are used for arrivals and which ones are used for departures. For this reason, a given runway configuration also influences runway capacity. When a runway is shared between arrivals and departures, inter-arrival spacing is longer. When a departure runway crosses the arrival runway, departures can only take place once the landing aircraft has crossed the runway intersection and it is clear of the departing runway. Three of the runways at Boston are equipped with high-speed taxiways and the other runway exits are set at 90-degree angles that force planes to slow down to a lower speed before exiting the runway. Boston's runway layout is shown in Figure 3-1.

La Guardia has two 7,000-feet runways, which limits operations for heavy aircraft. La Guardia's traffic consists of only small, large, and Boeing 757 aircraft. The two runways, as shown in Figure 3-1, are equipped with a total of seven high-speed exits.

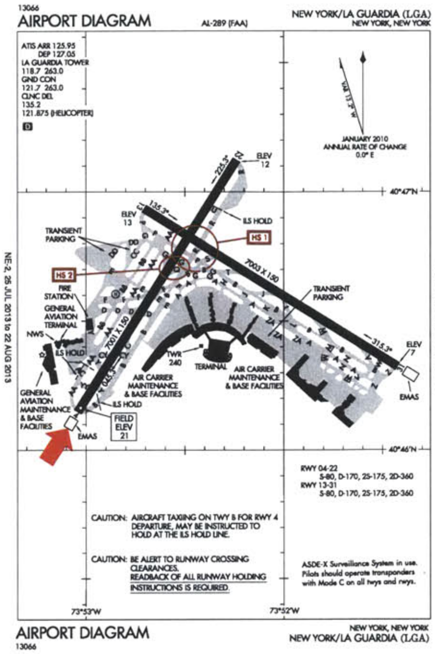
New York - Newark is equipped with three runways, two parallel and one crossing runway. The parallel runways are 10,000 and 11,000 feet long, and the crossing runway 11/29 is 6,800 feet. The parallel runways are only 950 feet apart, which is the 4th smallest separation among major airports in the US. Newark has eight high-speed taxiways; most of them are located on the two parallel runways.

Philadelphia has four runways, ranging from 5,000 feet to 10,506 feet and runway 17/35 has already been extended a few years ago to cope with capacity constraints. The long runways, 9R/27L and 9L/27R are parallel with the shortest runway, 8/26. Runway 17/35 is a crossing runway, which is usually used for small and large aircraft only. The airport is a big international hub with lots of heavy aircraft, and it is also the hub of a large Boeing 757 operator airline.

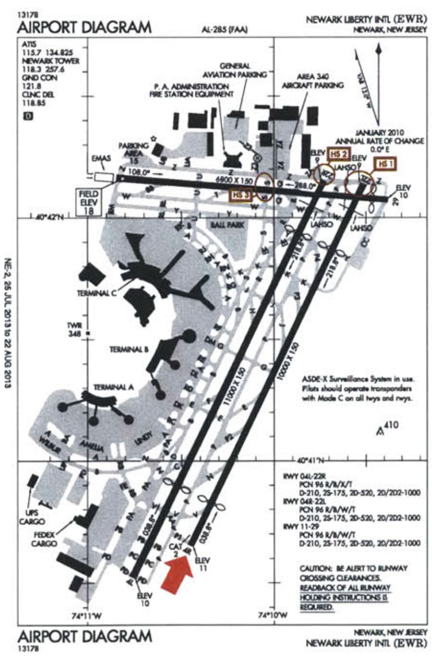
BOS



LGA



EWR



PHL

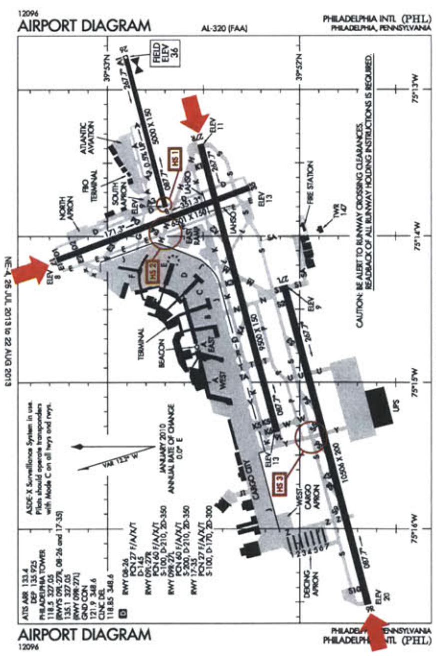


Figure 3-1. Arrival runways analyzed at Boston, La Guardia, Newark, and Philadelphia (FAA Airport Diagrams)

3.2.2 Measuring Runway Occupancy Time

Information about the runway configurations at the selected airports can be collected from the Aviation System Performance Metrics (ASPM) database. The ASPM database includes information on individual flight performance, airport efficiency, and runway configurations for every quarter hour. Historical weather information is limited to IMC or VMC information, temperature, wind, ceiling, and visibility. Once the arrival runways are defined, the in-polygon method can be implemented to capture all arriving traffic and to measure ROT. The in-polygon method creates a polygon around the edges of the runway, including all runway exits extended until the holding point marker. The exact locations of the runways are defined from Google Earth satellite images. Satellite images provide accurate geographical coordinates of runway geometries, latitude and longitude positions of the runway thresholds, runway exits, and all the holding point markers. From these coordinates, a polygon can be drawn around each runway.

Runway occupancy is measured from the moment an aircraft first appears inside the polygon to the instant when it exits the polygon. Figure 3-2 illustrates an example ROT measurement at BOS on runway 22L. The black contour line shows the polygon around the runway with four runway exits. The blue dots are aircraft position data points indicating the location of an arriving aircraft on final approach and then taxiing on the ground after exiting the polygon. The position of the aircraft is indicated at every second, which is the update rate of ASDE-X. At the green marker, the aircraft crosses the runway threshold and that is the moment when the ROT measurement begins. The red dots show the position of the aircraft when it is on the runway. When the aircraft exits at the runway holding point, the aircraft position marker switches back to blue, and in that instant the ROT measurement stops. ROT is measured in units of seconds, and it is recorded in a table along with the corresponding aircraft type.

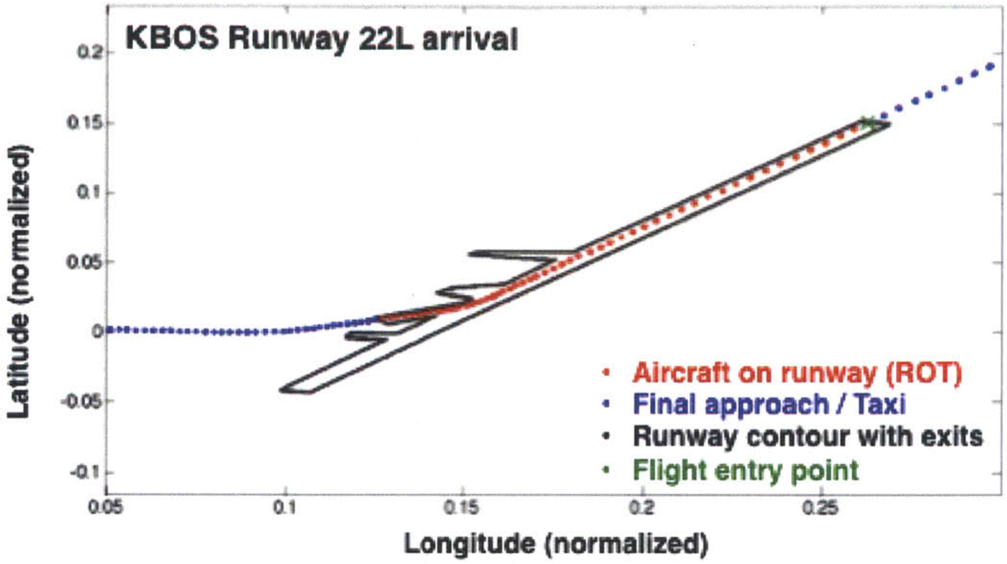


Figure 3-2. ROT measurement of a landing aircraft using the in-polygon method

In order to filter out taxiing, runway crossing, and overflying aircraft from arrivals, the minimum ROT is set to 20 seconds. To differentiate arriving aircraft from departing aircraft on the same runway, a minimum runway threshold crossing speed of 50 knots is selected. These two limitations ensure that all flights captured inside the polygon are arriving flights.

Once all arrival flights are selected, they are filtered again to account for high arrival demand hours only. As explained earlier, demand fluctuates throughout the day and it can impact runway occupancy. Continuous arrival demand ensures that pilots vacate the runway as soon as possible in order to permit the next aircraft to land. Accordingly, the ASDE-X arrival dataset is narrowed down to include flights where the hourly demand is greater than or equal to 30 arrivals. These hours mostly occur in late mornings and late afternoons. The 30 arrivals per hour criterion is applied at Boston, Philadelphia, and Newark, but not at La Guardia. At LGA arrival demand is constantly high throughout the day exceeding 30 arrivals almost every hour of the day, which does not require any filtering of arrival flights.

3.3 Runway Occupancy Results

The initial results in this section are presented for Boston, as an example airport of the study method. The results for the other airports are presented and compared in the summary level.

3.3.1 Runway Occupancy Measurements at Boston

Eighteen days of operations are evaluated under both IMC and VMC conditions in Boston. The test days include time periods during winter and summer months. The primary landing runways are 22L, 27, and 33L, highlighted with red in Figure 3-3. Runway 22L is the most utilized runway with 3942 landings taking place. 1203 flights land on runway 27, and 451 flights land on runway 33L.

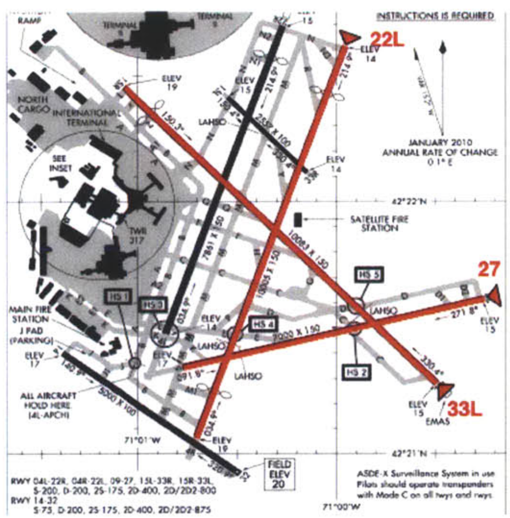


Figure 3-3. ROT data measured on runway 22L, 27, and 33L at Boston

A graphical representation of the runway occupancy times measured on runway 22L at Boston is shown below for each of the aircraft categories. For simplicity, only runway 22L results are shown here in form of cumulative distribution function. Results from other runways and other airports are shown in the next section of this chapter. The runway occupancy time is indicated on the x-axis. The results presented here included both VMC and IMC weather conditions, and reflect only peak-time operations.

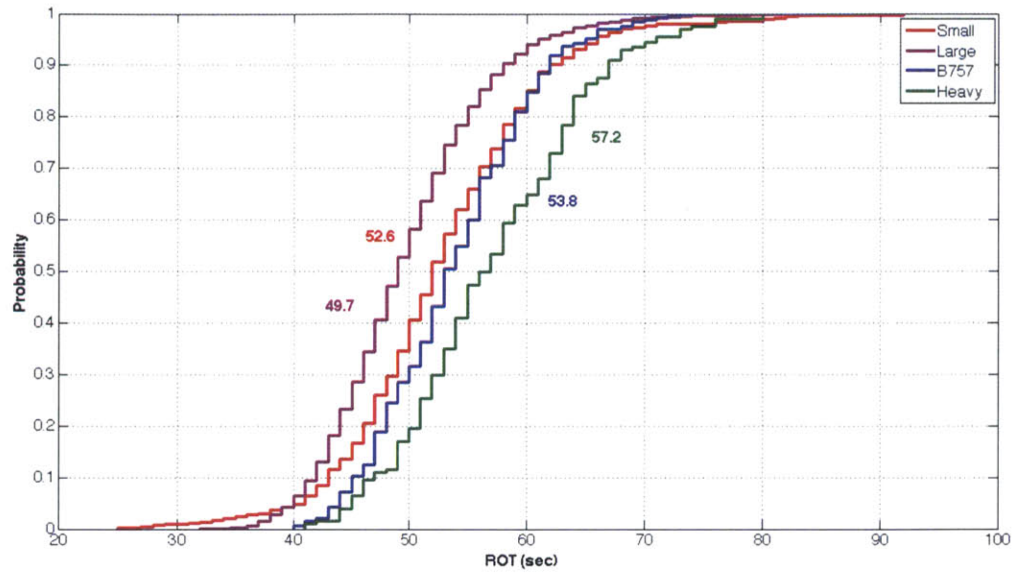


Figure 3-4. Cumulative distribution for each aircraft group on runway 22L at BOS

As seen from Figure 3-4, large aircraft have the shortest runway occupancy time, and heavy aircraft have the longest. Boeing 757 falls in between the large and heavy distributions. Small aircraft, interestingly, have very similar runway occupancy to Boeing 757s. They occupy the runway longer than large aircraft with a 52.6 second average ROT.

The average ROT for large aircraft is 49.7 seconds, which satisfies the 50 seconds runway occupancy requirement for the reduced, 2.5-NM, minimum radar separation on final approach for large-heavy and large-large pairs. Runway occupancy time ranges from 32 seconds to 88 seconds with a standard deviation of 6.8 seconds.

Boeing 757 ROTs on runway 22L have a 53.8 second mean, shown with the blue distribution. The data distribution ranges from 40 to 74 seconds with a 6.5 second standard deviation. Boeing 757 aircraft have longer runway occupancy times than large aircraft, possibly due to faster landing speed and larger momentum.

As expected, heavy aircraft have the highest average ROT with 57.2 seconds, shown with the green distribution. Heavy aircraft usually land faster than small aircraft and require longer landing rolls, which means that they exit further down the runway, resulting in higher runway occupancy times. Measured runway occupancy time ranges from 41 seconds to 80 seconds. The standard deviation is 7.9 seconds.

3.3.2 Discussion of Runway Occupancy Results at Boston

Runway occupancy is also evaluated for runway 27 and runway 33L. The results for the four aircraft groups are compared across Boston's three runways in a cumulative distribution function, which illustrates the differences between runways more clearly. These distributions describe the probability that a random aircraft with a given probability distribution will spend a certain time on the runway. In order to compare the results, the Kolmogorov-Smirnov (KS) test is used for two-samples. The KS test quantifies the distance between the distribution functions for two ROT samples, and it is sensitive to differences in both the shape and location of the cumulative distribution functions. The test assumes continuous distributions for the samples. The null hypothesis is that the difference in runway occupancy times is not significant. The alternative hypothesis is that difference in runway occupancy times is significant between the two samples.

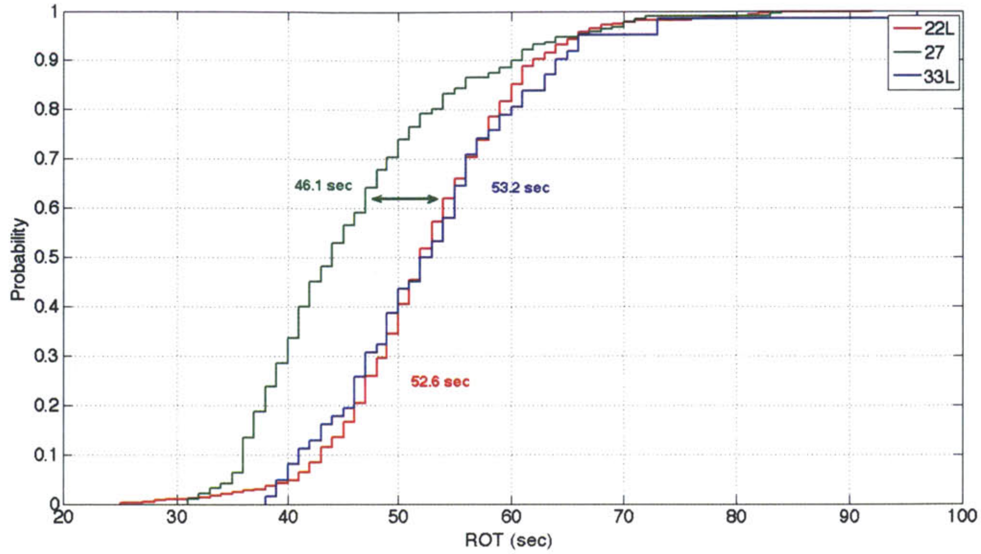


Figure 3-5. Cumulative distribution for small aircraft runway occupancy at BOS indicating that runway 27 had a significantly different ROT

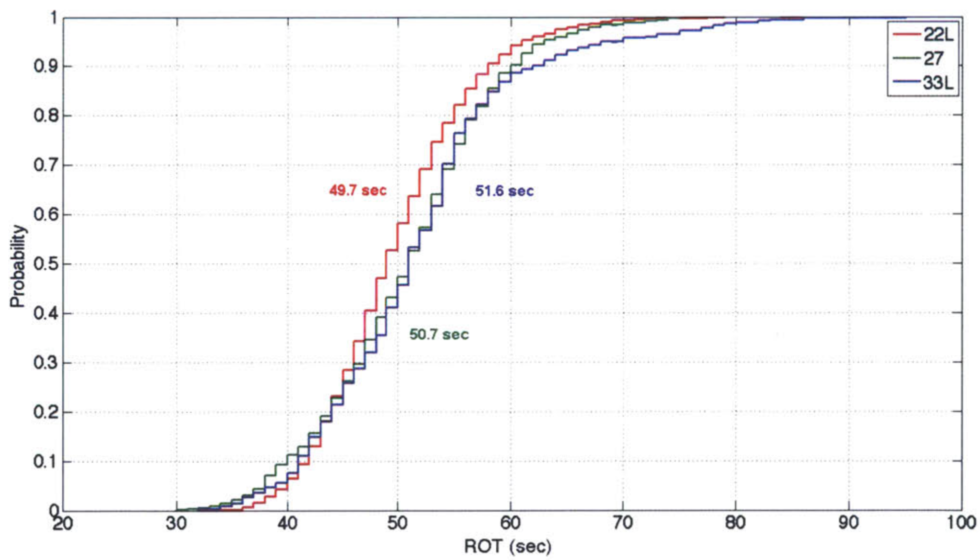


Figure 3-6. Cumulative distribution of ROT for large aircraft at BOS indicating no significant differences between the runways

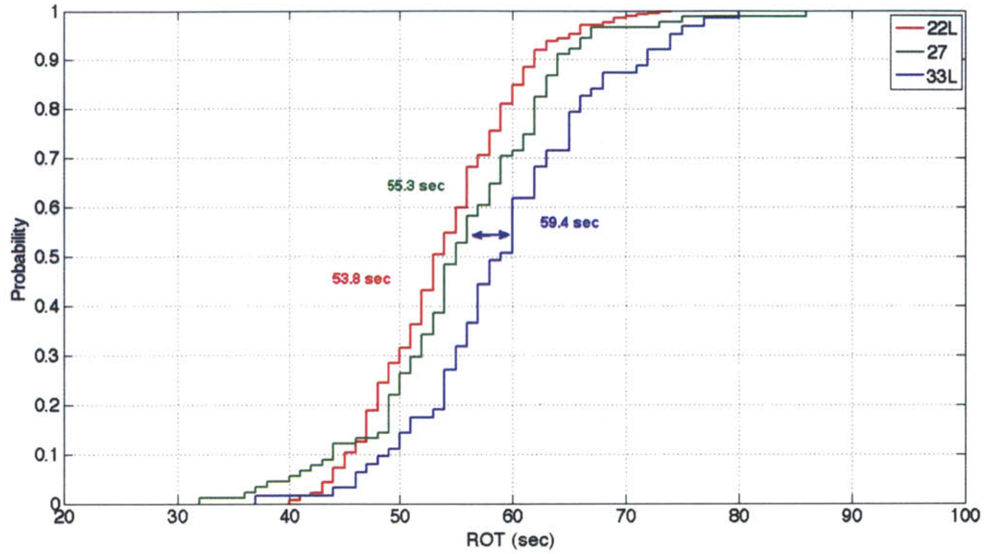


Figure 3-7. Cumulative distribution of ROT for B757 at BOS indicating significantly different runway occupancy on 33L

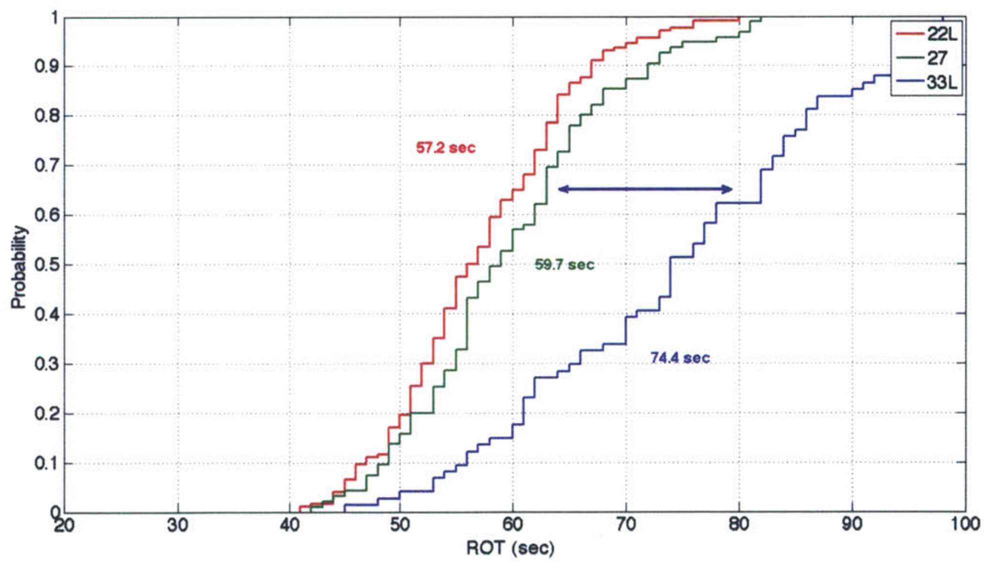


Figure 3-8. Cumulative distribution of ROT for heavy aircraft at BOS indicating significantly different runway occupancy on 33L

Figure 3-5 shows the cumulative distribution functions for small aircraft on runway 22L, 27, and 33L. Runway 27 has a generally faster ROT than the other two runways. The

KS test shows that ROT for small aircraft on runway 27 is significantly different from the other two runways.

The better performance for small aircraft on runway 27 is possibly due to the close location of a runway exit to the threshold. Taxiway Charlie (C), indicated by the red circle in Figure 3-9 is located 3,100 feet from the runway 27 threshold. Many of the small aircraft are twin piston engine aircraft at Boston, which are capable of slowing down and exiting the runway at taxiway Charlie, as opposed to other runways, where the closest exits are at 3,840 and 4,300 feet away from the thresholds.

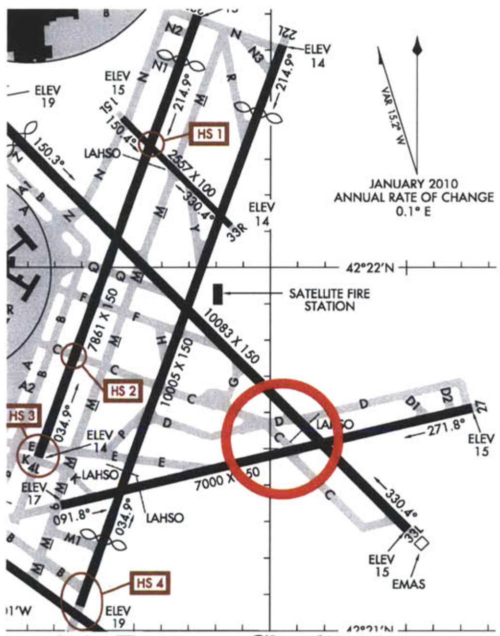


Figure 3-9. Taxiway Charlie on runway 27

For large aircraft, shown in Figure 3-6, the KS test confirms that there is no significant difference between runway 22L, 27, and 33L runway occupancy times. The means are 49.7, 50.7, and 51.6 seconds, respectively. Unlike small aircraft, large aircraft are unable to turnoff at taxiways Charlie on runway 27, which appears to result in similar runway occupancy times as on runway 22L and 33L.

Figure 3-7 shows the results for Boeing 757s. From the cumulative distribution plot runway 22L appears to provide the quickest runway exit, followed by runway 27 and then runway 33L. The KS test shows that runway 33L is significantly different from the other runways. The mean ROT is 53.8 seconds on runway 22L, 55.3 seconds on runway 27, and 59.4 seconds on runway 33L. The most desirable runway exits on runway 33L by B757 aircraft are taxiway Foxtrot (F) and taxiway Quebec (Q), circled red in Figure 3-10. These taxiways are located 4,280 and 5,600 feet from the runway threshold. However, some Boeing 757s extend their landing roll all the way to taxiway November (N), which significantly increases runway occupancy. An air traffic controller from Boston tower confirmed that one of the Boeing 757 operator airlines at the airport constantly exits and taxiway November.

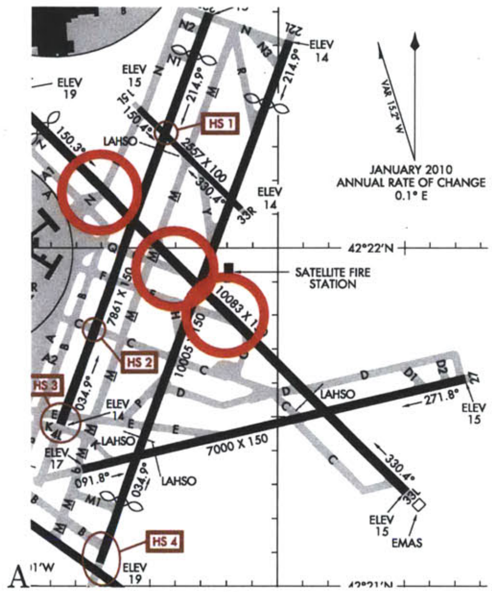


Figure 3-10. Runway exit Foxtrot, Quebec, and November on runway 33L

When heavy aircraft ROTs are compared, the cumulative distribution plot already indicates a difference between 33L and the other two runways, as shown in Figure 3-8. The KS test shows that runway occupancy time is significantly different for heavies on runway 33L from the other two runways. The significantly higher ROT on 33L can be due to the runway exit location spacing. If a heavy aircraft misses taxiways Foxtrot or Quebec, the next exit is taxiway November, which is located 7,600 feet from the runway threshold. Taking exit November requires aircraft to roll down the runway and cross both crossing runways before exiting. Hence, the long landing rolls result in high runway occupancy times. Another factor that might be influencing heavy ROT is the location of the international terminal, where most heavies taxi. The terminal is located in the North side of the airport, right off taxiway November, which might encourage pilots to extend the landing roll.

3.4 Runway Occupancy Results for Other Airports

The results of the runway occupancy study are summarized in the next four figures in a cumulative distribution plot form. The mean ROT values are shown on the right. The data presented here comes from high arrival demand time periods and it includes operations under both VMC and IMC weather conditions.

3.4.1 Runway Occupancy Results for Small Aircraft

Figure 3-11 illustrates runway occupancy times for small aircraft on five runways. The mean ROTs range from 46.1 seconds to 53.4 seconds. Runway 27 at Boston has the shortest mean ROT, and runway 9R at Philadelphia has the longest. Runway 22L, 33L, and 9R are all very similar with less than a second apart. Only runway 27 and 27R has the average runway occupancy below 50 seconds. It is interesting to note that mean ROT at Philadelphia on runway 9R is higher than on 27R because runway 9R is equipped with four high - speed exits, whereas runway 27R has only one. The four high - speed exits on 9R are located at 3,430 feet, 4,600 feet, 6,250 feet, and 8,260 feet from the threshold. The closest standard 90 - degree exit on runway 27R is 2,200 feet from the threshold, followed by exits at 3,410 feet, 4,400 feet, and 5,200 feet. Due to the standard exits on runway 27R, the minimum measured runway occupancy iss 31 seconds, 5 seconds higher than on runway 9R.

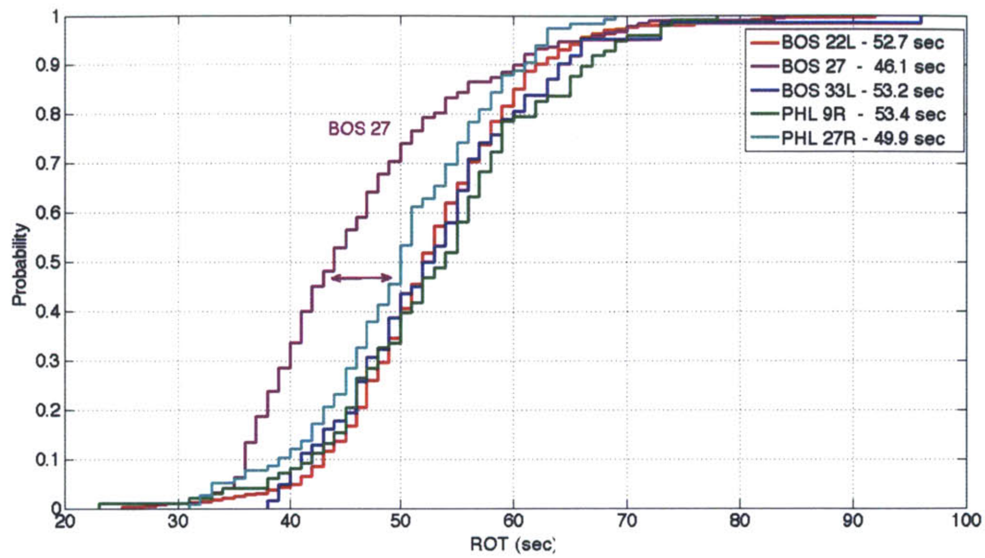


Figure 3-11. Cumulative distribution functions for small aircraft (note no small aircraft at EWR and at LGA) indicating significantly different runway occupancy on runway 27 at BOS

However, the maximum runway occupancy on 9R is 78 seconds as opposed to 69 seconds on 27R. Since runway 9R is better equipped for faster runway exits than 27R, the higher runway occupancy might be due to some external factors that encourages pilots to roll down longer on the runway. One such factor can be the location of terminal F at the North - East side of the airport, which hosts a regional express airline, where most small aircraft gates are assigned. Exiting the runway later on 9R can reduce taxi times to terminal F gates. The location of terminal F is shown with a red circle in Figure 3-12.

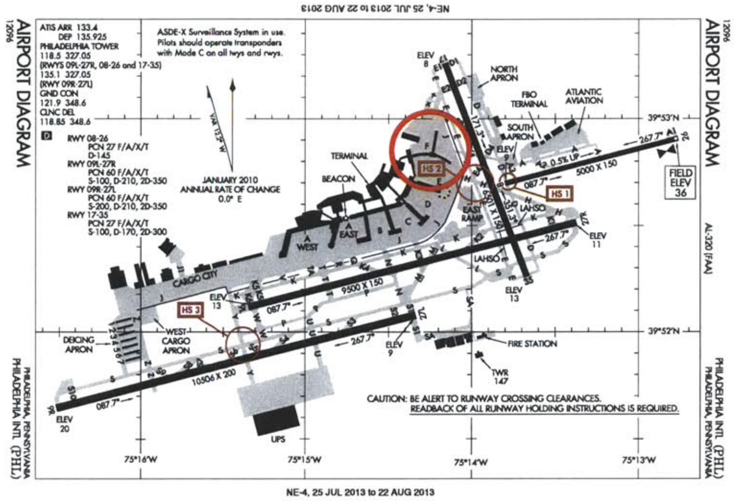


Figure 3-12. Gate location may influence runway occupancy time for small aircraft at PHL

3.4.2 Runway Occupancy Results for Large Aircraft

As it can be seen from Figure 3-13, La Guardia has the lowest mean runway occupancy time of 46.6 seconds and the lowest standard deviation of 6.8 seconds. This can be explained by the four runway exits, all located within close proximity of each other.

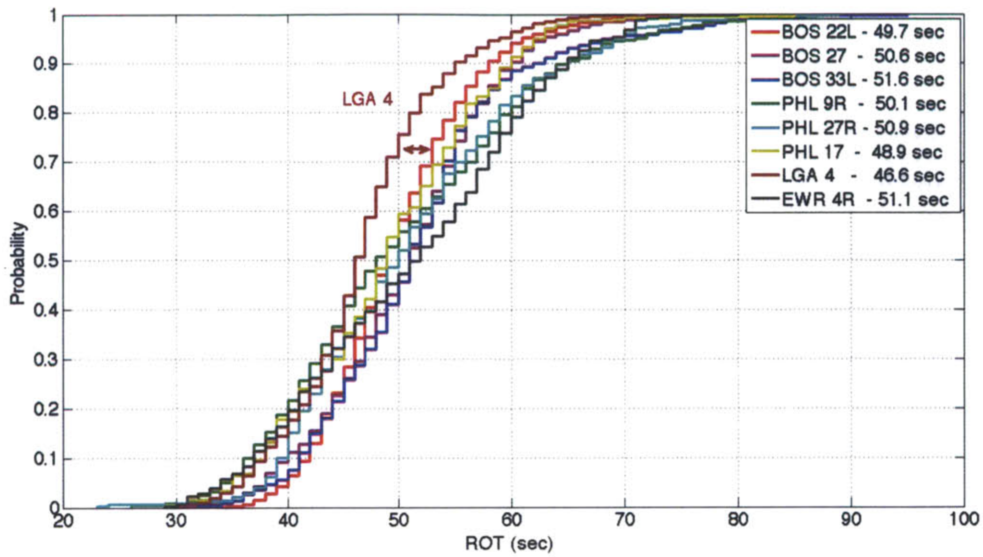


Figure 3-13. Cumulative distribution functions for large aircraft indicating significantly different runway occupancy on runway 4 at LGA

There are two high - speed exits at 3,100 feet and 3,500 feet from the threshold, and two standard runway exits at 4.200 feet and 4,500 feet from the threshold, which can expedite the runway turn off process. The runway 4 exit locations are shown in Figure 3-14. La Guardia is also the airport with continuous high arrival demand, which encourages pilots and controllers to minimize runway occupancy.

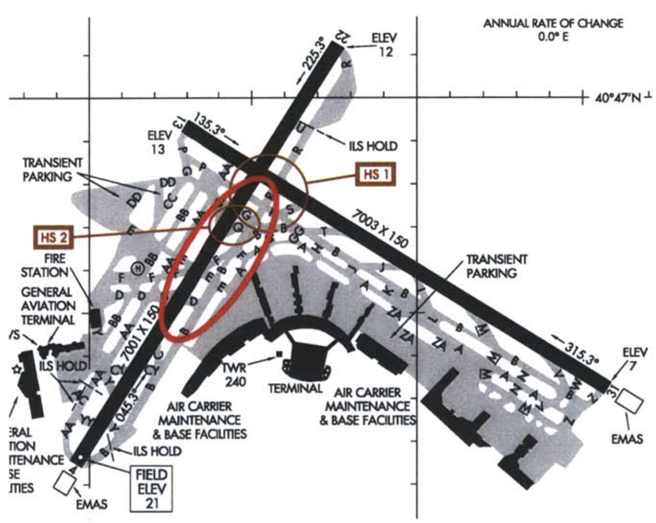


Figure 3-14. Runway 4 exits at LGA

3.4.3 Runway Occupancy Results for Boeing 757 Aircraft

For Boeing 757 aircraft, runway 22L at Boston and runway 4 at La Guardia have the shortest mean runway occupancy, as shown in Figure 3-15, both of them around 54 seconds. The reason for low Boeing 757 ROT values at La Guardia is similar to the case of large aircraft runway occupancy. The four closely spaced runway exits provide fast and efficient turn off opportunities. The mean ROT on runway 9R in Philadelphia is 2 seconds lower than on runway 27R due to the four high - speed exits available for aircraft to exit the runway faster. There is no statistically significant difference between Philadelphia's runway 27R and Newark's 4R, which are the slowest runways for Boeing 757s. It is interesting to note that runway 4R has a high-seed exit located at 4,100 feet from the threshold, and runway 27R at Philadelphia has a high-speed exit at 5,500 feet from the threshold, which would normally results in different runway occupancy times.

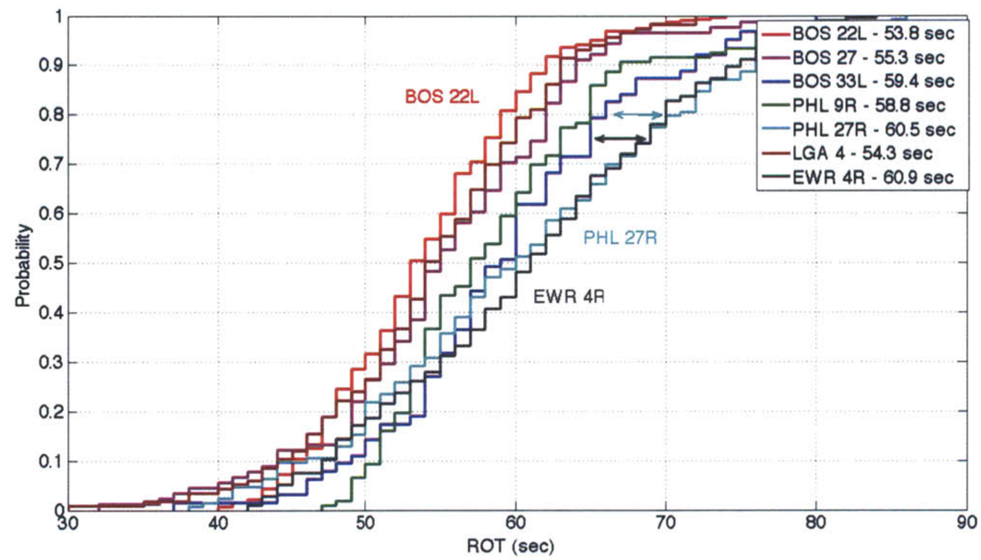


Figure 3-15. Cumulative distribution functions for B757 aircraft indicating significantly different runway occupancy on 4R at EWR and 27R at PHL

3.4.4 Runway Occupancy Results for Heavy Aircraft

Runway occupancy times for heavy aircraft show significant differences between runways. Boston's 22L and 27 have the lowest runway occupancy times: 57.2 and 59.7 seconds. Boston's runway 33L shows significant differences from all other runways. This runway has the lowest average runway occupancy time of 74.4 seconds. Newark's average ROT is 64.2 second with a standard deviation of 10.6 seconds. Runway 4 has two high - speed exits located 4,300 feet and 6.200 feet from the threshold, which lead to high runway occupancy times. However, in 2012 the airport announced that there are plans for two additional high - speed taxiways on the runway. These new runway exits have the potential to reduce average runway occupancy significantly in the future. Runway 27 at Philadelphia has longer runway occupancy than runway 9R, possibly due to the lack of high-speed exits.

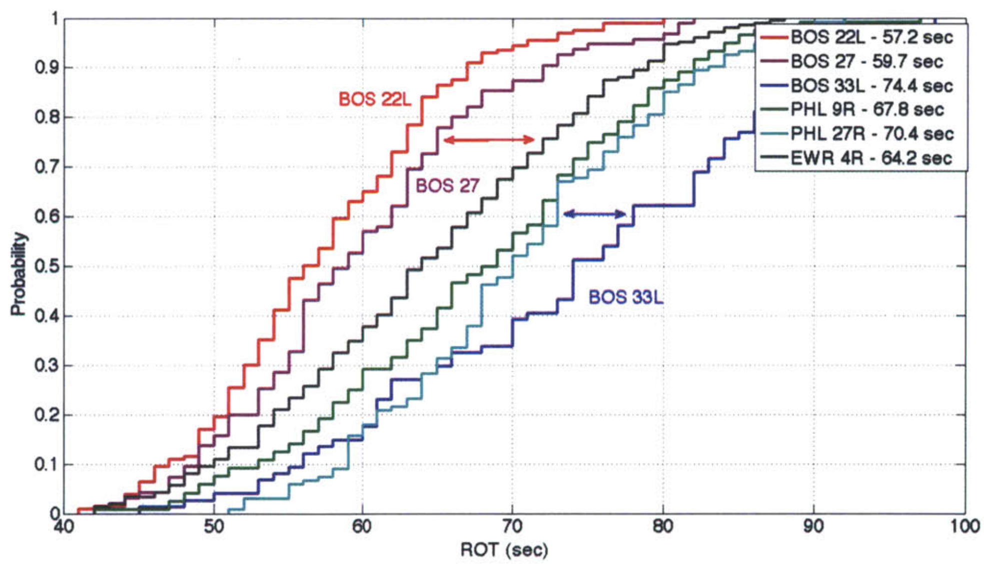


Figure 3-16. Runway occupancy results for heavy aircraft

3.4.5 Impact of Weather Conditions on Runway Occupancy

The runway occupancy results obtained in this chapter consider both VMC and IMC weather conditions, but it is also important to investigate if ROT is different in IMC and VMC. Any significant change in ROT due to bad weather can impact runway capacity and it can influence wake separation requirements.

In order to look at the impacts of weather on ROT, two runways are compared in IMC and VMC. The weather information is based on the ASPM database indication, other variables, such as visibility or runway surface conditions are not included. The two selected runways are 22L in Boston and 4 in La Guardia, because these two runways have the lowest mean ROT results. The comparison is performed only for large category aircraft due to the large data sample size.

The cumulative distributions are shown in Figure 3-17 for BOS 22L in VMC and IMC conditions for large aircraft. The difference in runway occupancy times is significant at the 5% significance level. At 10% significance level, however, the null hypothesis is not rejected, which means that the difference between VMC and IMC runway occupancy is not significant.

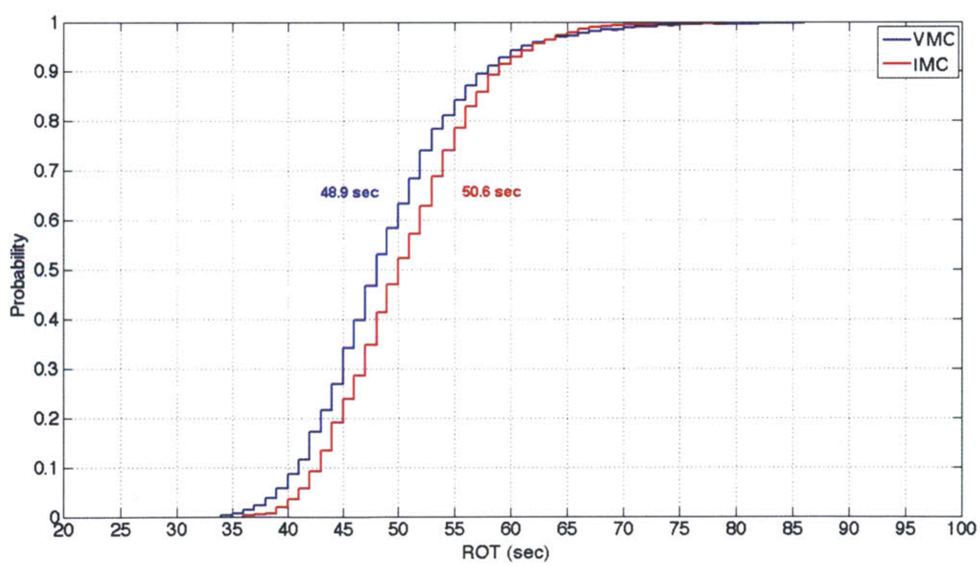


Figure 3-17. Cumulative ROT distribution in VMC and IMC conditions at BOS

Figure 3-18 compares weather conditions on runway 4 at LGA. The statistical test shows that runway occupancy is the same in VMC and IMC weather conditions.

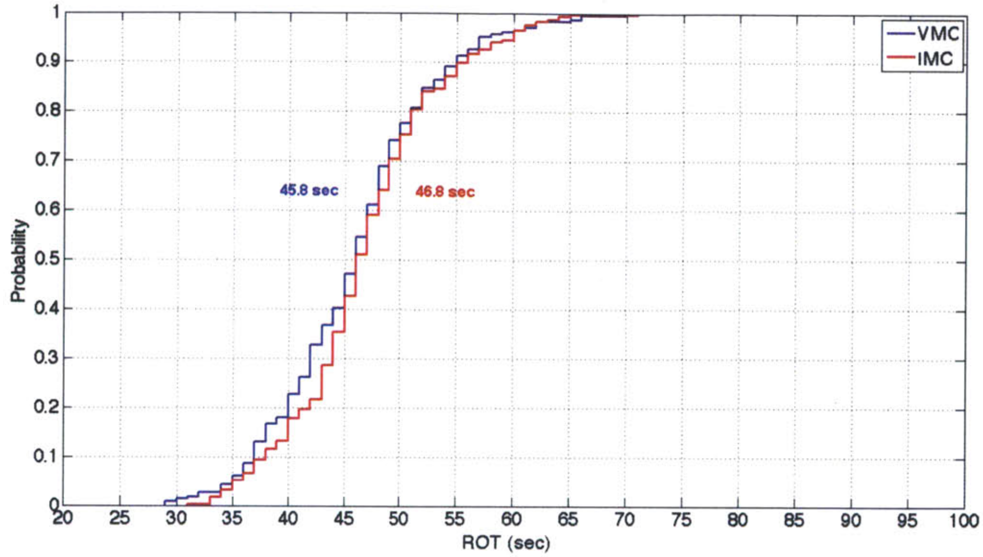


Figure 3-18. Cumulative ROT distribution in VMC and IMC conditions at LGA

The ROT results for VMC and IMC weather conditions are summarized in details in Table 3-3 below. The difference in runway occupancy is not significant, but a small increase is observed. The minimum ROT values increase in IMC conditions by 2 seconds in both cases. The standard deviations show less disparity in IMC than in VMC.

Table 3-3. Influence of weather conditions on ROT

Runway	Statistic	VMC	IMC
BOS 22L	Sample Size	1019	979
	Mean (sec)	48.9	50.6
	Range (sec)	[34,88]	[36,84]
	Std. Dev. (sec)	7.1	6.5
LGA 4	Sample Size	229	287
	Mean (sec)	45.8	46.8
	Range (sec)	[29,70]	[31,71]
	Std. Dev. (sec)	7.1	6.7

3.4.6 Runway Occupancy Study Summary

The runway occupancy study provides a detailed insight into how long typical ROT values are. Out of all runways compared, runway 4 at La Guardia shows the best runway occupancy performance. The mean ROTs are the lowest for large aircraft, and the second lowest for Boeing 757s. The low standard deviations (6.8 and 7.6 seconds, respectively) also indicate a very consistent performance and continuous quick landing rolls. This can be due to the high arrival demand at the airport that requires pilots to exit the runway as soon as they are able to do so. A short interview with two pilots who have flown into LGA supports the claim that pilots tend to focus more on quick and efficient runway exits at this airport than at other airports, because they are aware of the busy traffic and high demand.

The study finds that runway occupancy does not necessary scale with aircraft size. Although heavy aircraft have the longest ROTs at every runway, small aircraft often occupy the runway as long as large aircraft or Boeing 757s. This trend us observed in Boston and in Philadelphia as well. The small aircraft group also has high standard deviations ranging from 8.2 to 9.9 seconds. Small aircraft usually land at lower speeds, which means that they are able to turn off the runway sooner if there is an exit available. However, most runway exits are designed for larger aircraft flying at higher speeds, so they are spaced further from the threshold. This may require small aircraft to roll down the runway longer before they are able to take one of the exits.

Only small and large aircraft fall below the 50-second runway occupancy threshold, which permits 2.5 NM minimum radar separations. Small aircraft have less than 50-second averages at BOS on runway 27, and at PHL on runway 27R. Large aircraft also fall below 50 seconds at BOS on runway 22L, at LGA on runway 4, and at PHL on runway 17. On the remaining runways, the average ROT for small and large aircraft is slightly above 50 seconds. This small difference, however, can have a significant impact on runway capacity, as it requires a 3-NM minimum radar separation as opposed to the 2.5-NM separation, which can reduce the number of landings.

The study also shows that high - speed runway exits can make a significant difference in runway occupancy. For instance, runway 9R in Philadelphia has a better runway occupancy performance than runway 27R. This is attributed to the number of high-speed exits available on the runway. 9R has four high - speed exits, whereas 27R has only one. Heavy aircraft on 27R are often unable to slow down enough to make the high - speed turn off, and they are forced to take a standard 90-degree exit further down the runway.

The comparison of VMC and IMC weather conditions suggests that there is no significant difference in runway occupancy between the two weather conditions. The statistical test revealed that the difference is not significant at LGA at 5% significance level, and it is not significant in Boston either at the 10% significance level. Interestingly, the standard deviations are lower by half a second under IMC than in VMC conditions, although it should be noted that the weather information does not account for low visibility, rain or snow on the runway surface, or any other variables. Thus, including other complementary weather variables might indicate a distinction between VMC and IMC runway occupancy.

Chapter 4

4 Wake Vortex Separation

The objective of Chapter 4 is to measure inter-arrival separations in IMC weather conditions. Separations are measured as a distance between consecutive landings, as well as a landing time interval between two arrivals. These observed separations could be used to determine the length of the additional spacing controllers apply, and in what circumstances separations become the limiting factor for runway throughput. The results indicate that the largest buffer is applied between aircraft pairs with a small lead aircraft. The landing time interval measurements illustrate that there is an opportunity for reduced wake separation minimums for most aircraft pairs. However, runway occupancy becomes the limiting factor in case of small lead aircraft. Since small aircraft spend a long time on the runway, the additional separation buffer is needed to account for the variability in the system.

4.1 Wake Separation Study Objective

The objective of the wake vortex separation study is to measure final approach separations between consecutive landings and to determine under what conditions does wake separation limit runway capacity. The minimum separation standards are well defined by the FAA [5], but not all aircraft fly at the minimums. Typical separation values are often higher than the minimums due to additional safety margins, mixed departure-arrival runway use on the same runway, or due to interactions between crossing and closely spaced parallel runways.

In order to determine typical separation values, a data source with high position accuracy is desirable. Evaluating radar surveillance information to measure wake separations can provide important insight into airport operational efficiency and runway throughput. Based on typical separations, minimum separation requirements can be compared to observed separations, which defines how much of an additional spacing is applied by controllers and pilots between landings. Furthermore, comparing wake separations to runway occupancy can identify certain arrival pairs where there is an opportunity to reduce minimum allowable separation in order to enhance runway throughput.

In order to look at operational efficiency, measured separations can be compared to the required minimum separations introduced in Chapter 2. Observed separations between aircraft are often further apart than the minimum allowable separation. This additional spacing is called the buffer, and it can be described by a Poisson distribution due to the randomness in spacing between aircraft. The purpose of the additional spacing is to account for the variability inherent in controlling aircraft and to ensure that aircraft do not come too close together due to this variability. The buffer can vary between aircraft pairs, runways and airports, and it can also change from controller to controller. Although additional spacing increases safety margins, it also leads to a loss of runway throughput due to the inefficient flow of aircraft with longer spacing than necessary.

Additionally, observed wake separations can be compared to the results of the runway occupancy study. Looking at typical separations and runway occupancy times can tell where separations are too conservative, and where runway occupancy may impact inter-arrival spacing. If the ROT of a leading landing aircraft is greater than the separation between the leading and the trailing aircraft, the trailing aircraft needs to initiate a missed approach or go-around.

Lastly, this study also compares the minimum separation standards to typical runway occupancy times measured in Chapter 3. If the minimum separation standards fall behind runway occupancy, there is potential to increase runway throughput by reducing separation standards. On the other hand, if runway occupancy is as long as the wake separation, the minimum allowable separation cannot be reduced further. Measuring wake vortex separations from aircraft position data can help to identify potential wake separation concepts, which then can lead to runway throughput benefits.

4.2 Wake Separation Analysis Method

Inter-arrival spacing is measured at each of the selected runways in Chapter 3 for consecutive landings in IMC weather conditions and in peak hours. Measuring separations in IMC weather conditions is essential, because the minimum separation requirements only hold in bad weather conditions. Runway throughput is usually also lower during such periods; hence, this study focuses only on IMC days of data measurements. Furthermore, it is also important to consider only peak arrival demand time periods. When arrival demand is high, controllers are more likely to separate aircraft at the minimums to avoid delays and to ease congestions in the airspace.

For the purpose of this study, separation is measured both as a time interval, and as a distance interval between an aircraft pair on a common final approach path. Since runway occupancy is measured in units of seconds, but the separation requirements for arrivals are defined in units of nautical miles, assessing separations in both units is desired. The landing time interval (LTI) is defined as the time period between the leading aircraft crossing the runway threshold and the trailing aircraft crossing the same threshold. LTI is measured in units of seconds. The inter-arrival distance (IAD) is defined as the distance between two consecutive landings at the moment the lead aircraft crosses the runway threshold. The distance is calculated as the track line distance remaining for the trailing aircraft when the leading aircraft crosses the threshold and it is the cumulative vector of aircraft position distances on the x-y plane. The distances are measured only when both aircraft have turned on the common final approach path.

Similarly to the runway occupancy study, ASPM data provides information on the prevailing weather conditions and ASDE-X data is used for aircraft surveillance. In addition to the information collected in Chapter 3, the arrival and departure sequencing is also considered.

Figure 4-1 below shows an example of a typical separation distribution measured between large - large aircraft pairs on runway 27 at Boston. The runway iss used only for arrivals; no departure movements are sequenced in between. Trailing aircraft are separated by at least 2.5 NM from the leading aircraft.

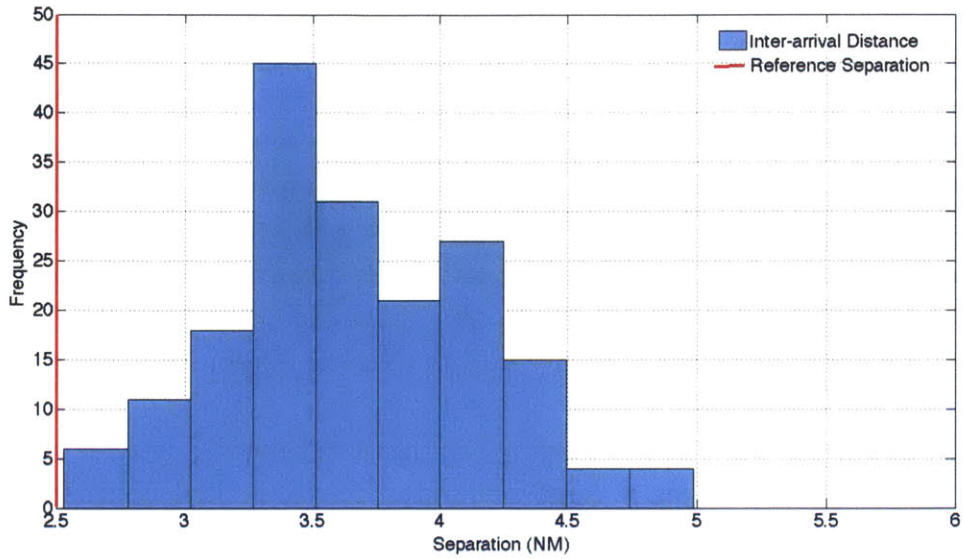


Figure 4-1. Inter-arrival distance on runway 27 at BOS for large-large aircraft pair

In some cases, a bimodal distribution can be observed. Certain runway configurations require that aircraft are spaced further apart to allow for a departure in between two landings, to allow for crossing traffic on a crossing runway, or to accommodate simultaneous landings on a parallel runway with required diagonal spacing between the aircraft. An example of a bimodal distribution is shown in Figure 4-2. Inter-arrival distances are measured for large-large aircraft pairs on runway 33L at Boston when the runway is used simultaneously for arrivals and departures. This shared use of the runway requires increased inter-arrival distance to allow departing aircraft to take off.

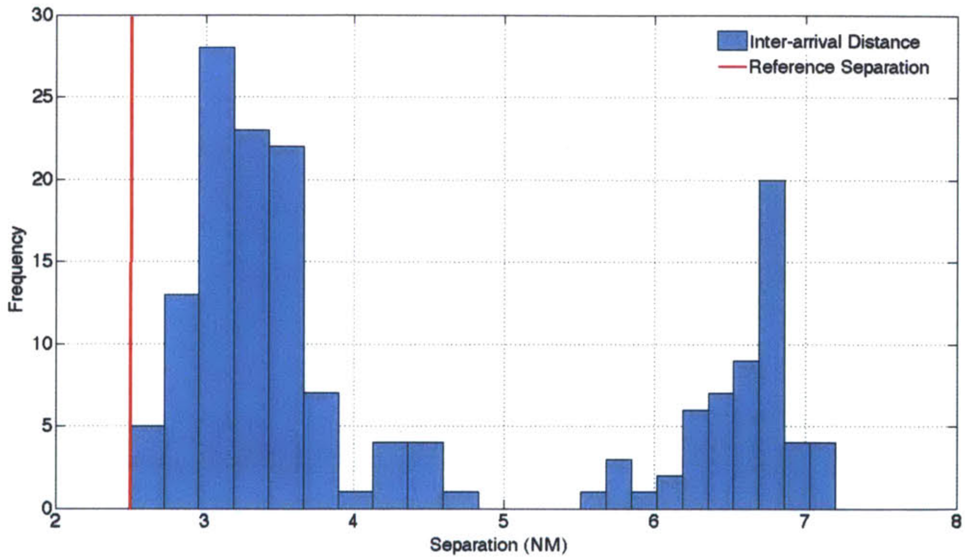


Figure 4-2. Inter-arrival distance on runway 33L at BOS for large-large pairs

In case of a bimodal distribution, comparing the full set of separation data to runway occupancy times or minimum separations requirements would not be beneficial for this study. That is because only the first peak is driven by the required separation minimums. The second peak is driven by an operational constraint, which is the shared use of runway for departures and arrivals in this case. Accordingly, the data set is divided into two small subsets, for separations less than equal 5 NM and separations more than 5 NM. The 5 NM border is chosen as the upper limit of the first peak, because this value is noted as the typical maximum separation between large-large pairs in case of one-peak separation distributions.

For the bimodal distribution, only the first peak is analyzed for the purpose of this study. The probability density function of the first data subset is shown below in Figure 4-3.

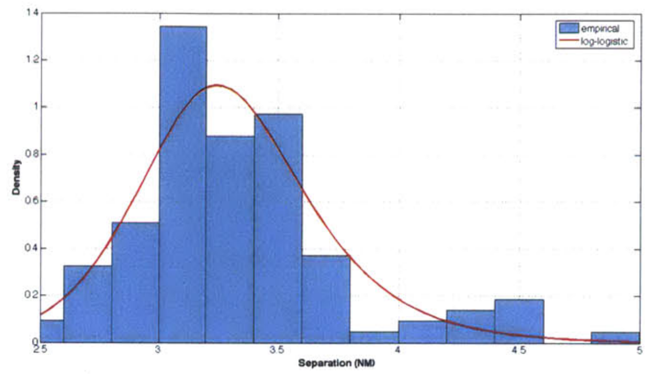


Figure 4-3. Probability density function of separations driven by minimum standards

Another interesting bimodal distribution is observed on runway 22L at Boston. A sharp 5.5 NM second peak follows the first distribution peak, as shown in Figure 4-4. This second peak is possibly due to an airport specific standard operating procedure at Boston and not due to departure sequencing, because runway 22L is used solely for arrivals. It is more likely that the approach sequenced arrivals at the 5.5 NM range to allow the simultaneous use of runway 27, which is a crossing runway. Incidentally, the 5.5 NM peak is also noted when runway 27 is not in use.

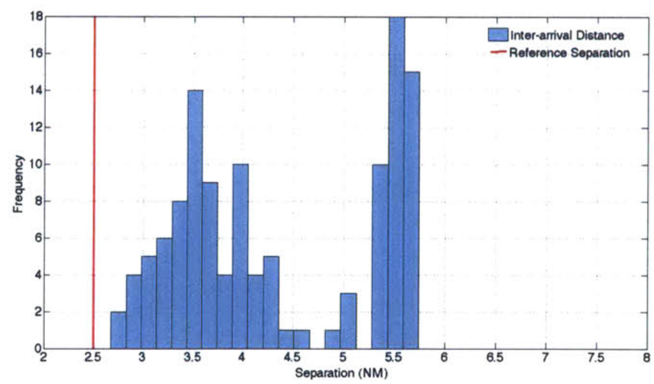


Figure 4-4. Inter-arrival separations with a sharp 5.5 NM peak on runway 22L at BOS for large-large pairs

For each runway with shared departure and arrival movements, the data is narrowed down to the subset driven by the separation minimums. For all other runways with only arrival operations, the full set of measurements is included in the analysis.

4.3 Wake Separation Results

4.3.1 Inter-Arrival Distance at Boston

In order to determine the additional spacing controllers apply to account for the variability in the air traffic system, the inter-arrival distances are evaluated. The results for Boston are presented here as an example of the method used in this study. The results of other airports are summarized at the end of the section. The data includes runway 22L, runway 27, and runway 33L arrival pairs. The vertical red line indicates the separation minimums between each pair. The mean, and the standard deviations are marked above the distributions with a blue circle and black whiskers. The mean distance is also written on the top. The vertical aircraft categories on the left are the leader aircraft, and the horizontal aircraft categories on the top are the follower aircraft. For instance, the Boeing 757 – large pairs are located in the second row, second column. The required minimum separation for these pairs is 4 NM, and the measured mean inter-arrival distance is 4.69 NM.

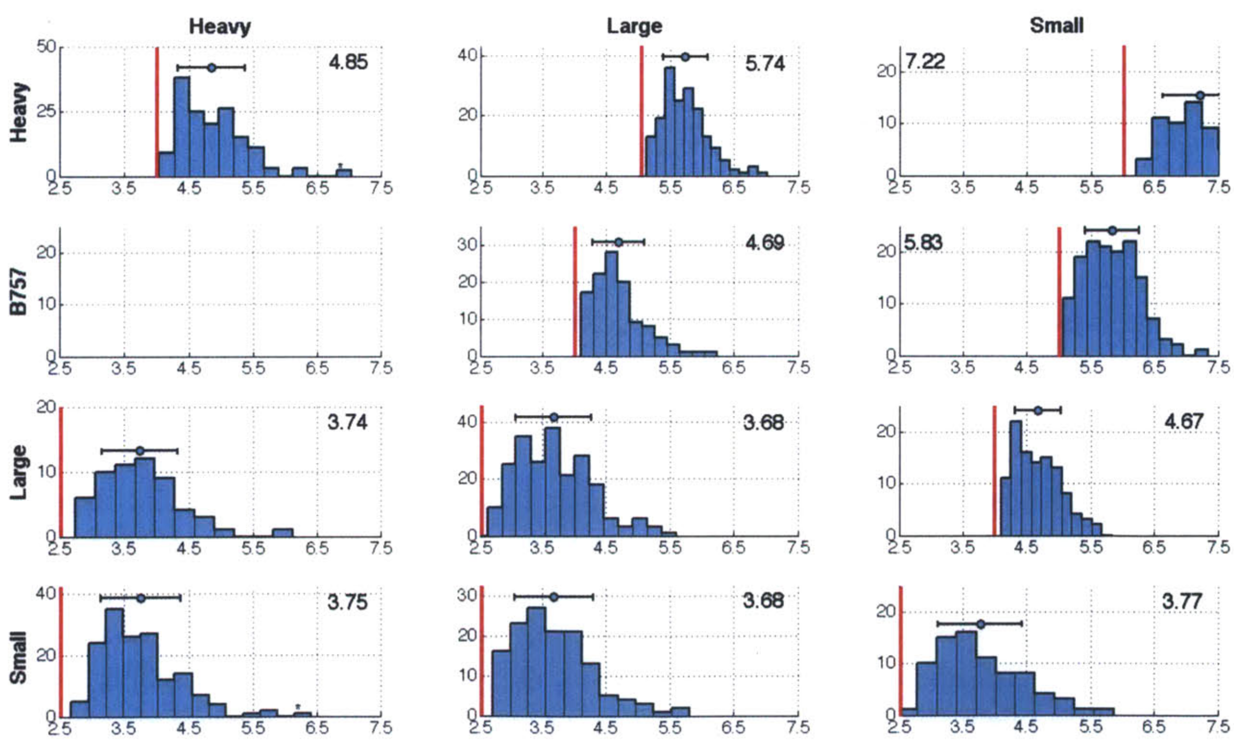


Figure 4-5. Inter-arrival distance measurements at Boston (no B757-heavy pairs)

For heavy-heavy pairs, the minimum observed separation, 4.04 NM, is very close to the minimum allowable separation. The longest observed separation is 6.35 NM with an overall average of 4.85 NM. The measured standard deviation is 0.53 NM with one outlier at 7.03 NM. For heavy-large and heavy-small aircraft, the minimum observed separations falls further from the minimum allowable separations. The minimum values are 5.13 and 6.21 NM, respectively. The average inter-arrival distance for heavy-large pairs is 5.74 NM, and 7.22 NM for heavy-small pairs. The longest heavy-small separation is 8.8 NM.

The second row illustrates the results for aircraft pairs with a Boeing 757 lead aircraft. There data is insufficient to measure any B757 - heavy pairs at BOS, therefore only two cases are presented here. The gap between observed minimum separations and minimum allowable separations is 0.1 NM for B757- large pairs. The measurements range from 4.1 NM to 6.14 NM with a 4.69 NM mean. B757- small pairs have a 5.83 NM average ranging from 5.06 NM to 7.17 NM. The standard deviations for both cases are close to 0.40 NM.

The minimum observed separation for large-heavy pairs is 2.75 NM, while the maximum is 5.81 NM. The average separation is 3.74 NM with a high 0.59 NM standard deviation. One aircraft pair is observed below the 2.5 NM allowable separations for large-large pairs. Although this would not be allowed under IFR separation requirements, the weather data only indicates that IMC weather conditions occur at the airport at the time when the data is taken. There could have been short time periods in between when an aircraft is cleared for a visual landing, but that information is not captured in the ASPM database. The average separation is 3.68 NM for large-large pairs, and 4.67 NM for large-small pairs.

The average separation is 3.75 NM for small - heavy, 3.68 NM for small - large, and 3.77 NM for small - small aircraft pairs, as seen in the last row. The small lead aircraft category has the largest standard deviations among all aircraft pairs with over 0.6 NM for all three examples shown below. The minimum observed separations are above MRS, except for small - small pairs, where there is an arrival pair with 2.47 NM inter-arrival spacing. This might due to a visual clearance for one of the landing aircraft.

4.3.2 Inter-Arrival Distance at Other Airports

The results of the inter-arrival distance measurements at the other airports are summarized in this section. The mean separations and the standard deviations are shown above the data distribution. The required minimum separations are marked with a red line.

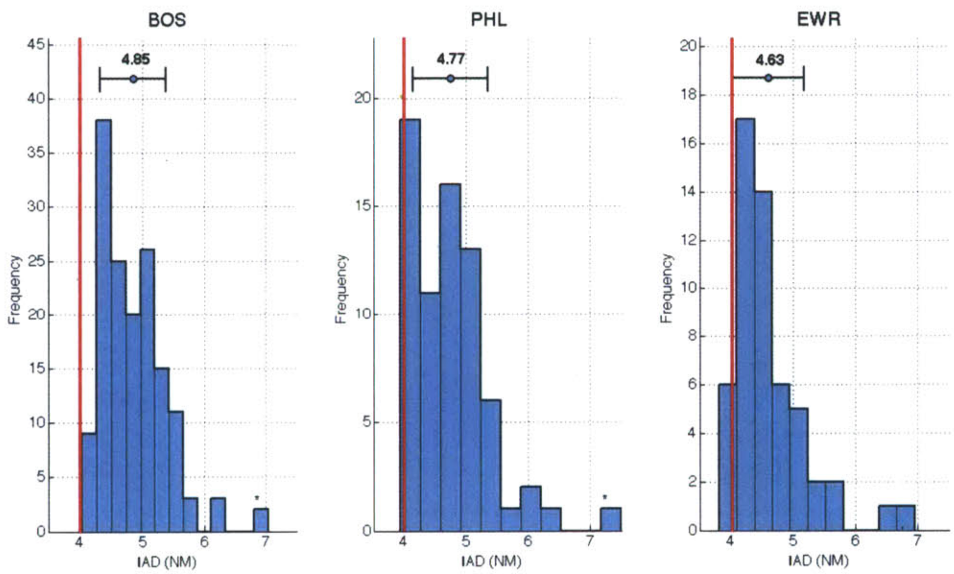


Figure 4-6. Inter-arrival distance distribution for heavy - heavy pairs (no heavy traffic at LGA)

Heavy - heavy pairs are shown in Figure 4-6 above for Boston, Philadelphia, and Newark. Boston has the highest average inter-arrival distance separation with 4.85 NM, followed by Philadelphia with 4.77 NM, and Newark with 4.63 NM. The Newark measurements, however, have separations below the required minimum 4 NM. This can be due to some visual separation periods in between IMC conditions. The standard deviations are also very close: 0.53 NM for Boston, 0.58 NM for Philadelphia, and 0.57 NM for Newark.

Figure 4-7 presents the separation results for heavy - large aircraft pairs. It is interesting to note that BOS has a very narrow distribution of data with a 0.35 NM standard deviation. Philadelphia and Newark have 0.67 NM and 0.73 NM, respectively. The mean separations are 5.74 NM, 5.65 NM, and 5.67 NM with the highest in Boston and the lowest in Philadelphia.

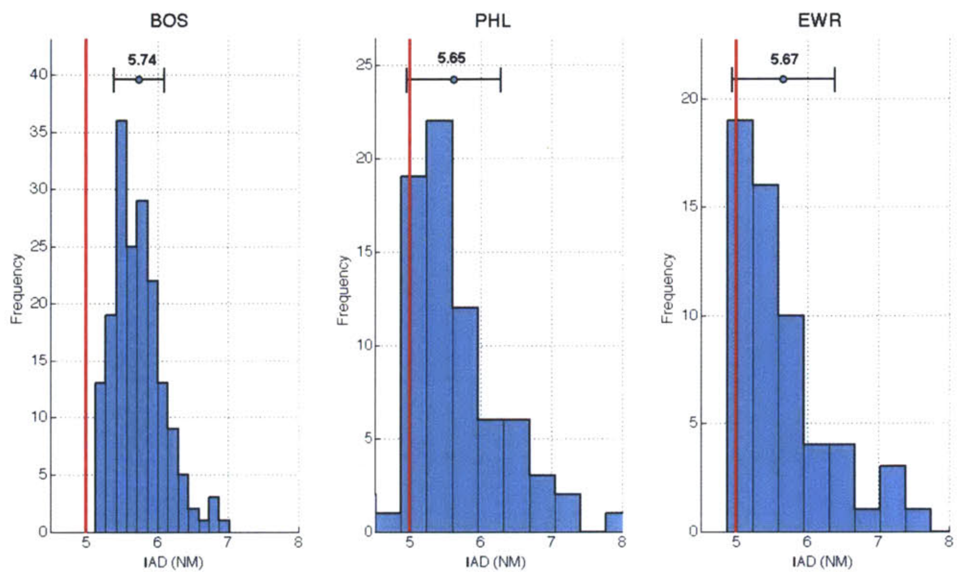


Figure 4-7. Inter-arrival distance distribution for heavy - large pairs (no heavy traffic at LGA)

Boeing 757 - large pairs have similar mean separations across four airports. La Guardia has the lowest average of 4.54 NM with a 0.38 NM standard deviation. Boston's and Philadelphia's averages are 4.69 NM and 4.71 NM. Newark has a very large standard deviation of 0.71 NM due to an aircraft pair flying 7.5 NM apart and a few pairs flying below the 4 NM required minimum separation. The lowest recorded inter-arrival distance at Newark is 3.14 NM. Since there are several pairs flying below the minimum, VMC weather conditions might have occurred for a very short period of time that is not recorded in the ASPM database.

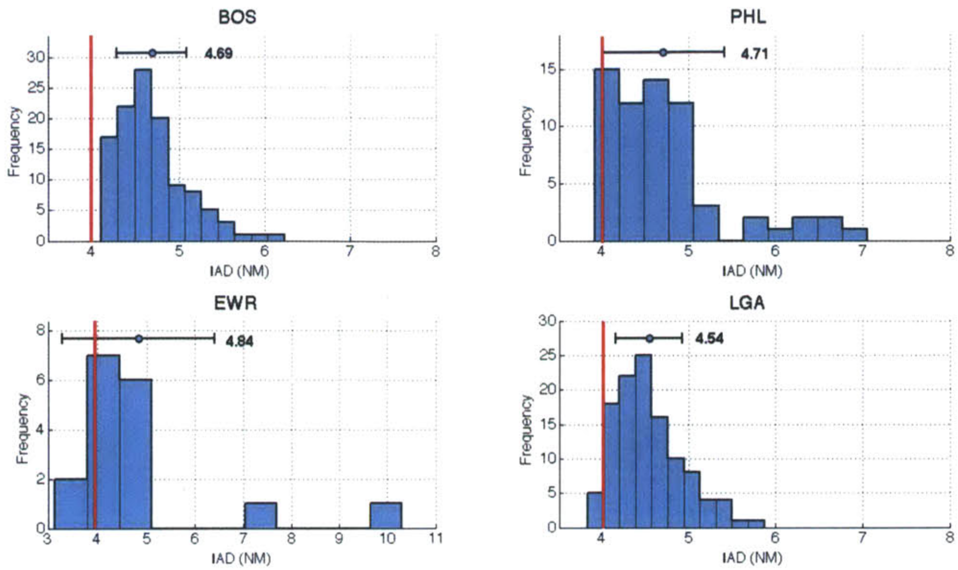


Figure 4-8. Inter-arrival distance distributions for B757 - large pairs

Large - heavy pairs show very small differences at Boston, Philadelphia, and at Newark, as shown in Figure 4-9. The mean inter-arrival separations are 3.74 NM, 3.61 NM, and 3.64 NM, respectively. All pairs are separated above the required minimum 2.5 NM.

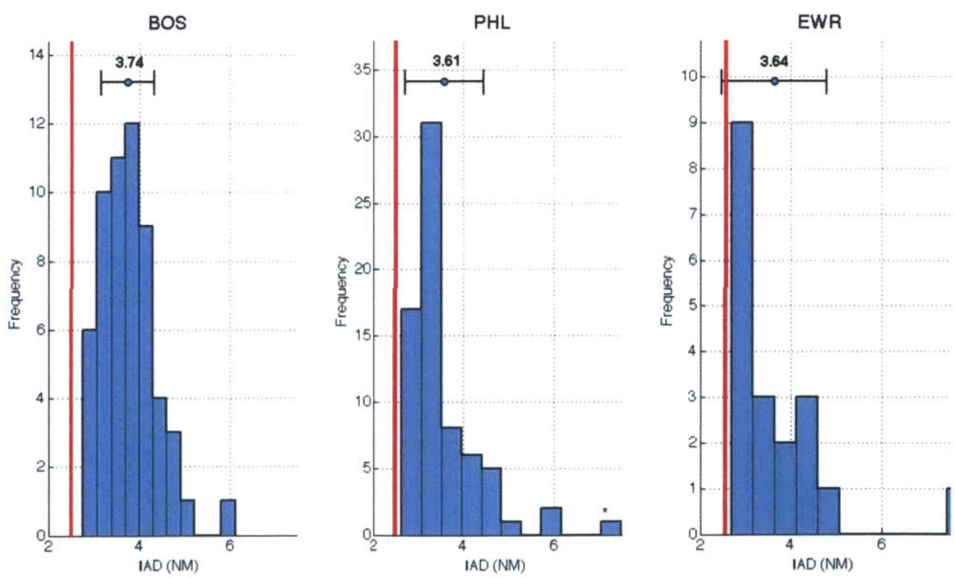


Figure 4-9. Inter-arrival distance distributions for large - heavy pairs

Figure 4-10 summarizes the results for large - large pairs, which are the most common pairs at all the airports. Boston, Philadelphia, and Newark all perform similarly, and La Guardia has the lowest mean separation of 3.35 NM. La Guardia also has the lowest runway occupancy times, which can permit shorter separation buffers.

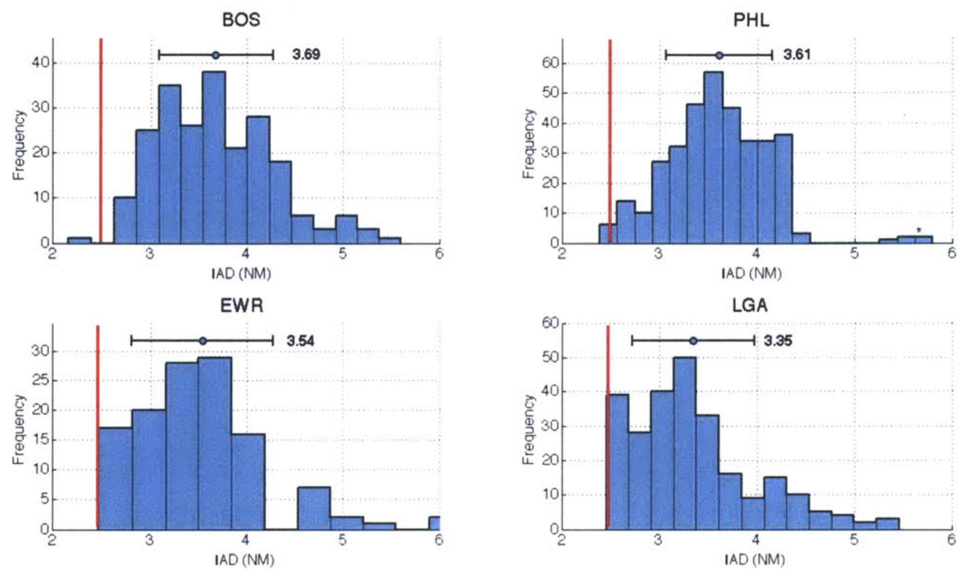


Figure 4-10. Inter-arrival distance distributions for large - large pairs

4.3.3 Separation Buffer

This study implements the buffer definition from Ballin and Erzberger (1996), who measure buffer as the distance between the required minimum separation and the distribution maximum point based on the best-fit density function [15]. The distribution maximum point is the observed separation distance where the density function reaches its maximum value. The distribution functions can be calculated by data fitting, as it is done in this study. It should be mentioned, that in other separation studies the buffer is measured between the required minimum and the average separation, or the buffer is obtained from a computationally more complex algorithm.

For distribution fitting, the Boeing 757 - large pairs at Boston are shown as an example in Figure 4-11. The results for other aircraft pairs are summarized at the end of this section. First, the independence of samples is tested by a one-lag scatter plot, which showed that the inter-arrival distance samples are independent with a one-lag correlation coefficient of 0.25. This test is carried out because of independence of samples is a requirement for distribution fitting. The maximum likelihood estimation method shows that a generalized extreme value fit is the best fit for this inter-arrival distance data set.

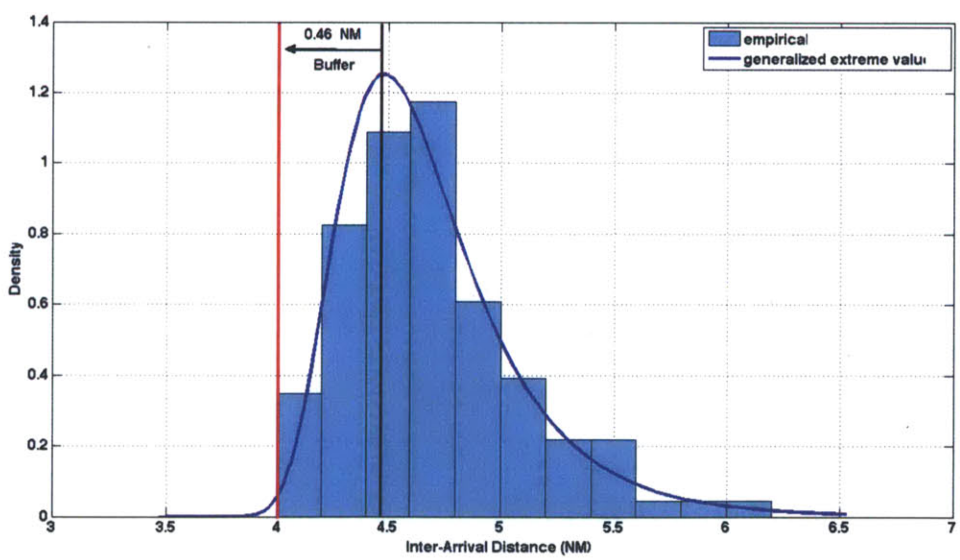


Figure 4-11. Inter-arrival distance histogram and the best distribution fit for B757 - large arrival pairs (separation buffer is shown on top)

The probability distribution is estimated by a generalized extreme value distribution (0.0659, 0.2943, 4.428) fit, shown with the blue curve. The values represent the shape, scale, and location, respectively. The generalized extreme value distribution is accepted by the KS test for significance levels of 0.1 or smaller. Based on the distribution fit, the distribution maximum is at 4.46 NM, indicated by the black vertical line. Since the required minimum separation for a Boeing 757 followed by a large aircraft is 4 NM (shown with the vertical red line), the buffer is computed to be the difference between the two, which is 0.46 NM. Similarly to the Boeing 757 - large pair measurements, the buffer is calculated for all other aircraft pairs, presented in Table 4-1. The overall average buffer at Boston across all observed aircraft pairs is 0.79 NM.

Table 4-1. Separation buffer measured at BOS (H - heavy, L - large, S -small, B7 - Boeing 757, buffer is measured in NM)

Pair	H-H	H-L	H-S	B7-L	B7-S	L-H	L-L	L-S	S-H	S-L	S-S
Buffer	0.55	0.54	1.1	0.46	0.71	1.13	0.99	0.51	0.91	0.83	1.02

The distribution fitting is also computed for Philadelphia, La Guardia, and Newark. The resulting arrival spacing buffers are summarized in Table 4-2. La Guardia has the lowest overall average buffer of 0.38 NM, although only Boeing 757 - large and large - large arrival pairs can be observed. The large - large pair buffer is only 0.41 NM, the lowest across all four airports. This low buffer is possibly due to the high arrival demand at the airport, which has been mentioned before as one of the plausible reasons for short runway occupancy.

Table 4-2. Separation buffer measured at PHL, LGA, and at EWR (values in NM) with comparison to BOS

	H-H	**H-L**	**B7-H**	**B7-L**	**L-H**	**L-L**
BOS	0.55	0.54	-	0.46	1.13	0.99
PHL	0.39	0.47	-	0.23	0.6	1.03
LGA	-	-	-	0.36	-	0.41
EWR	0.46	0.17	0.43	0.35	0.78	0.73

Newark's average buffer spacing is 0.49 NM. Heavy - large aircraft have the lowest observed buffer of 0.17 NM, and all the other arrival pair buffers are less than one mile. Philadelphia has a long buffer of 1.03 NM for large-large pairs, which increases the average buffer at the airport to 0.54 NM. When comparing individual aircraft pairs, heavy - small, and small - small aircraft pairs have the longest buffer, both of them above one mile. It is also interesting to note that largest average separation buffer is assigned when small aircraft are the leaders. The overall average buffer is calculated to be 0.7 NM across all aircraft pairs at all the four airports, as presented in Table 4-3.

Table 4-3. Average separation buffer across the four airports

		Follower			
		Heavy	**Large**	**Small**	**Average**
Leader	**Heavy**	0.47	0.39	1.1	0.65
	B757	0.43	0.35	0.71	0.5
	Large	0.84	0.79	0.51	0.71
	Small	0.91	0.83	1.02	0.92
	Average	0.66	0.59	0.84	**0.7**

4.4 Landing Time Intervals and Runway Occupancy

In order to compare wake separations to runway occupancy, inter-arrival separations are also measured in units of seconds. Although the required minimum wake separations are defined in units of distance, runway occupancy is measured in units of time. Accordingly, for every arrival aircraft pair, not only the inter-arrival distances are captured, but also the landing time intervals. A distribution of Boeing 757 - small separations at Boston is shown as an example below in Figure 4-12.

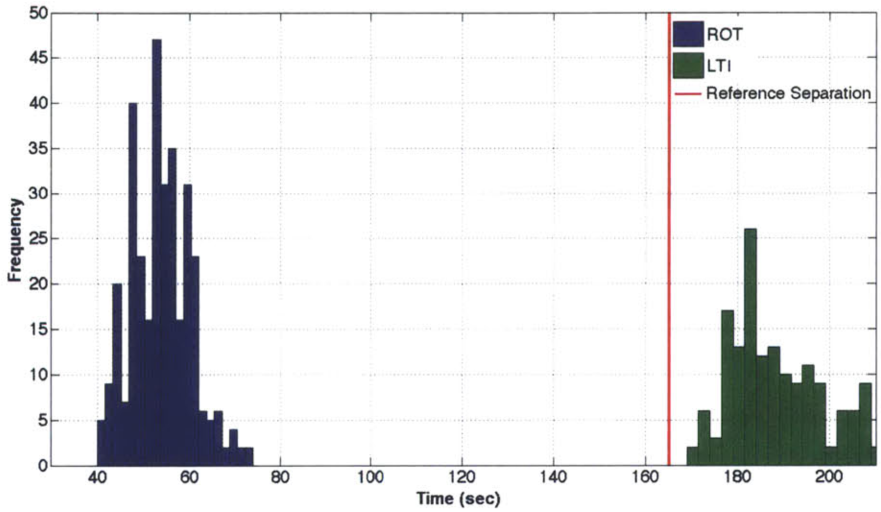


Figure 4-12. Runway occupancy and landing time interval for Boeing 757 - small arrival pairs

The green histogram represents the landing time interval distribution for every Boeing 757 - small arrival pair at Boston. The time interval is measured from the leader aircraft runway threshold crossing to the trailing aircraft runway threshold crossing. The runway occupancy data shown here is collected for the ROT study in Chapter 3 for Boeing 757 aircraft (the leader aircraft in this example).

On one hand, the ROT study in Chapter 3 analyzed individual runways in Boston and at the other airports. On the other hand, LTI is collected at an aggregate level for all the runways at an airport due to insufficient number of sample pairs landing on individual runways. To account for this difference, the ROT data is selected such that it included all runways. Since the goal of this study is to look at the limitations of runway occupancy and reduced wake vortex separation concepts, the worst-case scenario is considered. ROT samples are ranked for all Boeing 757 aircraft in orders of magnitude, and the worst 200 samples are selected for ROT and LTI evaluation. The reason for selecting the longest ROT samples is to look at cases where runway occupancy may impact inter-arrival separations.

The red line in Figure 4-12 shows the reference separation, which is the time equivalent required minimum separation. Since the minimums are defined in units of miles, they had to be converted to time equivalent separations. This is done by taking the required minimum separation and dividing it by the average final approach speed of each aircraft category. The final approach ground speeds are obtained from ASDE-X data, captured at the time of the threshold crossing. Since aircraft continuously slow down on approach, the measured values at the threshold represented a lower limit of typical final approach speeds. Due to large variations in the measures threshold speeds (head wind conditions are not accounted for), the estimated final approach speeds used in this study are the measured speeds (averaged over all landings for each aircraft category) rounded to the nearest ten knots. The estimated final approach speeds are shown in Table 4-4.

Table 4-4. Estimated final approach speeds based on ASDE-X data

Aircraft	Average Threshold Speed (knots)	Estimated Final Approach Speed (knots)
Heavy	145.3	150
B757	136.8	140
Large	125.7	130
Small	109.1	110

Based on these final approach speeds, the time equivalent required minimum separation for B757 - small pairs became 163 seconds, shown with the red line in Figure 4-12. The required minimum separation between a B757 and a small aircraft is 5 NM, which takes 163 seconds to fly at 110 knots for a small aircraft.

Figure 4-12 provides valuable information about B757 - small arrival pairs. Firstly, comparing the landing time interval to the reference separation shows that the minimum observed separation value is 7 seconds behind the reference separation line.

The average LTI is 189 seconds with a standard deviation of 11 seconds. In order to increase runway throughput, the mean landing time interval can be moved closer to the reference separation to reduce inter-arrival spacing and to permit more landings to take place. Reducing the spread of data, and moving those aircraft, which fly at 200 or more seconds apart, closer to the minimums, can do this. Moreover, it is also observed that runway occupancy is significantly lower for Boeing 757s than what the time equivalent required minimum separation is for B757 - small pairs. This means that additional runway capacity can be gained by lowering the required minimum separation, assuming today's safety standards are maintained at all times. If the required minimum separations are shifted closer to runway occupancy, the observed separations will also decrease, which can increase runway throughput.

Similarly to the Boeing 757 - small aircraft pair case, the study measures landing time intervals for all other aircraft pairs. The LTIs are plotted against ROTs and the corresponding reference separations.

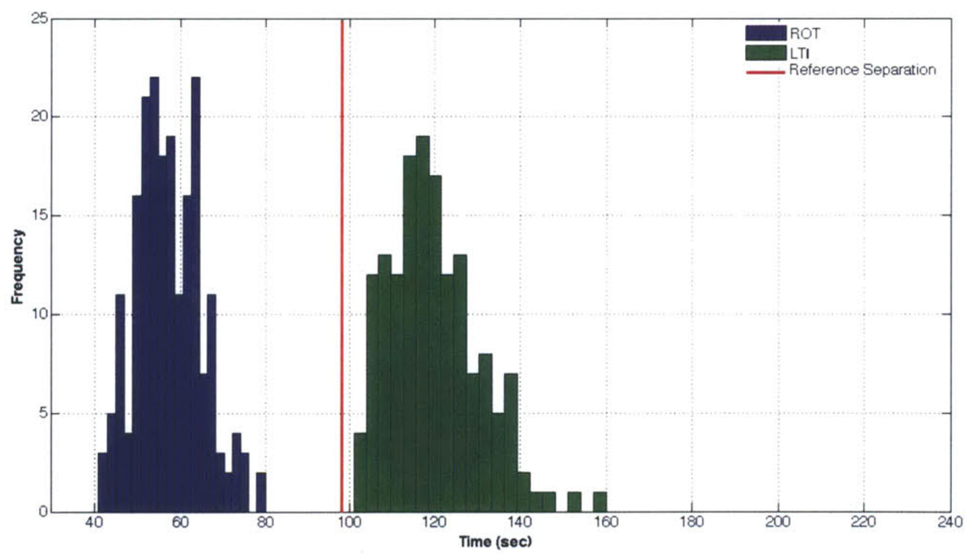


Figure 4-13. Landing time intervals and runway occupancy for heavy- heavy pairs at BOS

Figure 4-13 above shows the measured LTIs for heavy - heavy pairs. The runway occupancy data shown here is the 200 worst ROTs taken at Boston on runway 27 and runway 22L. Since ROT for heavy aircraft on runway 33L are influenced by outside factors and the data showed a skew distribution, it is not included here. The required minimum separation for heavy-heavy pairs is 4 NM described by the FAA, which translates to a 96 second reference separation, assuming an average 150 knot final approach speed for heavy aircraft, indicated by the red line. The observed minimum LTI is 101 seconds, with an average LTI of 119 seconds and a standard deviation of 10.9 seconds. Based on these observed separation values, additional runway throughput can be gained by lowering the mean LTI, which is 23 seconds behind the reference separation. Additionally, if wake turbulence measurements permit, the required minimum separation can be reduced, since the longest measured ROT is only 82 seconds.

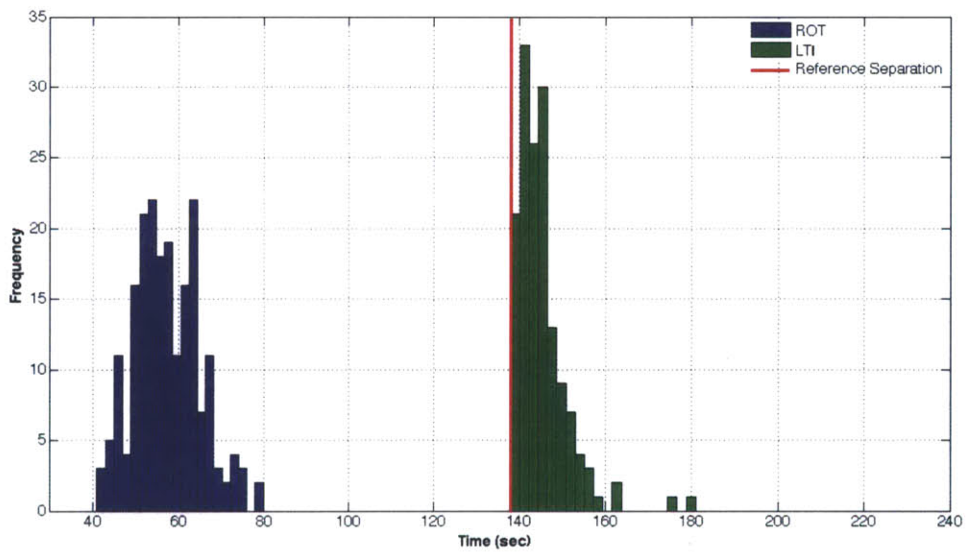


Figure 4-14. Landing time intervals and runway occupancy for heavy- large pairs at BOS

Between heavy - large pairs, the average LTI is 145 seconds, which is slightly above the 138-second reference separation line, as shown in Figure 4-14. The observed separations also have a very narrow distribution with a standard deviation of 5.43 seconds. In this case, runway throughput can be gained by lowering the required minimum separations, as large aircraft already fly very close to the minimums.

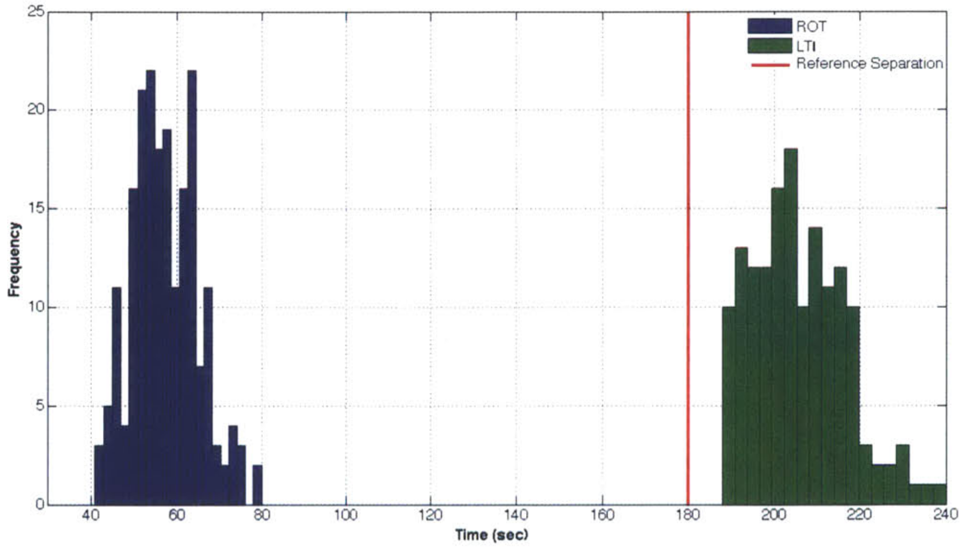


Figure 4-15. Landing time intervals and runway occupancy for heavy- small pairs at BOS

The minimum observed separation for heavy - small pairs is 190 seconds with an average of 206 seconds, presented in Figure 4-15. The data range spreads out wide with a maximum of 240 seconds, which results in in a large standard deviation of 10.6 seconds. In this case, decreasing the gap between reference separation and observed separations, as well as lowering required minimum separations (assuming safety is maintained) can lead to additional runway throughput.

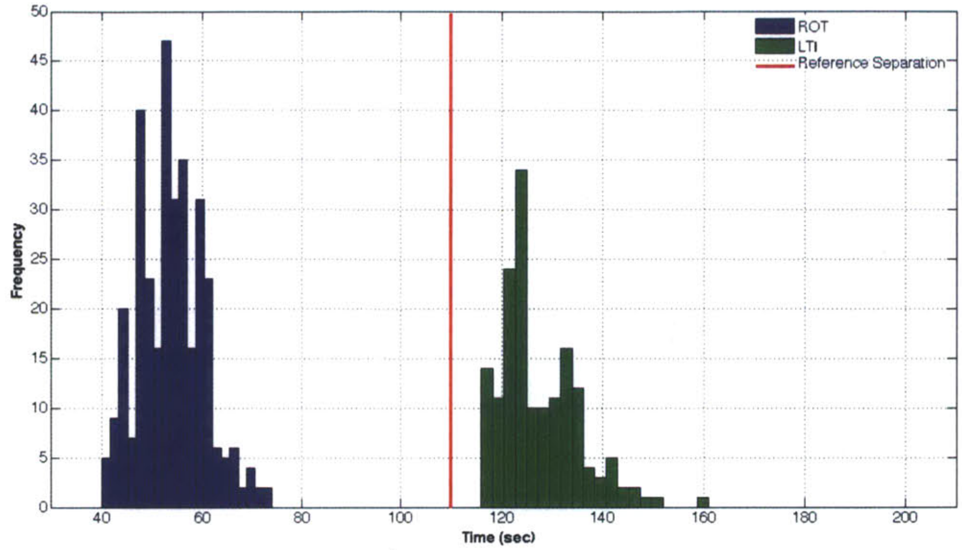


Figure 4-16. Landing time intervals and runway occupancy for B757 – large pairs at BOS

For arrival pairs with a Boeing 757 lead aircraft, only two cases have sufficient separation data. The first one is the Boeing 757 - large pair, and the second is the Boeing 757 - small pair, which has been explained earlier in this chapter. As Figure 4-16 illustrates there is a small, 6-second, gap between the 110-second reference separation line and the minimum observed separation at 116 seconds for B757 – large pairs. The average LTI is measured as 127.6 seconds with a standard deviation of 7.8 seconds. The most extreme LTI is 161 seconds. Based on these observations, runway throughput can be gained by lowering the required minimum separation and also by bringing the mean landing time interval closer to the minimums.

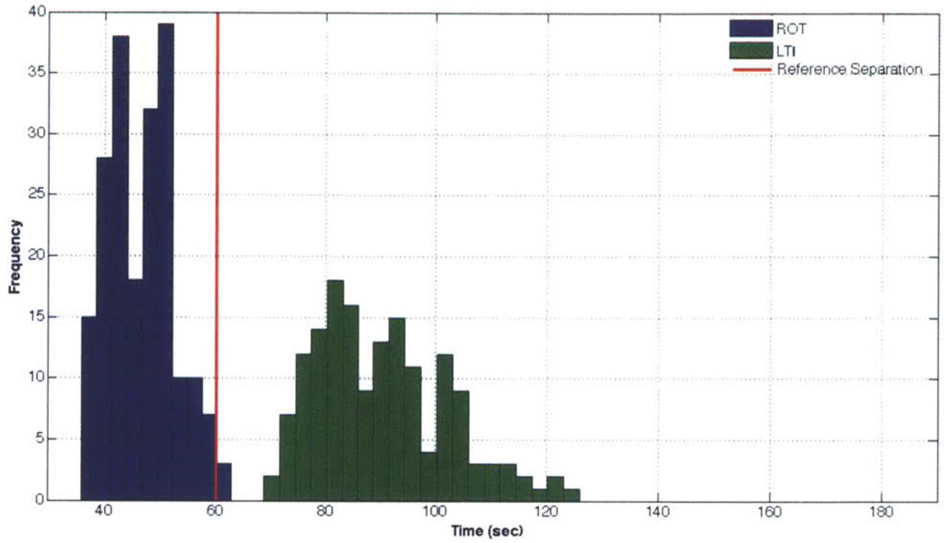


Figure 4-17. Landing time intervals and runway occupancy for large - heavy pairs at BOS

Figure 4-17 above represents large - heavy arrival pairs. Observed separations fall very close to large aircraft runway occupancy measurements. Three flights occupied the runway longer than the reference separation of 60 seconds. The measured LTIs range from 69 to 126 seconds with a large standard deviation of 12 seconds. The mean LTI between large and heavy pairs is 90.2 seconds. Although the mean fall 30 seconds behind the reference separation, ROT is limiting runway throughput. The required minimum separation cannot be reduced in this case. Runway throughput can be gained possibly by decreasing the landing time interval distribution range.

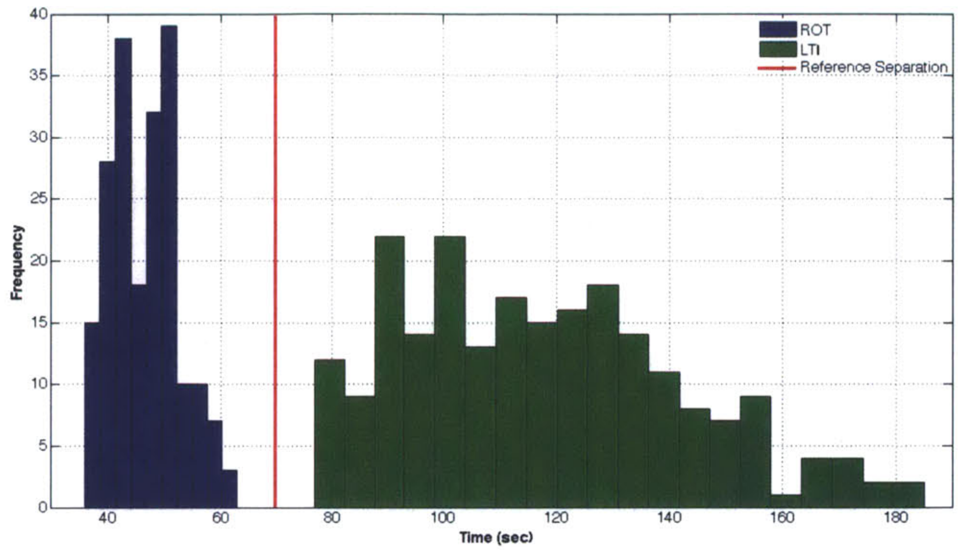


Figure 4-18. Landing time intervals and runway occupancy for large - large pairs at BOS

For large - large arrival pairs, the 70-second reference separation is behind the measured runway occupancy values in Figure 4-18. The observed LTIs range from 79 seconds to 187 seconds. This results in an extremely large 24.7-second standard deviation and a mean of 119.6 seconds. Reducing the required minimum separation for large - large pairs can bring separations too close to runway occupancy, and hence for additional runway throughput, the wide data spread should be narrowed. The mean LTI falls 50 seconds behind the reference separation, which gives a lot of potential for accommodate more landing by simply increasing consistency and efficiency in the current separation system. This result is consistent with the findings at PHL, LGA, and EWR, where aircraft fly very close to the reference separation, which is limited by runway occupancy. There is little potential to reduce the required minimum separation in this case.

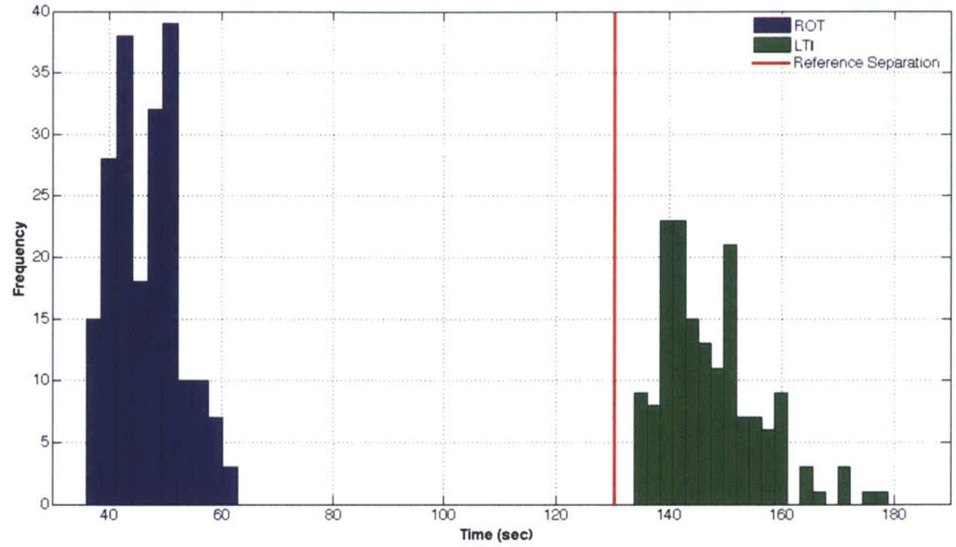


Figure 4-19. Landing time intervals and runway occupancy for large - small pairs at BOS

Lastly, large - small pairs are limited by the separation standards, as seen from Figure 4-19. The 130-second reference separation is far apart from the measured runway occupancy values. LTI ranges from 134 to 179 seconds with a mean of 146.8 seconds and a standard deviation of 9.7 seconds. In this case wake separation is the limiting element for additional runway throughput. Additional capacity can be gained by reducing required minimum separations.

Figure 4-20 through Figure 4-22 summarize the landing time interval findings for small lead aircraft pairs. As seen from the distributions, these results are very distinctive from the previous examples.

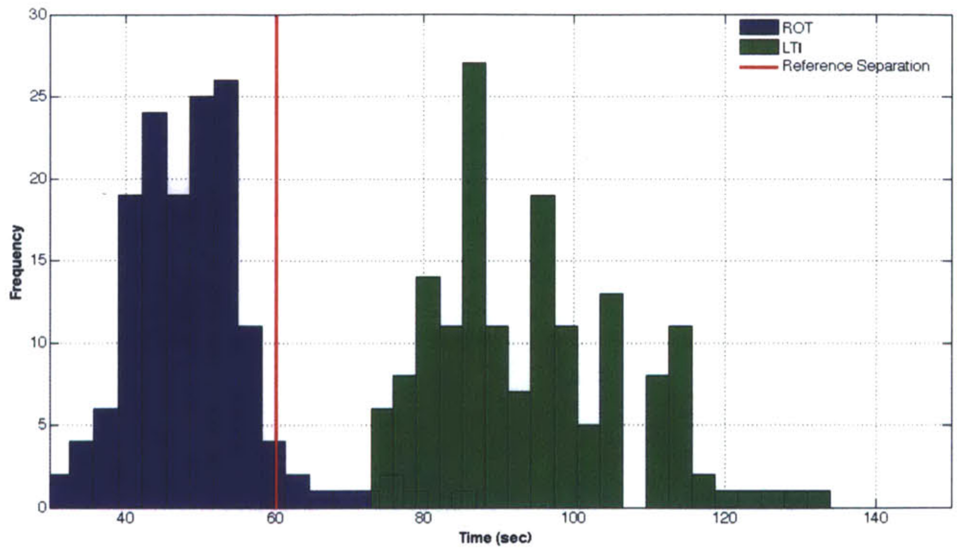


Figure 4-20. Landing time intervals and runway occupancy for small - heavy pairs at BOS

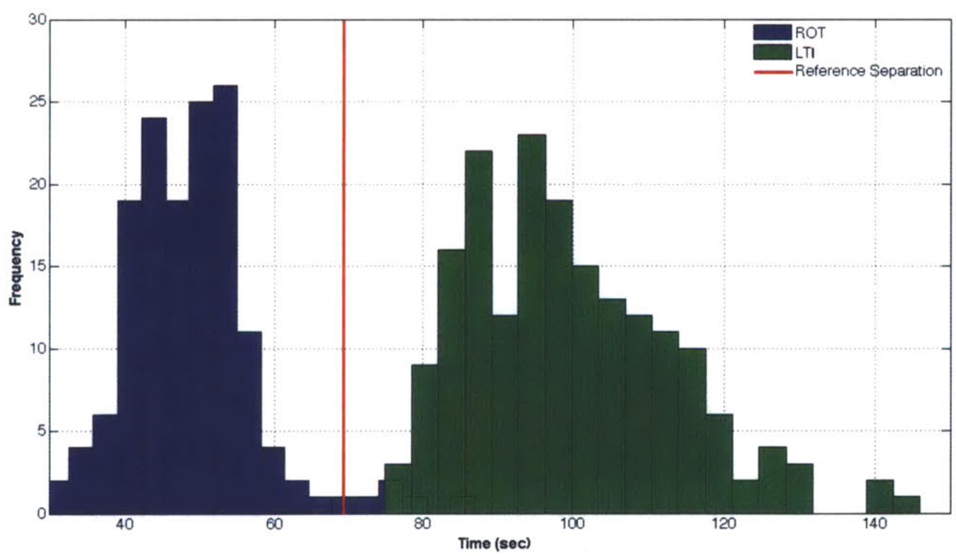


Figure 4-21. Landing time intervals and runway occupancy for small - large pairs at BOS

The measured runway occupancy times of small aircraft at Boston are as high as for heavy aircraft in some cases. This means that the runway occupancy often exceeds the reference separation, which is 60 seconds for small - heavy, 70 seconds for small - large, and 81 seconds for small - small pairs. The minimum observed LTIs are 75, 75, and 86 seconds respectively. Since runway occupancy takes longer than for other aircraft categories, the built in buffer is necessary to minimize go-around likelihood.

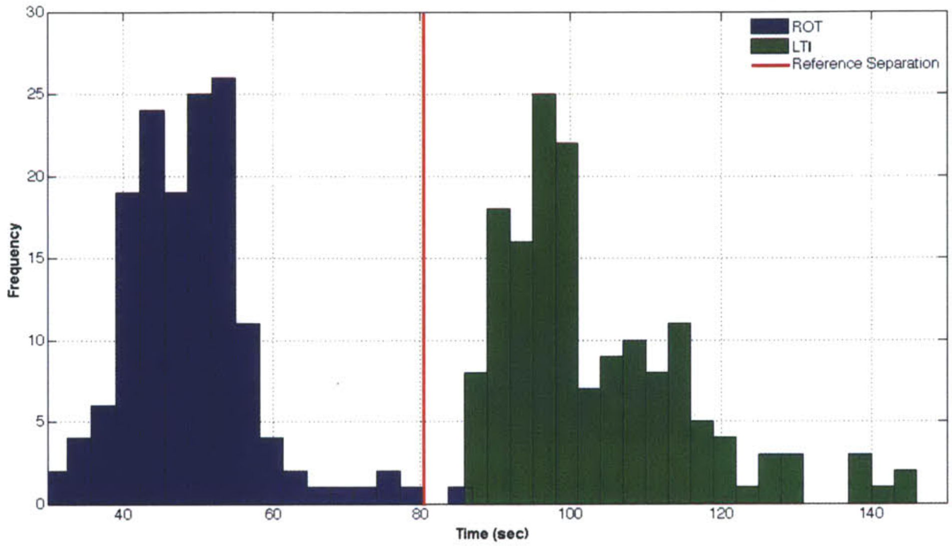


Figure 4-22. Landing time intervals and runway occupancy for small - small pairs at BOS

Although the ROT - LTI overlap indicates the increased probability of a go-around, the separation for those landings can be higher than normal due to the additional built-in spacing. From an operation point of view, the additional buffer is necessary for aircraft pairs with a small lead aircraft. Since the reference separation is very close to runway occupancy, and aircraft fly very close to the reference separation, which can lead to high runway throughput. However, throughput might be lost if go-arounds occur frequently. The mean LTIs are 96.4 seconds, 99.5 seconds, and 103.9 seconds respectively. All three of the arrival pair categories have a standard deviation between 12 and 14 seconds.

4.5 Wake Separation Study Summary

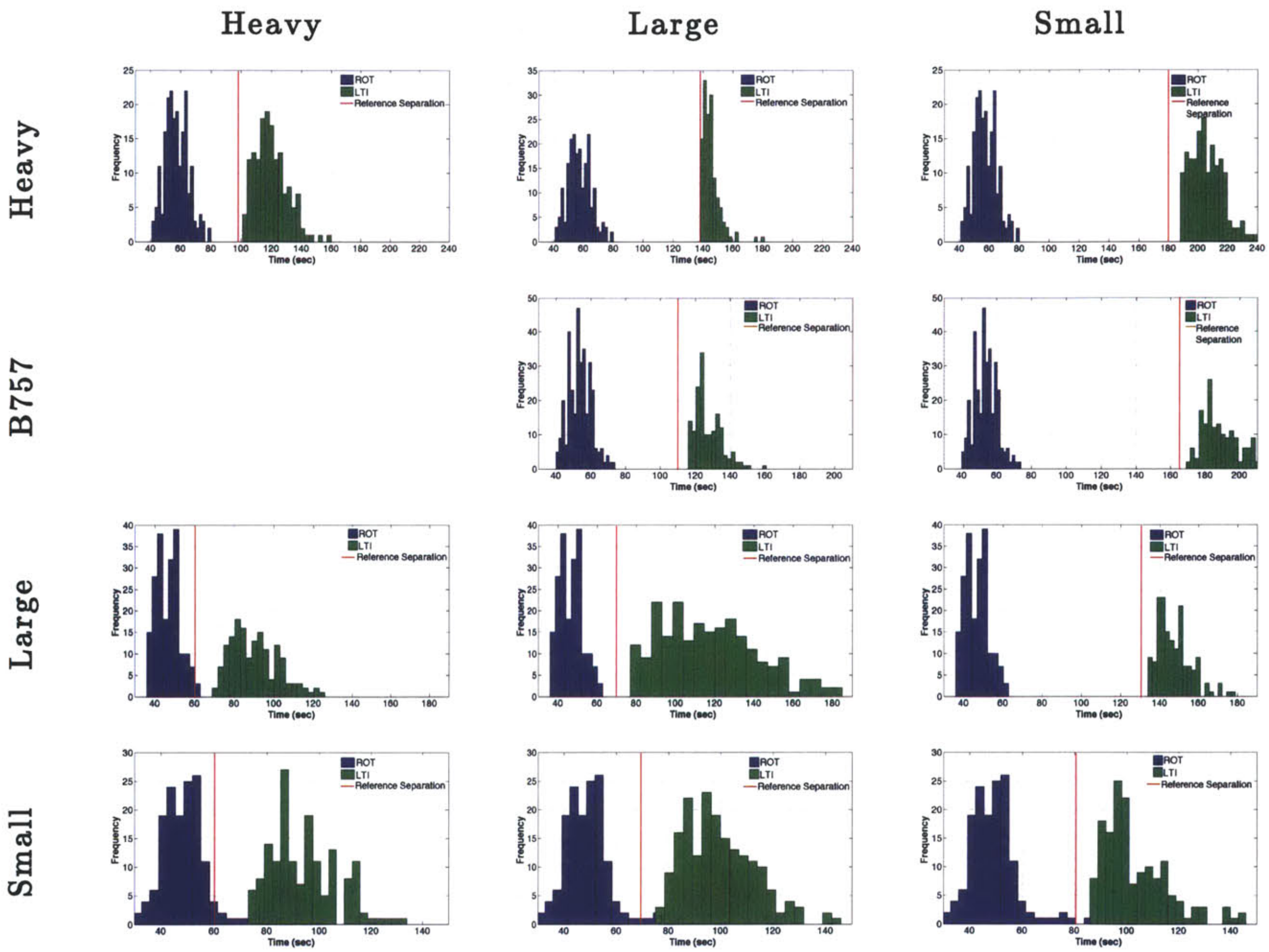
The wake separation study provides details on how much of an additional spacing do air traffic controllers apply on final approach, and how the observed separations compare to runway occupancy. The results of this study identify the arrival pair cases where runway occupancy is the limiting factor in determining runway throughput, and the aircraft pairs for which, the wake separation is the restrictive element.

Measuring inter-arrival distances between arriving aircraft helps to determine the average buffer controllers implement during high demand periods. The analyzed landings include only high arrival demand traffic during IMC weather conditions. The results indicate that La Guardia has the lowest average buffer out of the four airports, which is 0.38 NM, although only the Boeing 757 - large, and the large - large arrival pairs have sufficient number of landings to measure. It is interesting to note that LGA has the lowest average runway occupancy times as well. This can be due to the fact that the airport experiences high arrival demand at all times, which is well understood by both controllers and pilots flying to LGA. The continuous push can encourage controllers to separate aircraft as close to the minimums as plausible, and it can encourage pilots to exit the runway as soon as they are able to do so. Boston has the highest average separation buffer of 0.79 NM. Philadelphia and Newark are both around 0.5 NM.

When comparing individual aircraft pairs, surprisingly Boeing 757 lead aircraft receives the lowest average buffer of 0.5 NM across all the four airports. This aircraft type has its own wake category due to the fact that it generates stronger vortices than large category aircraft, and so it is expected that controllers apply a longer buffer. The study also points out that small aircraft receive the longest average separation buffer of 0.92 NM, although this figure is based only on observations at Boston, because the other airports have insufficient number of small lead aircraft pairs for the analysis. The long separation buffer can be explained by the long runway occupancy of these small aircraft. The minimum radar separation of 2.5 NM is not sufficient in some of the examined cases, as ROT exceeded the equivalent reference separation.

Landing time intervals are also measured in order to compare them to runway occupancy. A summary of the results is shown in Table 4-5.

Table 4-5. Summary of landing time interval and runway occupancy comparisons shown for Boston as an example (leader aircraft are shown on the left, follower aircraft are shown on top)



The landing time interval study shows that for many of the arrival pairs, wake separation is the limiting runway throughput, which can open up opportunities for reduced wake separation concepts, such as RECAT. On the other hand, there are cases where runway occupancy is the limiting factor. ROTs are very close to the reference separations, and hence, separation requirements could not be reduced without reducing runway occupancy. A summary of the runway throughput limiting factors is shown below in Table 4-6.

Table 4-6. Summary of LTI study indicating runway throughput limiting factors (B757 - heavy pair results are based on observations at EWR)

		Follower		
		Heavy	**Large**	**Small**
Leader	**Heavy**	Separation	Separation	Separation
	B757	Separation	Separation	Separation
	Large	ROT	ROT/Separation	Separation
	Small	ROT	ROT	ROT

For large - heavy, and for all small lead aircraft arrival pairs, runway occupancy is the limiting runway throughput. This result also aligns with those aircraft pairs, which are separated by the minimum radar separation of 2.5 NM. When ROT is limiting runway throughput, additional arrival movements can only be accommodated if aircraft exit the runways sooner, which can be accomplished by familiarizing pilots with the existing runway exit locations and including runway exit descriptions in the flight planning process.

For large - large aircraft pairs, there is very little room to reduce separation minimums, and very little room to fly aircraft closer to the minimums. However, reducing the variation in the system and flying aircraft closer to the required minimum separation can provide additional runway capacity benefits.

For all other aircraft pairs, wake separation is the limiting element for additional runway throughput. If reducing separation requirements does not sacrifice safety standards, the reduction in required minimum separations would likely lead to an increase in runway throughput. Furthermore, for heavy - small, B757 - large, and B757 - small arrival pairs, runway throughput can be also gained by separating aircraft closer to the minimum separations. If the gap between the observed minimums and the reference separations is reduced for these pairs, 4-8 seconds can be saved for each landing, which then can lead to 2-3 additional arrivals per hour.

In additional to reducing the gap between observed and required minimum separations, runway throughput can also be gained by reducing the variation in the separations. For large - heavy, large - large, and all small lead aircraft pairs, the standard deviation is above 12 seconds. Large - large pairs the highest standard deviation with 24.73 seconds. If separations are more consistent closer to the mean, the runway throughput benefits can be significant for airports.

Chapter 5

5 Runway Capacity Benefits of Re-Categorization

Chapter 5 evaluates runway capacity benefits of aircraft re-categorization using the runway occupancy and wake separation results from the previous chapters Applying these results, the runway capacity model shows that arrival capacity for a single runway can increase when reduced separation requirements are implemented. The magnitude of benefits, however, is strongly influenced by the traffic mix at the airports.

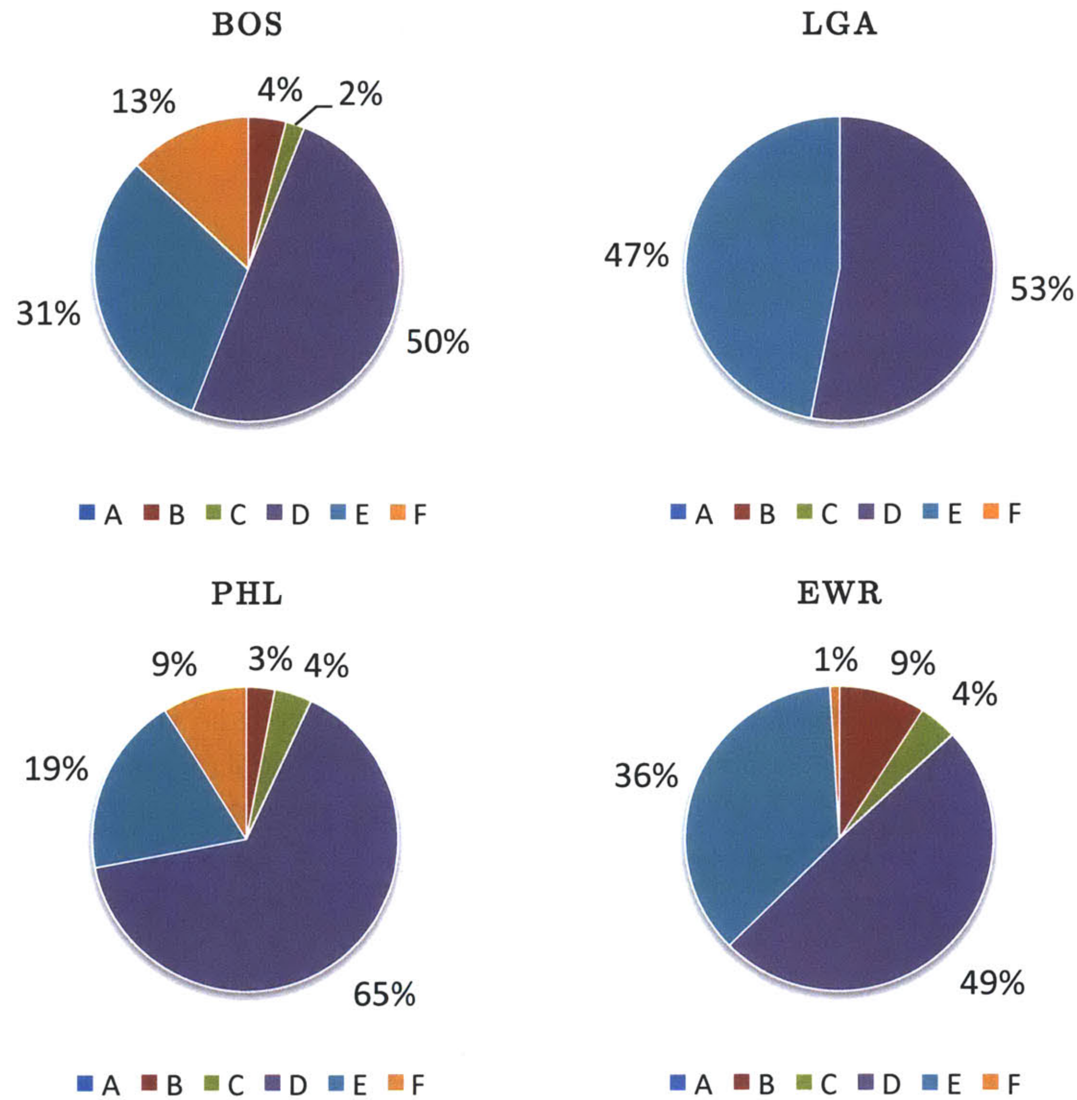
5.1 RECAT Traffic Mix

Table 5-1 shows the traffic mix at the four airports based on the re-categorization requirements. Group A aircraft are not present at any of the airports, as this category includes only the Airbus A380 and the Antonov An-225, both of which operate only to a limited number of airports in the United States.

As seen from the traffic mix at Boston, five RECAT aircraft categories are present. Group D and group E make up 81% of the traffic. These two groups include all the large aircraft and Boeing 757s, which now belong to group D. Group B and group C aircraft are previously assigned to the heavy category, but with the new re-categorization some of the heavies received shorter separation requirements. Group F aircraft are identical to small category aircraft, contributing 13% of the traffic mix.

Under the current aircraft classification system, La Guardia has only large and Boeing 757 aircraft. After re-categorization, the Boeing 757s have been moved to group D, and large category aircraft are assigned to two groups, D and E, which results in a 53% group D, and 47% group E traffic mix.

Table 5-1. RECAT Traffic Mix at Boston, La Guardia, Philadelphia, and Newark



Philadelphia's traffic mix is similar to Boston's. Group D is the largest group with 65% of the traffic mix, followed by group C with 19%. The heavies in Group B and group C make up 3% and 4% of the mix, respectively. The smallest category is group F with 9%.

About half of Newark's traffic is group D aircraft. Group E has the second largest presence with 36%. Since Newark sees a lot of international traffic operated by heavy aircraft, group B consisted 9% of the mix, followed by group C with 4%. Only 1% of the traffic is group F aircraft.

5.2 Runway Capacity Parameters for RECAT Groups

In order to evaluate runway capacity benefits of the RECAT wake mitigation program using the runway capacity model introduced in Chapter 2, common final approach path length, final approach speeds, average buffer, and runway occupancy times need to be determined. The length of the common final approach path is calculated by taking the mean of the final approach path lengths at each of the studied runways. These values are taken from the published FAA instrument approach procedures. The final approach path length ranged from 4.5 NM to 5.1 NM at Boston and from 5.1 NM to 6.3 NM at Philadelphia. The common final approach length is 5 NM at La Guardia, and 5.1 NM at Newark. Accordingly, the mean final approach path is calculated to be 5.2 NM, which is implemented in the runway capacity model.

The approach speeds for the RECAT aircraft groups are based on the estimated approach speeds discussed in Chapter 4. Since group B and C aircraft are previously classified as heavy aircraft, their approach speeds for this study are estimated to remain the same as before: 150 knots. Similarly, Group D and E are assigned a 130 -knot final approach speed, based on large aircraft approach speeds. Lastly, group F aircraft are assigned a 110 – knot final approach speed based on small aircraft approach speeds. The estimated final approach speeds are summarized in Table 5-2.

The average separation buffer is calculated in Chapter 4 as 0.7 NM. The study assumes that separation buffers would remain the same if RECAT is implemented at these airports, and so the same buffer could be applied for runway capacity calculation purposes. Dividing the separation buffer by the estimated final approach speeds, the average buffers are computed to be 17 seconds for group B and C trailing aircraft, 19 seconds for group D and E trailing aircraft, and 23 seconds for group F trailing aircraft.

In addition to the previously mentioned parameters, average runway occupancy also has to be evaluated for the new aircraft groups. From the ASDE-X runway occupancy measurements, aircraft types are categorized based on RECAT rules and runway occupancy is calculated for each of the groups. The calculated runway occupancy for each aircraft category is the average value over all runways.

Table 5-2. Estimated final approach speeds and calculated runway occupancy times for RECAT aircraft groups

RECAT Aircraft Category	Estimated Final Approach Speed (knots)	ROT (sec)
B	150	68
C	150	64
D	130	53
E	130	50
F	110	51

5.3 RECAT Runway Capacity Study Method

As an example, the RECAT runway capacity calculation is shown here for Boston and the results at the other airports are summarized in the next section of this chapter.

The RECAT traffic mix at Boston consists of 4% group B, 2% group C, 50% group D, 31% group E, and the remaining 13% group F aircraft. The estimated final approach speeds for each of these aircraft groups are summarized in Table 5-2 along with the calculated runway occupancy times (averaged over all runways).

The length of the common final approach has been calculated to be 5.2 NM, and the average buffer has been determined to be 0.7 NM. Dividing this buffer with the estimated final approach speed for each group gives the time equivalent separation buffer. For example, when group D aircraft follow the lead aircraft, the time buffer becomes (0.7 NM/130 knots) x 3600 sec/hr, or 19 seconds. The 130-knot speed is the estimated final approach speed for group D aircraft. Similarly, the time buffer becomes 17 seconds when group B or C aircraft follow, 21 seconds when group E aircraft follow, and 23 seconds when group F aircraft follow.

The minimum time separation between each aircraft pair is calculated from Equation 1 and Equitation 2 in Chapter 2. For example, consider a group D aircraft (j) following a group C aircraft (i). Since the group C aircraft flies faster on final approach then the group D trailing aircraft, this case is considered an opening case. The minimum time separation between the lead and follow aircraft can be calculated from the following equation:

$$T_{ij} = max\left[\left(\frac{5.2NM + 3.5NM}{130knots} - \frac{5.2NM}{150knots}\right) \times 3600\ \frac{sec}{hr}, 64.2sec\right]\ when\ v_i > v_j$$

$$T_{ij} = max[116.12sec, 64.2sec] = 116.12sec$$

Since the inter-arrival separation is longer than the runway occupancy time, the minimum time separation becomes 116.12 seconds. This time, however, does not include the calculated buffer (b) yet, which needs to be added to account for the additional arrival spacing:

$$T_{ij} + b = 116.12sec + 19sec = 135.12sec$$

The probability of a group C - group D aircraft pair occurring is the product of the probability of a group C aircraft in the traffic mix and the probability of a group D aircraft in the traffic mix. If we consider Boston as an example, the traffic mix includes 2% group C aircraft, and 50% group D aircraft. Then the probability of the C-D arrival pair becomes:

$$P_{ij} = 0.5 \times 0.02 = 0.01$$

Similarly to the C-D pair, the inter-arrival separations and the probabilities are calculated for each aircraft pair. Based on these calculations, the expected time (average time) an arrival pair takes to land can be calculated as:

$$E(t) = \sum P_{ij}\left(T_{ij} + b\right) = 104.9sec$$

Finally, if the expected amount of time between successive arrivals is computed, the RECAT runway capacity becomes:

$$\mu = \frac{1hr}{E(t)} \times 3600 \frac{sec}{hr} = 34.3 \frac{arrivals}{hr} = 8.58 \frac{arrivals}{15\ min}$$

5.4 Runway Capacity Results

Figure 5-1 illustrates the runway capacity results based on current and RECAT separation minimums for the four airports. The y-axis represents the number of arrivals per quarter hour. The exact values are presented on top of each column. The results represent the arrival capacity on a single runway that is used for arrivals only assuming continuous arrival demand. The arrival capacity is the maximum capacity observed under instrument flight rules with an average 0.7-NM buffer. The results indicate that runway capacity increased at all airports for RECAT separation standards. Boston has the lowest computed arrival capacity, while La Guardia has the highest. Philadelphia and Newark performs similarly to each other.

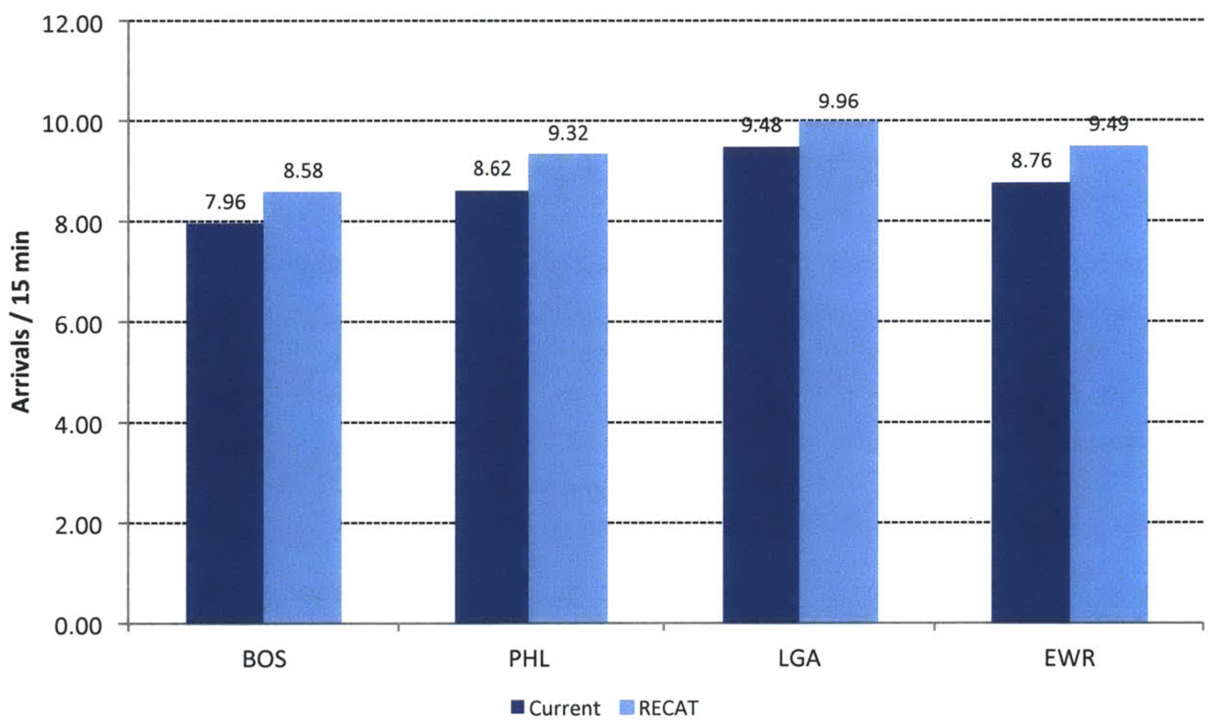


Figure 5-1. Runway capacity results based on current and RECAT wake separation minimums

Boston's arrival capacity increases from 7.96 to 8.58 arrivals per quarter hour, which is equivalent to a 7.8% growth. Philadelphia's capacity increases by 8.2% from 8.62 to 9.32 arrivals per quarter hour. La Guardia has the lowest capacity increase, 5.1%, from 9.48 to 9.96 arrivals. Newark's capacity grows by 8.3% from 8.76 to 9.49 arrivals.

In order to understand the differences in capacity growth between the four airports, the traffic mix needs to be evaluated. Philadelphia and Newark experiences the greatest benefits of RECAT. This is possibly due to the presence of group B and mostly group C aircraft at the airport. According to RECAT separation standards, group C lead aircraft pairs receive the largest reduction in separation minimums compared to current separation requirements. This means that Philadelphia's and Newark's traffic are influenced the most by these reduced separation requirements. Moreover, Boeing 757 aircraft are placed in the group D category, which also benefited these airports when a group D or E aircraft followed a Boeing 757. Under the current separation rules, the required minimum separation between a Boeing 757 and a large aircraft is 4 NM. Under RECAT, however, large aircraft belong to group D and E, which required only the minimum radar separation when a Boeing 757 is in the lead. La Guardia does not have any group B and C aircraft, therefore all the capacity benefits come from the previously mentioned Boeing 757 re-categorization, which contributed 5% to runway capacity. Boston's traffic includes group B and C aircraft, but the capacity benefits are lower than at Philadelphia and at Newark. The reason for the lower growth is the strong presence of small aircraft, which are placed in the F group under RECAT. This group receives longer separation minimums than it had before. When small aircraft follow large aircraft, the required separation minimum is 4 NM. With RECAT, group F aircraft require a minimum 5 NM separation behind group D aircraft, where most large aircraft are placed. This increased separation lowers the capacity benefits at Boston.

5.5 Summary of RECAT Benefits

Runway capacity increases when RECAT wake separation standards are applied for all the tested airports. The magnitude of benefits is strongly influenced by the traffic mix. The benefits are the greatest when group C aircraft are present, because aircraft pairs with group C leaders received the most significant reduction in minimum required separations. Capacity also increases because Boeing 757 aircraft are placed in group D, where the required minimum separation is MRS as opposed to 4 NM when followed by a large or another group D aircraft. It is also observed that the presence of group F aircraft reduce the magnitude of benefits, because aircraft pairs with group F follow aircraft receive longer separation requirements.

6 Conclusions

This study measures runway occupancy times and wake vortex separations from ASDE-X aircraft surveillance data. The runway occupancy analysis shows that runway occupancy time does not necessary scale with aircraft size. Although heavy aircraft occupy the runway the longest on average, small aircraft often take as long as large aircraft to exit the runway. The results also indicate that high – speed runway exits can make a significant difference in runway occupancy times. Runway 9R at Philadelphia for instance have significantly shorter runway occupancy times than runway 27R, because 9R is equipped with four high – speed runway exits as opposed to runway 27R, which has only one high – speed exit. The comparison of VMC and IMC runway occupancy times does not show any statistically significant difference as a result of weather conditions.

Evaluating inter-arrival separations shows the average buffer that air traffic controllers apply during high demand periods. Out of the four test airports, La Guardia has the lowest average separation buffer of 0.38 NM, and Boston has the longest average separation buffer of 0.79 NM. The buffers at Philadelphia and at Newark are both around 0.5 NM. This buffer can be related to the number of available arrival runways at the airport. Since La Guardia operations use only a single runway for arrivals, controllers can implement shorter separation buffers to increase runway throughput. From the wake separation analysis, it is also observed that aircraft pairs with a small lead aircraft receive longer average separation buffers than pairs with large, Boeing 757, or heavy lead aircraft.

The comparison of landing time intervals and runway occupancy reveals that wake separation requirements are limiting runway throughput for heavy and Boeing 757 lead aircraft pairs, as well as for large – small arrival pairs. For large – large pairs, the observed separations are close to runway occupancy times, leaving very little room to reduce separation requirements. For all other aircraft pairs with a large or a small lead aircraft, runway occupancy is limiting runway throughput.

The single runway arrival capacity model shows that RECAT wake separation standards can increase runway capacity given the observed runway occupancy and wake separation measurements. The magnitude of benefits, however, is strongly influenced by the arrival traffic mix.

Although this study provides valuable runway occupancy and inter-arrival separation results, it only considers arrival traffic. For future work, it would be beneficial to include departures in the analysis and to consider multiple runway systems, which can provide more realistic runway capacity estimates of reduced separation concepts. Furthermore, including weather data in the study could capture the effect of strong head wind on inter-arrival separations, and the effect of rain and snow on runway occupancy times.

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8 Appendix A

The proportion of lead-follow aircraft pairs is evaluated below for each of the airports. For some of the aircraft pairs, there are not enough cases to report statistically significant data. The traffic mix is shown before in Chapter 3 for the runway occupancy study and the occurrence of a given aircraft pair is shown here based on ASDE-X surveillance data. Controller sequencing strategies influences the occurrence of each pair. Considering all runways, the lead-follow transition matrix for Boston is shown below in Table 8-1.

Table 8-1. Lead-follow aircraft pair occurrence at BOS in peak demand

		Follower			
		Heavy	**Large**	**Small**	Total
Leader	**Heavy**	2.3 %	3.7 %	2.8 %	8.8 %
	Boeing 757	0.3 %	7.5 %	2.4 %	10.2 %
	Large	3.6 %	43.4 %	13.3 %	60.3 %
	Small	2.8 %	13.1 %	4.8 %	20.6 %
	Total	9.0 %	67.7 %	23.2 %	100 %

In 43.4% of landings a large aircraft follows a large aircraft. Large-small and small-large pairs occur about 13% of the time. Boeing 757 aircraft followed by heavies are the most rare cases that happen in only 0.3% of the time. This meant only three B757-heavy pairs at Boston, which is insufficient for any separation studies.

Table 8-2. Lead-follow aircraft pair occurrence at LGA

		Follower			
		Heavy	**Large**	**Small**	Total
Leader	**Heavy**	0.0 %	0.0 %	0.0%	0.0 %
	Boeing 757	0.0 %	3.1 %	0.0%	3.1 %
	Large	0.0 %	95.9 %	0.6 %	96.5 %
	Small	0.0 %	0.4 %	0.0 %	0.4 %
	Total	0.0 %	99.4 %	0.6 %	100 %

Table 8-2 summarizes the findings at La Guardia. 488 samples of inter-arrival separations are measured at LGA, which showed a very different transition matrix from Boston's. Large-small pairs dominated with 95.9% occurrence. Large aircraft followed B757 aircraft 3.1% of the time, while the other pairs occurred infrequently, and therefore they could not be analyzed at this airport.

Table 8-3. Lead-follow aircraft pair occurrence at PHL in peak demand

Leader	Follower: Heavy	Large	Small	Total
Heavy	1.3 %	4.5 %	0.0 %	5.8 %
Boeing 757	0.1 %	3.9 %	0.0 %	4.0 %
Large	4.6 %	83.8 %	1.0 %	89.4 %
Small	0.2 %	0.7 %	0.0 %	0.8 %
Total	6.2 %	92.9 %	1.0 %	100 %

1316 aircraft pairs are analyzed at Philadelphia, as shown in Table 8-3 above. Large-large aircraft pairs dominated the transition matrix with 83.8%. Heavy-large and large-heavy pairs also occurred 4.5 and 4.6% of the time, between 60 aircraft pairs. Heavy-small and small-small pairs are not observed in the data samples.

Table 8-4. Lead-follow aircraft pair occurrence at EWR in peak demand

Leader	Follower: Heavy	Large	Small	Total
Heavy	1.1 %	11.2 %	0.0 %	12.3 %
Boeing 757	1.1 %	9.1 %	0.0 %	10.2 %
Large	10.2 %	65.8 %	0.5 %	76.5 %
Small	0.0 %	1.1 %	0.0 %	1.1 %
Total	12.3 %	87.2 %	0.5 %	100 %

Table 8-4 summarizes the aircraft pair frequency at Newark. Aircraft pairs with small leader or follower did not occur for most cases, and there are only a limited number of small-large pairs, which is insufficient for any detailed separation analysis. The most frequent aircraft pair at EWR is the large-large pair, which occurred 187 times.

9 Appendix B

Landing time intervals and runway occupancy times are compared at La Guardia, Philadelphia, and Newark for large-large arrival pairs.

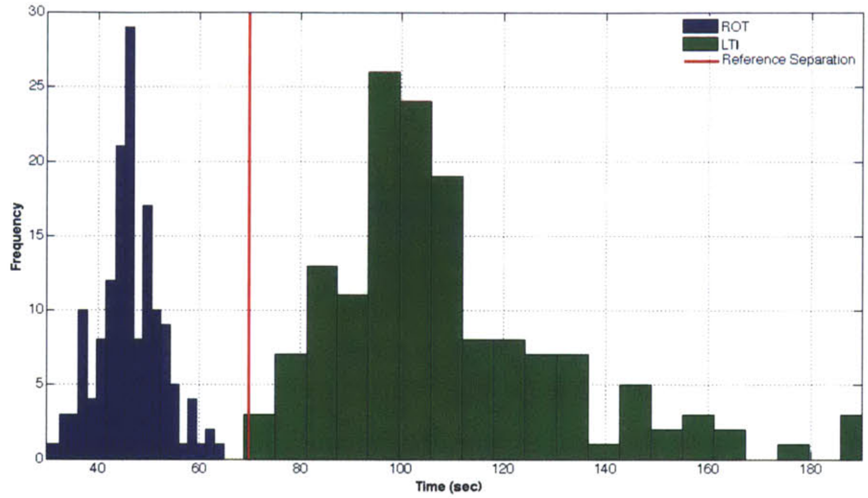

Figure 9-1. Landing time intervals and runway occupancy for large-large pairs at LGA

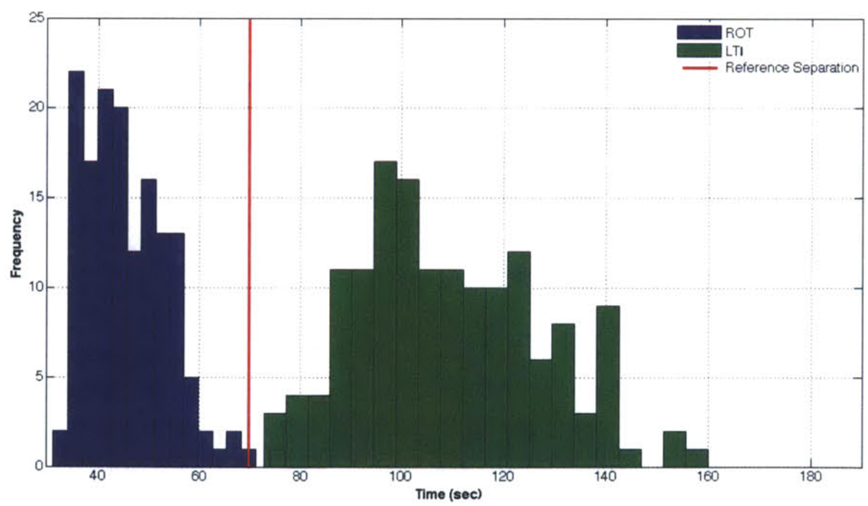

Figure 9-2. Landing time intervals and runway occupancy for large-large pairs at PHL

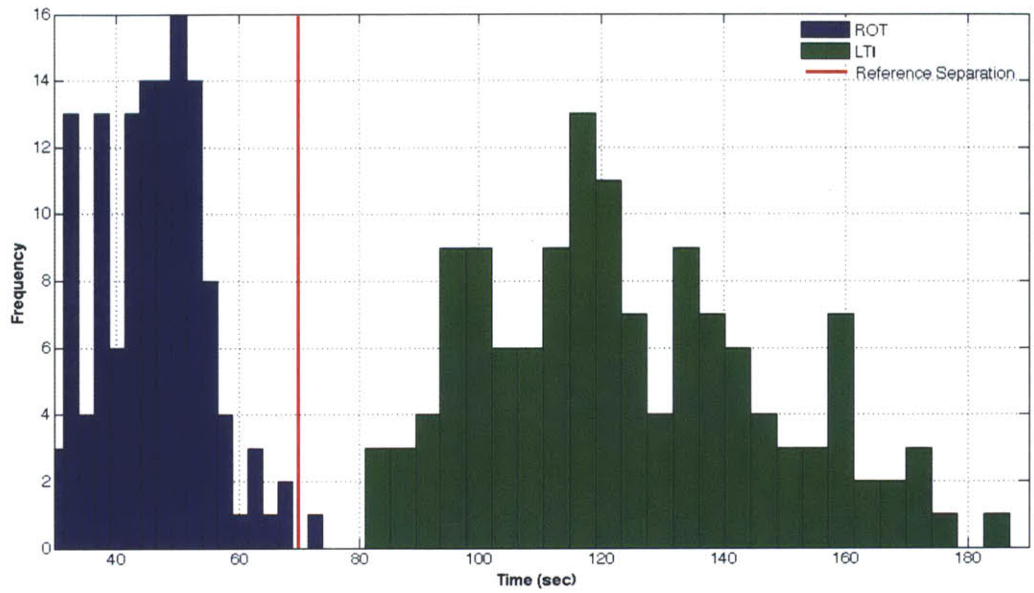

Figure 9-3. Landing time intervals and runway occupancy for large-large pairs at EWR

For large - large aircraft pairs, there is very little room to reduce separation minimums, as runway occupancy often exceeds the reference separation. At LGA and at PHL, there is very little room to fly aircraft closer to the minimums. At EWR, there is a 10 second gap between the reference separation and the minimum observed separation, which opens up the possibility to fly aircraft closer to the reference separation in order to increase runway throughput. Moreover, reducing the variation in the system and flying aircraft closer to the required minimum separation can provide additional runway capacity benefits.