Development of Aircraft Wake Vortex Dynamic Separations Using Computer Simulation and Modeling

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(ABSTRACT)

This dissertation presents a research effort to evaluate wake vortex mitigation procedures and technologies in order to decrease aircraft separations, which could result in a runway capacity increase. Aircraft separation is a major obstacle to increasing the operational efficiency of the final approach segment and the runway.

An aircraft in motion creates an invisible movement of air called wake turbulence, which has been shown to be dangerous to aircraft that encounter it. To avoid this danger, aircraft separations were developed in the 1970s, that allows time for wake to be dissipated and displaced from an aircraft’s path. Though wake vortex separations have been revised, they remain overly conservative.

This research identified 16 concepts and 3 sub-concepts for wake mitigation from the literature. The dissertation describes each concept along with its associated benefits and drawbacks. All concepts are grouped, based on common dependencies required for implementation, into four categories: airport fleet dependent, parallel runway dependent, single runway dependent, and aircraft or environmental condition dependent.

Dynamic wake vortex mitigation was the concept chosen for further development because of its potential to provide capacity benefit in the near term and because it is initiated by air traffic control, not the pilot. Dynamic wake vortex mitigation discretizes current wake vortex aircraft groups by analyzing characteristics for each individual pair of leader and follower aircraft as well as the environment where the aircraft travel. This results in reduced aircraft separations from current static separation standards.

Monte Carlo simulations that calculate the dynamic wake vortex separation required for a follower aircraft were performed by using the National Aeronautics and Space Administration (NASA) Aircraft Vortex Spacing System (AVOSS) Prediction Algorithm (APA) model, a semi-empirical wake vortex behavior model that predicts wake vortex decay as a function of atmospheric turbulence and stratification. Maximum circulation capacities were calculated
based on the Federal Aviation Administration’s (FAA) proposed wake recategorization phase II (RECAT II) 123 x 123 matrix of wake vortex separations.

This research identified environmental turbulence and aircraft weight as the parameters with the greatest influence on wake vortex circulation strength. Wind has the greatest influence on wake vortex lateral behavior, and aircraft mass, environmental turbulence, and wind have the greatest influence on wake vortex vertical position.

The research simulated RECAT II and RECAT III dynamic wake separations for Chicago O’Hare International (ORD), Denver International Airport (DEN) and LaGuardia Airport (LGA). The simulation accounted for real-world conditions of aircraft operations during arrival and departure: static and dynamic wake vortex separations, aircraft fleet mix, runway occupancy times, aircraft approach speeds, aircraft wake vortex circulation capacity, environmental conditions, and operational error buffers. Airport data considered for this analysis were based on Airport Surface Detection Equipment Model X (ASDE-X) data records at ORD during a 10-month period in the year 2016, a 3-month period at DEN, and a 4-month period at LGA.

Results indicate that further reducing wake vortex separation distances from the FAA’s proposed RECAT II static matrix, of 2 nm and less, shifts the operational bottleneck from the final approach segment to the runway. Consequently, given current values of aircraft runway occupancy time under some conditions, the airport runway becomes the limiting factor for inter-arrival separations.

One of the major constraints of dynamic wake vortex separation at airports is its dependence on real-time or near-real-time data collection and broadcasting technologies. These technologies would need to measure and report temperature, environmental turbulence, wind speed, air humidity, air density, and aircraft weight, altitude, and speed.
An aircraft in motion creates an invisible movement of air called wake turbulence, which has been shown to be dangerous to aircraft that encounter it. To avoid this danger, aircraft separations were developed in the 1970s, that allows time for wake to be dissipated and displaced from an aircraft’s path. Though wake vortex separations have been revised, they remain overly conservative.

The separation of aircraft approaching a runway is a major obstacle to increasing the operational efficiency of airports. This dissertation presents a research effort to decrease aircraft separations as they approach and depart the airport, which could result in a runway capacity increase.

This research identified 16 concepts and 3 sub-concepts for wake mitigation from the literature. The dissertation describes each concept along with its associated benefits and drawbacks.

Dynamic wake vortex mitigation was the concept chosen for further development because of its potential to provide capacity benefit in the near term and because it is controlled the by air traffic control, not the pilot. Dynamic wake vortex mitigation, analyzes the characteristics for each individual pair of leader and follower aircraft as well as the environment where the aircraft travel.

This research identified environmental turbulence and aircraft weight as the parameters with the greatest influence on wake vortex circulation strength. The wind has the greatest influence on wake vortex lateral behavior, and aircraft mass, environmental turbulence, and wind have the greatest influence on wake vortex vertical position.

The research simulated aircraft operations for Chicago O'Hare International Airport, Denver International Airport and LaGuardia Airport. The simulation accounted for real-world conditions of aircraft operations during arrival and departure: aircraft fleet mix, aircraft runway occupancy time, aircraft approach speeds, aircraft wake vortex circulation capacity, environmental conditions, and pilot-controller human error.
Results indicate that further reducing aircraft separation distances from static aircraft separations, shifts the operational bottleneck from the airspace to the runway. Consequently, given current values of aircraft runway occupancy time, the airport runway becomes the limiting factor to increase capacity.

One of the major constraints of dynamic wake vortex separation at airports is its dependence on real-time data collection and broadcasting technologies. These technologies would need to measure and report temperature, environmental turbulence, wind speed, air humidity, air density, and aircraft weight, altitude, and speed.
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Abbreviations & Acronyms

Air Navigation Service Providers (ANSP)
Airbus A300-600 (A306)
Airbus A319-100 (A319)
Airbus A320-200 (A320)
Airbus A321-200 (A321)
Airbus A330-200 (A332)
Airbus A330-300 (A333)
Airbus A340-300 (A340)
Airbus A340-600 (A346)
Airbus A380-800 (A388)
Airport Surface Detection Equipment Model X (ASDX)
Atlanta International Airport (ATL)
Automated Surface Observing System (ASOS)
Automated Terminal Proximity Alert (ATPA)
Automatic Dependent Surveillance-Broadcast (ADS-B)
Aviation System Performance Data (ASPM)
AVOSS (Aircraft Vortex Spacing System)
AVOSS Prediction Algorithm (APA)
Base of Aircraft Data (BADA)
Boeing 712-200 (B712)
Boeing 737-200 (B732)
Boeing 737-300 (B733)
Boeing 737-400 (B734)
Boeing 737-500 (B735)
Boeing 737-600 (B736)
Boeing 737-700 (B737)
Boeing 737-800 (B738)
Boeing 737-900 (B739)
Boeing 747-400 (B744)
Boeing 747-800 (B748)
Boeing 757-200 (B752)
Boeing 757-300 (B753)
Boeing 767-200 (B762)
Boeing 767-300 (B763)
Boeing 767-400 (B764)
Boeing 777-200 (B772)
Boeing 787-800 (B788)
Bombardier CRJ-200 (CRJ2)
Bombardier CRJ-700 (CRJ7)
Bombardier CRJ-900 (CRJ9)
Certified Crosswind Speed (CCS)
Cessna 172 Skyhawk (C172)
Cessna 208 Grand Caravan (C208)
Cessna 750 Citation X (C750)
Charlotte Douglas International Airport (CLT)
Chicago O'Hare International Airport (ORD)
Closely Spaced Parallel Runway (CSPR)
Closest Point of Approach (CPA)
Controller Decision Support Tool (DST)
Dallas/Ft. Worth International Airport (DFW)
De Havilland Canada DHC-8-100 (DH8A)
De Havilland Canada DHC-8-200 (DH8B)
DE Havilland Canada DHC-8-300 (DH8C)
De Havilland Canada DHC-8-400 (DH8D)
Denver International Airport (DEN)
Detroit Metro Airport (DTW)
Distance Based Separation to Time Based Separation (DBS-TBS)
Douglas DC-10 (DC10)
Douglas DC-9-50 (DC95)
Eddy Dissipation Rate (EDR)
Embraer EMB-120 Brasilia (E120)
Embraer EMB-145XR (E45X)
Embraer ERJ-135 (E135)
Embraer ERJ-145 (E145)
Embraer ERJ-170 (E170)
Embraer ERJ-190 (E190)
European Aviation Safety Agency (EASA)
European Organization for Safety of Air Navigation (EUROCONTROL)
Federal Aviation Administration (FAA)
Frankfurt International Airport (FRA)
George Bush Intercontinental Airport (IAH)
Ground-Based Augmentation System (GBAS)
Identifier (ID)
Instrument Flight Regulations (IFR)
Instrument Meteorological Conditions (IMC)
International Civil Aviation Organization (ICAO)
Interval Management Paired Approach (IM-PA)
Japan Aerospace Exploration Agency (JAXA)
John F. Kennedy International Airport (JFK)
Kelvin (K)
La Guardia Airport (LGA)
Light Detection and Ranging (LIDAR)
London City Airport (LHR)
Los Angeles International Airport (LAX)
Louisville International-Standiford Field (KSDF)
Maximum Allowable Landing Weight (MALW)
Maximum Circulation Capacity (MCC)
Maximum Take-off Weights (MTOW)
McDonnell Douglas MD83 (MD83)
McDonnell Douglas MD88 (MD88)
McDonnell Douglas MD90 (MD90)
Memphis International Airport (MEM)
Miami International Airport (MIA)
National Aeronautics and Space Administration (NASA)
National Airspace System (NAS)
National Center for Atmospheric Research (NCAR)
National Center of Excellence for Aviation Operations Research (NEXTOR)
National Oceanic and Atmospheric Administration (NOAA)
Nautical Mile (nm)
Newark Liberty International Airport (EWR)
Next Generation Air Transportation System (NextGen)
Omnidirectional Range (VOR)
Philadelphia International Airport (PHL)
Precision Runway Monitor (PRM)
Rapid Update Cycle (RUC)
Recategorization Phase I (RECAT I)
Recategorization Phase II (RECAT II)
Recategorization Phase III (RECAT III)
Runway Occupancy Time (ROT)
San Francisco International Airport (SFO)
Simultaneous Offset Instrument Approach (SOIA)
Steeper Approach Procedures (SAP)
TASS (Terminal Area Simulation System)
TASS Derived Algorithms for Wake Prediction (TDAWP)
TASS Driven Algorithm for Wake Prediction (TDAWP)
Terminal Area Simulation System (TASS)
Time Based Separation (TBS)
Tokyo Haneda International Airport (HND)
Variance Inflation Factor (VIF)
Very High Frequency (VHF)
Visual Flight Regulations (VFR)
Wake Circulation Capacity (WCC)
Wake Turbulence Mitigation Arrivals (WTMA)
Wake Turbulence Mitigation Departures (WTMD)
Wake Turbulence Mitigation for Departures – Paired Departures (WTMD-PD)
Wind Forecast Algorithm (WFA)
WTMA Procedural (WTMA-P)
WTMA System (WTMA-S)
1. Introduction

For an aircraft in motion, the pressure on the wing lower surface is higher than the pressure on the wing upper surface. Air flowing around the wingtip from the lower surface to the upper surface causes a wake vortex, leaving a trail of invisible wake turbulence. Depending on flight conditions and airplane parameters, a wake vortex can exhibit cross-flow velocities of 360 km/h or higher in its core region (Breitsamter 2010). Aircraft encountering wake vortices could experience considerable roll and altitude disturbance.

To avoid this danger, the Federal Aviation Administration (FAA) developed minimum wake-dependent following distances between aircraft called wake separations, in the 1970s. Wake separations allow time for wakes to be dissipated and displaced from an aircraft’s path as shown in Figure 1.1. However, aircraft separation has been a major obstacle to increasing the operational efficiency, natural resource conservation, and economic viability of sustainable airport systems (National Research Council 2008), and today’s wake separations are based on data and technology from the 1970s to the 1990s. Reducing wake vortex separation between aircraft can increase airport capacity, though at the cost of increased complexity to pilots and controllers and capital outlay in aircraft and airport instrumentation.

In the United States, the FAA is leading efforts to increase the capacity of the National Airspace System (NAS). The main constraint on airport throughput and the item with the highest investment cost is the runway. Runway throughput performance currently depends on wake turbulence separation, communication, surveillance, and collision avoidance. Advanced aircraft surveillance technologies and communication systems, such as satellite and terrestrial-based navigation, can monitor aircraft with greater frequency than current surveillance systems. As these newer technologies are implemented, wake turbulence separation is becoming the limiting parameter to increased runway throughput.

There is a need to study wake vortex behavior under different flight conditions, study wake vortex mitigation concepts and procedures with potential to reduce wake vortex separation and evaluate their performance and implications. This can be accomplished through a better understanding of wake vortex behavior and its interaction with environmental parameters, aircraft-dependent parameters, and aircraft limitations.
Figure 1.1: Wake Vortex Separation Between Aircraft.

This research studied wake vortex mitigation procedures, to understand the interaction between wake vortex and environmental conditions, wake vortex circulation behavior, and the typical wake vortex capacity for each aircraft category. The research simulates aircraft operations under selected wake vortex mitigation procedures during arrival and departure as well as the environmental conditions in the aircraft flight path. The study also calculates runway occupancy time limitation and technical implications of wake vortex mitigation procedures.

1.1 Background

In 1966, the close formation flying of five different airplanes—an XB-70A, F-4, F-5, T-38, and F-104—caused one of them to lose control, resulting in the death of two experienced pilots and the loss of two aircraft (NASA 1974). Since this event, the National Aeronautics and Space Administration (NASA) Armstrong Flight Research Center and the FAA have tried to understand better the interaction between aircraft flying in proximity and the wake vortex hazard.

In the early 1970s, NASA and the FAA studied the wake vortex hazard potential of newer, heavier passenger planes, such as the Boeing 747, Lockheed L-1011, and Donald Douglas 10, on smaller airplanes. They tested a series of flight combinations and aircraft configurations with NASA’s Boeing
727, Boeing 747, Cessna T-37, and Learjet to record data and gain knowledge on wake vortices (Vicroy, Brandon et al. 1998).

Later in the decade, NASA’s Armstrong Flight Research Center in conjunction with the FAA conducted wake vortex experiments to test different aircraft configurations and mechanical devices on a Boeing 747. They installed smoke emitters under the wings of the 747 to help visualize and better understand the behavior of trailing wake vortices. To evaluate the vortices’ strength and influence on trailing aircraft, NASA Ames Research Center’s Cessna T-37 and Learjet trailed the Boeing 747 (NASA 1974).

To avoid hazardous wake vortex encounters, in the 1970s the FAA and International Civil Aviation Organization (ICAO) grouped similar aircraft regarding size and weight-carrying capabilities and developed wake vortex separation matrices between leading aircraft groups and following aircraft groups. However, more recent work suggests that the earlier era’s limited knowledge of wake vortices may have made the resulting wake vortex safe separations overly conservative (Matayoshi, Okuno et al. 2010).

As knowledge about wake vortices has increased over the last 30 years, categories of aircraft wake vortex have been created and modified. Recategorization Phase I (RECAT I) evolved wake vortex separation standards from five legacy groups to six groups. Memphis International Airport (MEM) and Louisville International-Standiford Field (KSDF) already employ RECAT I, and it will soon be introduced to Miami International, Cincinnati/Northern Kentucky International, Atlanta International (ATL), and Philadelphia International (PHL) (FAA 2013).

During the past decade, the FAA, European Organization for Safety of Air Navigation (EUROCONTROL), and ICAO have established focused research groups to study aircraft wake separations. As part of this effort, experienced pilots, air traffic controllers, aircraft manufacturers, industry representatives, and university researchers have been working to better understand wake vortex strength, behavior, and intensity as well as to provide solutions for managing the impact of wake turbulence in aviation. However, there remains a need to study wake vortex mitigation concepts with the goal of reduced wake vortex separation between aircraft (Witzberger and Robinson 2013).

In the United States, Europe, and countries such as Japan, there is a strong demand to increase the capacity of metropolitan airports (Matayoshi, Okuno et al. 2010). Because the infrastructure growth of these airports is often heavily constrained by the surrounding populated areas, new operational methods with reduced aircraft separations are necessary for further airport capacity increases.
In 2005 the FAA and NASA undertook a multi-phased research and development program to develop wake vortex avoidance solutions that can safely reduce aircraft separations (Mayer 2005). In recent years, research has studied different aircraft configurations, aircraft landing and departing procedures, and mechanical devices for breaking up or reducing the strength of the vortices. The results of wake vortex research could lead to shorter aircraft spacing between landings and takeoffs, potentially alleviating air-traffic congestion and improving capacity at airports in the NAS.

1.2 Problem Statement

Wake vortex separations are a major constraining obstacle to increase airport capacity. Current wake vortex categories and separations degrade aviation efficiency when traffic congestion limits airport capacity during landing and takeoff (Holzäpfel and Kladetzke 2011). Legacy wake vortex separations are 70 to 80 seconds between leading and the following aircraft. These separations are above runway occupancy times for operating aircraft; potentially leaving the runway unused for 45-60 seconds after each operation as shown in Figure 1.2.

Though Next Generation Air Transportation System (NextGen) planning clearly acknowledges the need to address wake vortex mitigation, the research required to provide a solution is not yet underway (National Research Council 2008).

As more aircraft types are introduced into the NAS, the wake vortex separation standards need to be updated accordingly. Without any improvement in today’s separation distances, other NextGen technologies such as Automatic Dependent Surveillance-Broadcast (ADS-B) will have a less significant role in improving the operational capacity of the system.

Wake vortex technical research needs wake modeling not just to advance the fundamental understanding of wake behavior, but also to analyze the implications and limitations of wake mitigation concepts and procedures.

Research is also needed to estimate potential wake vortex interactions between aircraft in future NextGen systems. This objective can only be achieved through a better understanding of wake vortex strength and decay.
Some factors that must be considered during wake vortex mitigation are the airport fleet mix, runway configuration, and weather data available at airport locations.

1.3 Research Motivation / Purpose of the Study

Wake vortex separation is only one-factor constraining airport capacity. Runway occupancy times, noise regulations, and gates availability may limit capacity to the same extent as wake vortex separations. However, arriving aircraft wake vortex separation is the current limiting factor for runway and gate capacity to be reached.

In recent years, not only has the composition of the aircraft fleet mix changed but wake vortex measurement technologies and wind forecasting capabilities have also advanced, along with air traffic control tools. The combination of these developments has driven the development of several new wake turbulence separation concepts and opened the door for new approaches to wake vortex management.

A better understanding of wake vortex behavior, intensity, location, and decay would have several benefits, including maximizing the use of existing infrastructures and increasing airport capacity by decreasing delays and servicing more aircraft per hour.

The goal of this research effort is to:

- Understand wake vortex behavior and the parameters that influence its decay.
- Determine wake mitigation concepts and procedures that could optimally reduce wake separation.
- Develop a concept wake concept and show how it could be implemented.
Quantify concept the resulting benefit and drawback for chosen/develop concept.

Recommendations for implementation

This research effort helps the FAA better understand how wake vortex is coupled in various sub-elements of the NextGen system. It will also help FAA officials understand mitigation techniques and prioritize wake vortex hazards to aid policy decisions on future airport operations.

1.4 Scope and Delimitations

The research aimed to identify proposed wake vortex mitigation concepts, study their potential and select a wake vortex mitigation concept to be studied in more detail. For this, the research compiled and compared proposed wake vortex mitigation research efforts and concepts and rated their technical feasibility.

Immediacy can classify wake vortex mitigation concepts, as short-term or long-term mitigation procedures, and initiation, as pilot initiated or air traffic control initiated. This study addressed those short-term mitigation concepts initiated by air traffic control that has the potential to provide capacity benefit prior 2025, selected the most promising concept.

Dynamic wake vortex separation was the concept chosen for further study because it can provide capacity benefits before 2025 and is initiated by air traffic control. The calculation of the benefits of this concept has been accomplished by developing density functions to compute wake vortex circulation strength and decay given a specified set of input conditions. The study then developed a methodology to calculate maximum circulation strengths and dynamic separation reductions.

The primary goal of this research was not to develop wake vortex separations to be immediately applicable to aircraft operations, because for this a more holistic approach is needed were other factors such as measured values of runway occupancy times and data on gate availability need to be studied. The goal of this research is to develop a methodology to show the potential benefits and implications of dynamic wake vortex separations and to study how typical wake vortex circulation strength and wake vortex behavior interact with environmental conditions.

Among the limitations of this study are the availability and access to data collected and frequency distributions of environmental and aircraft dependent parameters.
1.5 Significance of the Study

In the past decade, wake turbulence studies have focused on the safety of the air transportation system. Current research has shown that the transport and persistence of wake vortices depend heavily on meteorological conditions. As new technologies for meteorological data collection have been developed and national efforts began to collect meteorological data for aviation studies, there is a need to assess if current separation standards between aircraft are overly conservative (WakeNet Europe 2012).

This dissertation addresses whether current separations can be reduced while maintaining safety. In doing so, it studies proposed wake vortex mitigation concepts, selects the most promising, and evaluates its potential capacity benefit.

This study advances the practical understanding of wake vortex behavior in aviation by using the NASA APA model to study which environmental factors have the greatest influence on wake vortex circulation strength and decay and which combinations of parameters enable shorter wake vortex separations between aircraft.

Advances in practice will include the calculation of a maximum wake vortex circulation capacity as well as the wake vortex circulation strength produced by each studied aircraft. This information will demystify for a broader audience the typical values of wake vortex circulation strength versus wake vortex duration for those aircraft with the highest frequency in the NAS. Consequently, general aviation pilots and other interested parties will better understand wake vortex behavior, based on the NASA empirical model. This information will expand the boundary of research in wake vortex and aircraft interaction, the main factors in determining wake vortex separation.

Current wake vortex separations RECAT I have been developed by grouping all aircraft into six categories. Current research and field data collection is focused on individualizing current aircraft groups and this effort is called RECAT II. This research focuses on RECAT III implementation of dynamic wake vortex separations.

This research fills the gap in the literature on the methodology to calculate aircraft maximum circulation capacity and present the actual values of produced wake vortex circulation and wake vortex circulation capacity of the following aircraft. Proposed wake vortex mitigation concepts and the benefits implications of implementing dynamic wake vortex separation are also presented.
1.6 Organization of the Dissertation

This dissertation, structured in a manuscript format, presents the research executed in the topic of wake vortex mitigation using the following chapters:

**Chapter 1** explains the phenomenon of wake vortex turbulence generated by aircraft in motion and introduces wake vortex as the next constraining obstacle to increase airport capacity. This chapter also presents background on wake vortex mitigation concepts and procedures and explains the research significance and motivation for this dissertation.

**Chapter 2** provides an overview of the significance of vortices in aviation as well as previous research work on wake vortex models. This chapter also presents the efforts of the Federal Aviation Administration to mitigate wake vortex by grouping all aircraft into categories to implement leading-trailing aircraft wake vortex separations while guaranteeing safe operations in the national airspace system.

**Chapter 3** presents a critical review that surveys and studies wake vortex mitigation efforts including concepts, procedures, technologies, and model development that have been proposed could reduce current policies for wake vortex separations between aircraft. This chapter considers a wide range of benefits and drawbacks to these concepts and summarizes their technical feasibility, implementation complexity, and potential for capacity improvement. This chapter identifies dynamic time separation as the wake vortex mitigation concept chosen for further study in this dissertation.

**Chapter 4** presents scientific work for modeling wake vortex and research findings on a statistical analysis of wake vortex behavior and its interaction with environmental and aircraft dependent parameters. This chapter identifies those parameters with higher influence on wake vortex circulation strength, lateral behavior, and vertical behavior and recommends where near-future efforts on data collection and transmission technologies should be focused.

**Chapter 5** presents a methodology for deriving maximum circulation capacity to enable future research on dynamic wake vortex separation calculations.

The chapter presents the potential for wake vortex separation reductions if dynamic wake vortex separations RECAT III are implemented.

The chapter presents a Monte Carlo simulation of aircraft operations and the development of a methodology to calculate the maximum circulation capacities for each critical aircraft in RECAT II categories. This chapter presents a range of possible values for wake vortex dynamic separation reductions.
Chapter 6 presents a computer simulation and modeling study of aircraft operations to calculate how often runway occupancy time is the limiting factor to increasing runway capacity airport under RECAT II and RECAT III conditions. This chapter simulates aircraft operations at Chicago O’Hare International Airport during final approach utilizing RECAT II, RECAT III separation rules and considering individual runway fleet mix, runway occupancy time, operational buffers, and aircraft approach speed; parameters collected using radar data.

Chapter 7 presents a study of how much of the aircraft-to-aircraft separation reductions that result from relating aircraft and environmental parameters to wake vortex behavior can translate to an operational airport capacity increase. In this chapter simulation and modeling of aircraft operations at each runway end that is operated under capacity constraints at Denver International Airport and at La Guardia Airport has been performed. It also discusses implications of dynamic wake separation RECAT III implementation.

Chapter 8 provides the conclusion, research significance, and recommendations for future research in wake vortex mitigation as well as suggested studies to be done prior the implementation of dynamic wake vortex separation. This study also identify future research needs and gaps to understand the implications of reduced wake vortex separations to the airport system.

Appendix A provides MATLAB computer codes for the most important programs created during the development of this research. This computer code includes topics such as the simulation of wake vortex behavior, calculation of maximum circulation capacities for each aircraft under study, validation of wake vortex dynamic separations, simulation of runway operation under dynamic wake vortex separations, data parsing, visualization of RECAT II vs. RECAT III, among others.

1.7 References


2. Literature Review

The purpose of this literature review is to survey, review, and summarize already developed or proposed research on wake vortex behavior and decay models, aircraft separations, and wake vortex mitigation procedures.

Although fundamental research in wake vortex goes back to the beginning of the 1900s, applied research on mitigating wake turbulence effects in aviation operations can only be traced to the 1970s. It is not until recently that research in wake turbulence has directly contributed to tangible implementation and regulation changes (Tittsworth, Lang et al. 2012).

2.1 Wake Vortex Research Models

In 1907 scientist Frederick William Lanchester studied the significance of vortices in aviation during the pioneering search for a theory of human flight. He developed a model for vortices that included the first description of lift and drag. In 1918 the named father of modern fluid mechanics, German physicist Ludwig Prandtl, researched and presented on boundary layers and drag in the field of aviation (Hoffman, Jansson et al. 2012).

Wake vortices are an unavoidable consequence of lift. In the ideal flight scenario, this vortex would be eliminated from the path of aircraft near a generator. Because this has not been possible, research has focused on reducing the hazard posed by the wake vortex.

The most common approaches are altering vortex characteristics and understanding vortex location and strength so that aircraft in the vicinity of wake vortex can avoid it. The focus of this study is the latter approach.

Simulation and visualization models develop by the NASA, and other agencies can help researchers and policymakers understand and analyze the efficacy of wake vortex mitigation methods. The following section introduces the most known wake vortex models.

2.1.1 AVOSS (Aircraft Vortex Spacing System) Prediction Algorithm (APA)

AVOSS is a wake vortex behavior model developed by NASA that estimates the trajectory and length of time in which a wake vortex can remain a threat to aircraft in its vicinity. In the year 2000 additions were made to the model to include the wake vortex interaction with the ground at low altitudes during the in-ground-effect (Proctor, Hamilton et al. 2006) (Ahmad, VanValkenburg et al. 2014).
The atmospheric conditions represented in the model are vertical profiles of potential temperature, crosswind, and eddy dissipation rate (EDR). The modeling algorithm considers that all trailing vorticity due to lift is rolled up into a vortex pair. The model also assumes that wake vortices are transported laterally at the speed of the local crosswind and does not consider transport behavior resulting from large-scale turbulence. AVOSS does not include crosswind shear, except those that arise from the previous assumption. The circulation decay rate for each member of the vortex pair is the same (Robins and Delisi 2002).

2.1.2 TASS (Terminal Area Simulation System) Derived Algorithms for Wake Prediction (TDAWP)

TDAWP is a semi-empirical wake behavior model developed by NASA. Studies done by NASA showed that wake vortex descent rates have a non-uniform relationship to vortex radius and thus different decay rates. Application of these results in TDAWP’s circulation algorithms for both decay and vertical descent behavior of the wake vortex increased the accuracy of the model. The model also divided the wake vortex decay procedure into two phases based on the vortex core evolution process observed in Large Eddy Simulation: an initial phase of weak decay followed by an enhanced rate of decay (Riddick and Hinton 2000).

The model has been validated and calibrated for different aircraft types and under various atmospheric conditions during the field data collection for the Memphis International Airport AVOSS program (Proctor, Ahmad et al. 2010).

2.1.3 Holzapfel P2P

Holzapfel P2P is a probabilistic, two-phase wake behavior model developed by Frank Holzapfel. To account for the uncertainties of weather and environmental parameters, Holzapfel introduced probabilistic components that formulated related factors into a normalized form, where all the characteristics are scaled to the initial vortex status. Among the parameters included are the crosswind, atmospheric turbulence, atmospheric stratification, and altitude, as well as aircraft configuration and proximity to the ground. Also, the probabilistic model simulated the vortex decay process in a non-linear function, dividing the phenomenon into two phases: a wake vortex slow decay followed by a rapid dissipation behavior. The output of the P2P model contains the upper and lower thresholds of the potential wake vortex position (Holzäpfel, Schwarz et al. 2011).
2.2 Wake Vortex Separation Standards

Wake vortex separation standards are established by aviation regulatory agencies such as the FAA, ICAO, and EUROCONTROL to provide the spacing between a leader and a follower needed to avoid a wake encounter. A safe revision of current wake turbulence separations can enable high-density operations.

Unless the academic community, FAA consultants, and other researchers address wake turbulence separations, concepts based on the NextGen trajectory will not be able to perform at their full potential. It is for this reason that since the 2000s the FAA wake turbulence program has been working with ICAO, EUROCONTROL, the European Aviation Safety Agency (EASA), Air Navigation Service Providers (ANSP), Volpe National Transportation Systems Center, NASA, National Oceanic and Atmospheric Administration (NOAA), MITRE Corporation, and MIT Lincoln Laboratory and Research Universities (Gerz, Holzäpfel et al. 2005).

2.2.1 Legacy

Aircraft separation standards were originally derived based on empirical data collected through flight test and operational experience and was designed according to aircraft MTOW. From this experience, four wake vortex classifications (Table 2.1) and five separation minimums (Table 2.2) were defined.

Table 2.1: Final Approach Aircraft Wake Vortex Classification (FAA Order N JO 7110.608).

<table>
<thead>
<tr>
<th>Group</th>
<th>Takeoff Gross Weight (lb)</th>
<th>Example Aircraft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>&lt;41,000</td>
<td>All single-engine aircraft, light twins, most business jets, and commuter aircraft</td>
</tr>
<tr>
<td>Large</td>
<td>41,000 – 225,000</td>
<td>Large turboprop commuters, short and medium range transport aircraft (MD-80, B737, B727, A320, F100, etc.)</td>
</tr>
<tr>
<td>Heavy</td>
<td>&gt;225,000</td>
<td>Boeing 757, Boeing 747, Douglas DC-10, MD-11, Airbus A300, A340</td>
</tr>
<tr>
<td>Superheavy</td>
<td>1,234,000</td>
<td>Airbus A380</td>
</tr>
</tbody>
</table>

Minimum separations between two aircraft are based on the wake vortex category of the leading aircraft and the wake vortex category of the following aircraft. Each leader-follower pair is assigned a required minimum separation distance for arrivals and a required minimum time separation for departures. “MRS” indicates that Minimum Radar Separation applies between leader and follower. In the United States the current value of MRS is 2.5 nm (FAA-RECAT 2015).
Table 2.2: Final Approach Separation Minimums Based on FAA 7110.65W (IFR).

<table>
<thead>
<tr>
<th>Leader</th>
<th>Super</th>
<th>Heavy</th>
<th>B757</th>
<th>Large</th>
<th>Small</th>
</tr>
</thead>
<tbody>
<tr>
<td>Super</td>
<td>MRS</td>
<td>6</td>
<td>7</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>Heavy</td>
<td>MRS</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>B757</td>
<td>MRS</td>
<td>MRS</td>
<td>MRS</td>
<td>MRS</td>
<td>4</td>
</tr>
<tr>
<td>Large</td>
<td>MRS</td>
<td>MRS</td>
<td>MRS</td>
<td>MRS</td>
<td>4</td>
</tr>
<tr>
<td>Small</td>
<td>MRS</td>
<td>MRS</td>
<td>MRS</td>
<td>MRS</td>
<td>MRS</td>
</tr>
</tbody>
</table>

*Arrival Separations (nautical miles) 7110.65W*

2.2.2 RECAT I

In the late 1990s and early 2000s, NASA’s Aircraft Vortex Spacing System program researched the possible benefits of reducing wake vortex separations. Wake Turbulence Recategorization I (RECAT I) was a joint effort by the FAA and EUROCONTROL, who shared data, analysis expertise, and operational experience to revise current wake vortex separations. The impetus for this revision was unnecessarily large separations for follower aircraft in the upper spectrum of each weight category (for example, the Boeing 747, the heaviest in its class) because of the wide ranges of aircraft weight (Soares, Wang et al. 2015).

RECAT I replaced the five legacy weight classes with six static wake vortex categories and developed a more efficient set of wake vortex separation minima as shown in Table 2.3. RECAT I accounted for not only aircraft operational weight, but also aircraft approach speed, wingspan, wake vortex physics, and aircraft dynamics. RECAT I provided a more accurate representation than Legacy, of wake circulation strength and behavior as well as the vulnerability of the following aircraft. RECAT I was based on data collected for 61 aircraft that made up 85% of operations from 5 airports in the United States and 3 in Europe (FAA-RECAT 2015).
Table 2.3: RECAT Arrival Separations On Single Runway and CSPR.

<table>
<thead>
<tr>
<th>Leader Separations</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>MRS</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>B</td>
<td>MRS</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>C</td>
<td>MRS</td>
<td>MRS</td>
<td>MRS</td>
<td>3.5</td>
<td>3.5</td>
<td>6</td>
</tr>
<tr>
<td>D</td>
<td>MRS</td>
<td>MRS</td>
<td>MRS</td>
<td>MRS</td>
<td>MRS</td>
<td>4</td>
</tr>
<tr>
<td>E</td>
<td>MRS</td>
<td>MRS</td>
<td>MRS</td>
<td>MRS</td>
<td>MRS</td>
<td>MRS</td>
</tr>
<tr>
<td>F</td>
<td>MRS</td>
<td>MRS</td>
<td>MRS</td>
<td>MRS</td>
<td>MRS</td>
<td>MRS</td>
</tr>
</tbody>
</table>

*Arrival Separations (nautical miles)*

RECAT I support tools, such as controller decision support tool (DST) and Automated Terminal Proximity Alert (ATPA), have been developed and deployed. They alert controllers and help them monitor compression effects due to loss of separation for each pair of aircraft. The results of RECAT I were finalized in 2011 and introduced for testing at Memphis International Airport (MEM) in 2012. Under RECAT I MEM has experienced a capacity increase of 19 percent. (VOLPE 2015) (Pruis, Delisi et al. 2016).

2.2.3 RECAT II

The FAA has made several efforts to expand the number of wake vortex categories. Recent RECAT II efforts propose a static pairwise separation matrix that removes category boundaries. RECAT II would stop the current application of a single separation category to a broad class of aircraft weights, which has led to larger-than-needed aircraft separations. The goal of RECAT II is to achieve airport-specific capacity benefits while maintaining a manageable wake vortex separation matrix for air traffic controllers. The size of the matrix will be customized for each airport based on its operating fleet mix.

RECAT II assumes that if wake vortex capabilities for the most common aircraft are known, then each pair can be assigned a pairwise separation, resulting in an optimized, airport-specific matrix of the static wake vortex. RECAT II focuses on the most prevalent 123 aircraft in the NAS as shown in Table 2.4, drawn from traffic at 32 airports in the United States. RECAT II requires more data and data processing than RECAT I, which has led to substantial enhancement in aircraft performance and environmental condition databases (Tittsworth, Cheng et al. 2016).
Data on wake vortex circulation strength at a specified altitude was collected using pulsed Light Detection and Ranging (LIDAR) equipment at San Francisco International Airport (SFO), John F. Kennedy International Airport (JFK) and Frankfurt International Airport (FRA). Data from 230,000 arrivals and departures were collected, and near-worst-case scenarios were identified for the derivation of safe separations. RECAT II static pairwise wake vortex separation is currently being designed and developed. The FAA is expected to publish it in the early 2018 and start the initial phase of implementation between the year 2019 to 2025 (Pruis, Delisi et al. 2013).

### 2.2.4 RECAT III

RECAT III aims to develop what the FAA considers the NextGen’s ultimate dynamic pairwise separation: dynamically derived separations that account for near-real-time environmental conditions and aircraft data. This effort is in the very early stages of conceptualization and directly supports FAA Next Generation goals to safely enhance the capacity and efficiency of the National Airspace System (NAS). The timeframe for RECAT III initial implementation is roughly the 2020s (Lakatos 2017).

Dynamic separations in RECAT III maximize the benefits of RECAT II pairwise separation. However, human factors limitations may make implementation impractical without the appropriate computer decision support tools.

---

**Table 2.4: RECAT II Matrix, Sample of the 123 x 123 Wake Vortex Separation Matrix.**

<table>
<thead>
<tr>
<th>Leader</th>
<th>A388</th>
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*Note: *No effect.*
2.3 Literature Summary

There is a growing amount of research on wake vortex behavior and data collection that includes aircraft configuration and airport environmental conditions. For the implementation of dynamic wake separations to become a reality, data on wake vortex circulation strength and behavior, as well as aircraft parameters such as weight, approach speed, aircraft altitude and flap configuration, needs to be collected and shared between the airlines, aircraft manufacturers, government institutions, and researchers.

The ultimate goal of wake vortex research models and wake vortex recategorization RECAT III efforts, is that at a later stage of development, and after several stages of validation with real data they could be used operationally. Research models could be used not only within the terminal airspace but also as onboard tools to support concepts such as dynamic separation of aircraft (Tittsworth, Cheng et al. 2016)

2.4 References


3.1 Abstract

To increase capacity, the air transportation industry has shown interest in wake mitigation, with the goal of reducing the in-trail separation between leading and trailing aircraft operations. Wake vortex separation is a major impediment to this goal. Replacing the current, static wake separations with dynamic separations, based on airport fleet mix or environmental and aircraft factors, could increase airport and airspace capacity. This paper describes a research effort to locate, review, and summarize already developed or currently proposed dynamic wake mitigation separation concepts. This study also discusses the technical feasibility and implementation challenges of each concept, identifies possible research gaps, and proposes future research recommendations.

3.2 Introduction

There is a need to study wake mitigation concepts to reduce wake separation between aircraft. NASA Langley Research Center, in conjunction with the Federal Aviation Administration (FAA), industry partners, and universities, has been developing concepts, systems, and technologies that provide real-time observations and predictions of wake turbulence behaviors. Their goal is to develop dynamic procedures to reduce wake separation under different flight operations (Rutishauser 2003). Several studies have shown the possibility of increasing capacity by reducing wake-vortex separations between a leading and following aircraft (Witzberger and Robinson 2013). In recent years, the International Civil Aviation Organization (ICAO), FAA, EUROCONTROL, Japan Aerospace Exploration Agency (JAXA), and universities have proposed several initiatives (Gerben Van, Lennaert et al. 2006, Hoogstraten, Visser et al. 2014) for reducing wake mitigation separation and consequently increasing airport capacity.

The purpose of this literature review is to survey, review, and summarize already developed or proposed dynamic wake mitigation separation concepts that could reduce standard minimum wake separations between aircraft. Wake mitigation concepts are classified along two dimensions: a) time until implementation and benefit, near-term or far-term, and b) initiation, pilot-initiated or air traffic
control initiated. The literature review addresses 16 wake mitigation concepts that are near-term, with the potential to provide capacity benefit before 2025, and that rely on separation initiated by air traffic control. The study then critically compares them on potential arrival operations improvement, potential departure operations improvement, allowance of closely spaced runway use, requirements for new technologies, requirements for training of pilots or air traffic controllers, and dependency on environmental conditions or aircraft parameters. The study considers a wide range of benefits and drawbacks to these concepts and summarizes their capacity improvement, technical feasibility, and implementation complexity. It also presents gaps in wake mitigation research and practices.

3.3 Methodology

The study searched for information of interest in a wide variety of sources: white papers, reports, journal papers, and ongoing research presented at conferences. The following journals were searched: American Institute of Aeronautics and Astronautics, Journal of Air Transportation, Journal of Aircraft, Journal of Aircraft Engineering and Aerospace Technology, Journal of Aerospace Science and Technology, and Journal of Guidance Control and Dynamics. Additionally, the study searched several databases to locate technical reports authored by NASA Langley Technical Reports, Volpe Publication, WakeNet USA, WakeNet Europe, MIT Lincoln Laboratory, and National Center for Atmospheric Research (NCAR). The following keywords were used to identify relevant material: wake mitigation concepts, dynamic wake separation, and wake vortex separation reduction.

Initial searches identified more than 100 documents related to the topic. The search was narrowed to include articles and reports published since the year 2000. After reading the abstracts of this subset, the set of documents was again narrowed to 67 that discussed concepts that could be considered for near-term mitigation, with the potential to provide capacity benefit before 2025, and whose separation is initiated outside the cockpit. In all concepts selected from this final set of documents, the risk of a reduced separation is deemed to be equal or lower than the risk of current separation regulations.

Documents selected were grouped by the 16 unique concepts they presented, all of which were selected for this study. The potential benefits and drawbacks of each concept were identified from the literature or inferred from current wake regulations and procedures by team members from three NEXTOR universities (Virginia Tech, Massachusetts Institute of Technology, and George Mason).

To measure the value of each concept, benchmarks were defined based on the main factors that affect short-term wake mitigation. These factors are potential to increase arrival operations only,
potential to increase departure operations only, complexity (requires training and certification),
dependence on environmental conditions, or dependence on aircraft or fleet parameters (see Table 3.1).

### Table 3.1: Concept Benchmarks.

<table>
<thead>
<tr>
<th>Concepts</th>
<th>Potential for increased arrivals</th>
<th>Potential for increased departures</th>
<th>Requires training or certification</th>
<th>Environmental condition dependent</th>
<th>Aircraft / fleet dependent</th>
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<tr>
<td>Simultaneous Offset Instrument Approach (SOIA)</td>
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<td>Dynamic Time-Based Separation for Individual Aircraft Pairings</td>
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<td>Pair Departures</td>
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<td>Curved Approach</td>
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Some concepts could belong to more than one category; for example, Wake Turbulence Mitigation Departure (WTMD) is applicable only for departures but is also wind dependent; this relationship can be seen in Table 3.1.

3.4 Concepts Overview

Sixteen concepts and three sub-concepts were identified from the literature. Each concept is described below along with the associated benefits and drawbacks. All concepts were grouped, based on common dependencies required for implementation, into four categories: airport fleet dependent, parallel runway dependent, single runway dependent, and aircraft or environmental condition dependent.

3.4.1 Airport Fleet Dependent

Recategorization Phase I (RECAT I) is the result of revising the legacy single-runway wake separation to improve airport capacity while maintaining the same level of safety. Lang (2015) reported up to a 20% increase in airport capacity at the airport in Memphis, TN, USA, and $1.8 million in monthly fuel savings. For airports where a high percentage of the fleet is heavy, RECAT I yields only an improvement in overall capacity. For example, at the Tokyo International Airport (HND), 70% of the fleet is heavy, and RECAT I barely reduces the separation minima for this group (Matayoshi, Okuno et al. 2010).

Recategorization Phase II (RECAT II) is a revision of the single-runway wake separation matrix based on the possibility of further separation reductions of RECAT I. The FAA has not released many aspects of this criterion, but it is expected to be a 123 by 123 wake separation matrix. This matrix will be adapted according to specific airport fleet mix (Tittsworth, Cheng et al. 2016).

The Large-Large 2 NM Separation concept is based on reducing the minimum separation between large-large pairs to 2 NM for a single runway. It assumes average runway occupancy time less than 45 seconds and a separation buffer big enough that average separation for large leading aircraft to following large aircraft becomes ~3 NM with 2 NM minimum.

The Large-Large 2 NM Separation concept applies to same-runway separation, either on a single runway or independent parallel runways. The testing phase of Large-Large 2 NM Separation has been estimated with 4%-12% additional throughput over current rules at ATL, LGA, and ORD. Other benefits of this method include that it does not require additional technology nor additional tools for its integration into current infrastructure, and additional pilot training is not mandatory. The main
drawback for this concept is that it excludes possible separation decreases between non-large aircraft categories. Also, the 45 seconds runway occupancy time is difficult to achieve because airplanes are above the max safe speed to use the exit or maybe the exits need to be relocated.

3.4.2 Parallel Runway Dependent

Dynamic wake separation procedures allow reduced wake separation when the duration and strength of the wake are proven short enough to allow further in-trail separation reductions beyond RECAT II. Proposed concepts include Closely Spaced Parallel Runway (CSPR): Wake Turbulence Mitigation Arrivals (WTMA) and Wake Turbulence Mitigation Departures (WTMD).

CSPR procedures are designed for runways whose centerlines are separated by less than 762 meters (2,500 feet). Their ultimate intention is to reduce wake separation to minimum radar separation below minimum radar separation. CSPR procedures have been used at 35 of the largest airports in the United States, including Detroit (DTW), Newark (EWR), San Francisco (SFO), and Los Angeles (LAX) (Williams and Lohr 2008). CSPR takes advantage of crosswinds with sufficient intensity to transport the wake vortex away from the parallel runway and allow the two runways to be treated as independent of each other (FAA-Order-7110.308 2008).

The greatest benefit attributed to CSPR is that under visual meteorological conditions, simultaneous operations can be conducted on the closely spaced runways. The downside of this method is that it excludes airports with runways that cross each other, and airports with runways that already comply with the 762 m (2,500-ft) separation receive no additional benefit. Also, the arrival rate is reduced significantly during instrument meteorological conditions because simultaneous operations are not permitted (Mayer 2005).

WTMD is a crosswind-based concept that operates under specific wind conditions and enables closely spaced departures and arrivals without wake constraints (Lang 2015). This concept takes advantage of live-forecast wind conditions to keep vortices away from the protected runway (see Figure 3.1). WTMD optimizes and increases departures under favorable wind conditions, improves capacity during visual meteorological conditions, and eliminates the need for the standard CSPR separation if the crosswind prevents a departing aircraft’s wake from reaching the parallel runway (FAA Order AC 90-23G 2014).

In WTMD, the crosswind restriction must be met from the ground to the maximum divergence altitude. This limitation must be forecast to remain true for several minutes so that the conditions are unlikely to change between the time the departure is authorized and when it occurs. The Automated
Surface Observing System (ASOS) can be used for surface crosswind readings and the Rapid Refresh (RAP) forecast for higher altitude crosswind (Burnham 2014).

WTMD eliminates the need for wake vortex separation behind a Boeing 757 or category Heavy aircraft departing on the adjacent runway when specific wind conditions exist that reduce the vortex hazard. WTMD also allows airports to maintain airport departure during favorable wind conditions (Gentry, Duffy et al. 2014).

Among the limitations for WTMD are its wind dependence and its requirement for several instruments. This intruments are terminal radar with automation, Tower Radar Display, communications (air-ground voice), ASOS, Rapid Update Cycle (RUC), displays to support WTMD information requirements, aural alert for WTMD, a stand-alone processor hosting the WTMD Wind Forecast Algorithm (WFA), and supporting software (FAA-Order-7110.316 2013).

![Diagram of Wake Turbulence Mitigation Departures](image)

**Figure 3.1: Wake Turbulence Mitigation Departures.**

Wake Turbulence Mitigation for Departures – Paired Departures (WTMD-PD) is considered a sub-concept of WTMD that reduces the departure separation for CSPR in the presence of a crosswind of 1.54 m/s (3 knots) or greater. The trailing aircraft begins takeoff roll in a specified time envelope, which increases operational availability. This procedure is applicable for CSPR runways. Green light/red light and aural alerts notify controllers when WTMD conditions are present, and operations
can be conducted under this procedure (Lang 2007). Regarding implementation complexity, WTMD-PD requires new procedures to manage the rear gate by controllers (displays and alerting). Also, the flight crew needs to be aware of the procedure, and controller training is required (Lunsford 2009).

WTMA reduces wake turbulence separation standards for trailing aircraft during arrivals in high crosswind conditions (see Figure 3.2).

![Figure 3.2: Wake Turbulence Mitigation Arrivals.](image)

There have been some modifications to WTMA, such as WTMA Procedural (WTMA-P) and WTMA System (WTMA-S); an airport may use one or both procedures.

WTMA-P reduces the diagonal separation between closely spaced parallel arrivals for all categories of lead aircraft, expanding the 7110.308 procedures to Heavy and Boeing 757 aircraft (see Figure 3.3).
This concept is considered an extension of the 7110.308 order to 7110.308A. In this concept, any aircraft may lead in a pair (allowing Heavy and B757 leaders, or Cat B and Cat C leaders in RECAT airports) with the exception of the RECAT Cat A. In some cases, a precision approach capability will be required to support a second arrival stream (Gentry, Duffy et al. 2014). Philadelphia (PHL) and Detroit Metro Airport (DTW) were the first sites to implement WTMA-P (Tittsworth 2014).

WTMA-S makes use of wind forecasting algorithms to reduce the separation between closely spaced parallel arrivals under specific wind conditions. Many of the airports authorized in FAA Order 7110.308 are also eligible for WTMA-S. In some cases, a precision approach capability will be required to support a second arrival stream (Gentry, Duffy et al. 2014).

This concept has been attributed to increasing throughput up to 15% over WTMA-P. It also enhances the use of reduced separation standards for CSPR. On the downside, the concept depends on favorable wind conditions, which will exclude some airports.

Simultaneous Offset Instrument Approach (SOIA) enables dual arrival streams under limited ceiling and visibility conditions. Even though SOIA runway separation does not meet the 762 m (2,500-ft) independent runway operation requirement, the approach course separation does meet parallel approach criteria (Williams, Foster et al. 2008).
SOIA maximizes instrument approach procedures to a set of parallel runways less than 914 m (3,000 ft) apart through the use of straight-in precision approach to one runway and an offset instrument approach with a transition to a visual landing for the other runway (see Figure 3.4). This procedure requires a Precision Runway Monitor (PRM) and is only applicable to particular wind and weather.

According to reports from FAA, San Francisco International (SFO) capacity under visual meteorological conditions increases by 90% compared to Instrument Meteorological Conditions (IMC). SFO under IFR conditions Typically these SOIA procedures add two to four arrivals an hour, depending on condition (FAA 2013).

Figure 3.4: SOIA Approach.

Interval Management Paired Approach (IM-PA) creates arrival pairs for parallel approaches with an assigned safety zone, where trailing diagonal aircraft can maintain position relative to leading aircraft. IM-PA applies to CSPRs with more than 700-ft. centerline separation, and it is estimated to create an additional throughput of 4%-32% over WTMA-P.

Among the technologies required for the implementation of IM-PA are Automatic Dependent Surveillance-Broadcast (ADS-B) for trailing aircraft, ADS-B Out for leading aircraft, cockpit display support tools and algorithm, WFA forecast, and a controller support tool. IM-PA also requires front
and rear gate position calculation and display, as well as speed command guidance training for pilots if additional cockpit display is present.

Paired Departures is a concept that consists of sequencing the trailing aircraft to depart in time to stay ahead of the in-ground-effect of the wake of a leading aircraft. Studies on wake behavior and decay have shown that it takes some time for the wake vortex to displace to its surroundings, and the Pair Departures concept benefits from this window to launch operations. Among the benefits of this concept are that it makes use of existing WTMD algorithms and infrastructure and that it applies to CSPRs. This procedure does require a 1.54 m/s (3-knot) or greater crosswind to reduce departure separation for CSPR (Lunsford 2009).

3.4.3 Single Runway Dependent

Curved Approach is a proposed method that dynamically minimizes wake separations by using meteorological wake behavior prediction information coupled with Ground-Based Augmentation System (GBAS) to fly curved approach paths (Naoki 2013). The Aircraft Vortex Spacing System (AVOSS) model was used to predict wake behavior information throughout the entire wake life cycle. The concept includes wake vortex interactions with the ground and uses eddy dissipation rate (EDR) as the parameter for quantifying the strength of atmospheric turbulence; greater EDR values result in ambient turbulence with a strong intensity, which results in a faster wake dissipation rate. Because EDR is greater below 1,000 ft., where the atmosphere is turbulent, use of a curved approach path above 1,000 ft. can reduce separation of the following aircraft (Matayoshi, Okuno et al. 2010).

Using four intersecting runways at Tokyo Haneda International Airport (HND), simulations using curved approach path revealed a 12% airport capacity improvement. This improvement will vary depending on runway fleet mix and runway configuration. One of the drawbacks of this concept is that noise is spread over a larger surrounding area.

The Dual Threshold on Single Runway concept depends on the use of the Steeper Approach and Departures concept (Verbeek 1998). Advisory Circular 90-23G (FAA Order AC 90-23G 2014) and the work of Naoki (Naoki 2013) explain the details for Dual Threshold. Dual Threshold reduces noise and increases airport capacity, but it may increase runway occupancy times on landing.

Dual Threshold for arrivals is an instrument approach procedure that assigns trailing aircraft steeper approach paths to CSPRs than the leading aircraft. Currently, these paths can use glide slope angles of three, five, and seven degrees, obtained from instrument landing systems supporting the runways. This procedure has been used at six airports in Europe and has also been tested in San
Francisco International (SFO), but the complexity of its implementation is a major constraint (Milan 2007). Further studies are needed to estimate the implications of Steeper Approach procedures on runway occupancy times. London City Airport (LHR) has a five-degree steep approach, and only certain aircraft have been certified for such approaches.

Figure 3.5: Dual Threshold Arrivals.

Dual Threshold increases IMC arrival capacity and provides more stable functioning under all weather conditions, resulting in higher airline operation reliability. It also reduces noise. Due to its complexity and extra load for controllers, aircraft, pilots, and controllers need to be certified for Steeper Approach Procedures (SAP). In addition, some aircraft have physical aerodynamic limitations that do not allow them to execute this concept (see Figure 3.5). Also, steeper approaches might increase the number of missed approaches, and it is not usable in IMC.

3.4.4 Aircraft and Environmental Condition-Dependent

Aircraft Measuring and Reporting Wake for Self-Separation proposes the use of onboard aircraft vortex measuring equipment (see Figure 3.6). This concept considers aircraft wingspan, actual aircraft weight, current flap setting, and onboard Lidar measurements to calculate the strength of the wake vortex in the near field (Thomas, Meiko et al. 2013). The idea is to optimize takeoff and landing sequences by using a computer model (onboard prediction of wake behavior).
Aircraft measuring wake could help reduce separations to minimum radar separation and increase the capacity of the airport. In this concept, the wake produced by each aircraft could be transmitted to other aircraft or air traffic control facilities. Though wake vortex computation must account for aircraft weight, airlines do not typically share aircraft weight data to prevent competitors from learning their cost index and load factors (Thomas, Meiko et al. 2013). However, one of the benefits of the Aircraft Measuring and Reporting Wake is the ability to read and insert live flight data and aircraft weight into the algorithm. Aircraft reporting wake eliminates the need to share sensitive information and keeps wake vortices inside the range of radar at all times. However, this concept does require high investment in equipment and training.

Figure 3.6: Measuring and Reporting Wake for Separation.

The objective of the Wake Mitigation Using Control Surfaces concept is to reduce the wake vortex by the use of control surfaces on the wing of the aircraft. The effectiveness of the method has been questioned, in particular, because the existence of instabilities in the vortex system alone does not lead to significant mitigation of the hazard posed by following aircraft (Nan and Jacob 1999, Haverkamp, Neuwerth et al. 2005). Some of the proposed concepts are wing spoilers, fins, splines, oscillating ailerons, and non-standard flap settings during landing. These surfaces are relatively easy to retrofit to the existing aircraft fleet. However, the lift distribution that leads to unstable vortices would cause excessive loading of the outer wing, entailing high bending moments and greater maintenance cost.

Dynamic Time-Based Separation for Individual Aircraft Pairings is a concept for dynamically adapting aircraft wake separations, depending on specific weather conditions and wake behavior. Initially designed for CSPR, it is now used for dynamic predictions of pairwise aircraft separation. It
can be applied to single runways, independent parallel runways, converging/diverging runways, and intersecting runways. It has been tested at Frankfurt International Airport (FRA) for different scenarios (Lau and Lorenz 2012). This concept does require training and a controller support tool.

Wake vortices dissipate more quickly in strong headwind conditions, but strong headwind also reduces an aircraft’s ground speed. Time-Based Separation (TBS) applies a constant amount of time between arrivals in all wind conditions to minimize the impact of strong headwind on landing rates. The forecast system uses real-time, Mode-S Radar Downlink from every aircraft on approach, and the TBS support tool (Optimized Separation Delivery tool) guides controllers (initial target distance and final target distance). At London Heathrow Airport’s (LHR), TBS has been operational since 2012. TBS applies to same-runway arrivals and requires controller training for the new support tool as well as Distance Based Separation to Time Based Separation (DBS-TBS) mode transition.

London Heathrow Airport’s (LHR) expected runway capacity benefit from TBS is two to three additional arrivals per hour over DBS in a strong headwind. However, in its current form, TBS only helps recover lost capacity, not provide additional capacity. The modular design of TBS enables portability, integrated radar sequence, real-time wind readings, separation rules, and runway configuration controller display.

3.5 Conclusion and Recommendations

This research identified 16 wake mitigation concepts and three sub-concepts and categorized them according to dependency on airport fleet, runway orientation, single runway operation, and aircraft or environmental condition. According to the research findings, several concepts enable dynamic wake separation. Separations can be determined dynamically based on specific airport fleet operations or by environmental conditions and aircraft factors. This research does not consider any concept to be the best. Each concept has different input parameters, and some concepts will perform better in some airports than in others. Overall, according to results from concepts that have already been implemented, wake separation reduction can increase airport and airspace capacity by more than 4%.

The research shows that knowing the environmental conditions of the location of wake generation increases the potential to improve airport capacity. A better understanding of how dynamic parameters such as wind, temperature, and environmental turbulence affect wake behavior intensity, location, and decay can provide several benefits, including the reduction of wake encounters. Besides the capacity benefit, some of the selected concepts affect the noise impact on the area around the airport; this can
be of interest for airport noise management and policy. The size of the current wake separations matrix is limited to what controllers can memorize. Reliable technologies for calculating and managing dynamic separations have to be developed, as well as cost-benefit analyses to contrast the potential savings from wake separation reductions with the cost of implementing and approving the selected concepts and needed technology.

Many of the wake separation concepts are quite recent, and some are still ideas with no implementations in an airport or aircraft. Many details regarding their effectiveness are inconclusive, so the authors critically analyzed the drawbacks of these concepts based on the parameters that drive each model.

A research gap was found in the most important benchmark: capacity benefit. Only those concepts that were already in testing presented a preliminary measure of increased operations at airports under study. Because capacity improvement is one of the most attractive benefits of wake separation, the potential airport capacity improvement under each of the proposed concepts needs to be studied. Airport capacity studies, preferably of one of the top 50 airports worldwide regarding enplanement, could be performed through simulations with variable fleet mixes and capacity constraints.

Other research gaps include the complexity of traffic controller procedure implementation and demand, as well as cost-benefit of each concept. These gaps affect most of the concepts and are essential for decision making.

3.6 Acknowledgment

This critical review has been made possible thanks to the research contributions of the Federal Aviation Administration Wake Program, National Aeronautics and Space Administration (NASA) wake program, Eurocontrol, Japan Aerospace Exploration Agency, Wakenet meeting members, MIT Lincoln Laboratory, The MITRE Corporation, Volpe, and Virginia Tech, George Mason University, and the Massachusetts Institute of Technology. The authors would also like to thank John Hansman, John Shortle, Edward Johnson and Thomas Proeschel for their support and contribution.

3.7 Disclaimer

The contents of this material reflect the views of the author only. Neither the Federal Aviation Administration nor the United States Department of Transportation nor National Aeronautics and
Space Administration makes any warranty or guarantee, or promise, expressed or implied, concerning the content or accuracy of the views expressed herein.

3.8 References


Bell, A. (2012). Developing Standards for Time-Based Sequencing & Separation of Aircraft, IEEE.


FAA (2013). SOIA AT SFO.


FAA (2013). SOIA AT SFO.


Lang, S. (2007). Wake Vortex R&D Status Briefing, FAA.


* this reference has been used for the critical review but was not cited in the chapter.
4. Modeling and Statistical Analysis of Wake Vortex Behavior and Its Interaction with Environmental and Aircraft-Dependent Factors

4.1 Abstract

This research simulates aircraft operations during arrival and departure as well as the environmental conditions in the aircraft flight path to understand the interaction among wake vortex behavior, aircraft-dependent parameters, and environmental conditions.

A methodology to calculate maximum circulation capacity based on RECAT II separations, which would allow the use of cumulative density curves to derive dynamic wake separations, is presented.

This research identified environmental turbulence and aircraft weight as the parameters with the greatest influence on wake circulation strength. The wind has the greatest influence on wake lateral behavior, and aircraft mass, environmental turbulence, and wind have the greatest influence on vertical wake position.

Near-future efforts should be focused on data collection of environmental turbulence at different altitudes; and on aircraft transmission technologies, to improve implementation efforts of RECAT III dynamic wake vortex separations.

4.2 Introduction

Aircraft in flight generate wake vortices which are counter-rotating tubes of air that originate from the aircraft wingtip—which have proven to be dangerous to aircraft in their vicinity (Proctor, Hamilton et al. 2004).

Wake separations between aircraft allow time for wake turbulence from a leading aircraft to be dissipated and displaced from a following aircraft’s path. Aircraft vortices remain an important challenge to shortening the standard separations between leading and following aircraft and thereby increasing runway capacity. Dynamic wake mitigation is one near-term effort that could provide capacity benefit before 2025 and could be initiated by air traffic control.
The dynamic wake mitigation concept proposes to increase runway capacity without modifying existing infrastructure. Its approach is to discretize wake aircraft groups by analyzing characteristics of each pair of leader and follower aircraft as well as the environment where the aircraft travel. This approach requires a thorough understanding of wake vortex decay and the parameters that influence wake behavior.

The research presented in this paper uses a fast-time wake transport and decay model called NASA’s AVOSS TASS Driven Algorithm for Wake Prediction (TDAWP), in conjunction with Monte Carlo simulation, to understand how aircraft-dependent conditions and environmental parameters influence wake behavior and to develop probability density functions that can help the wake vortex capacity of aircraft.

Fast-time wake transport and decay models are empirical algorithms used for real-time prediction of wake transport and decay based on aircraft parameters and ambient weather conditions (Ahmad, VanValkenburg et al. 2016).

NASA’s AVOSS TDAWP combines fast-time wake vortex models with flight data and can provide wake hazard bounds regarding wake circulation strength as well as wake lateral and vertical behavior. Previous studies have shown that TDAWP predictions of vortex locations compare well with flight test data and LIDAR measurements (Ahmad, VanValkenburg et al. 2016).

4.3 Objective

The objective of this research is to simulate aircraft operations during arrival and departure, as well as the environmental conditions in the aircraft flight path, to understand the interaction between wake vortex behavior, aircraft-dependent parameters, and environmental conditions.

Despite the critical impact of wake vortex on aviation, as well as the great danger attributed to wake encounters, wake behavior and the influence of its variables remain largely unknown (National Research Council 2008).

This research identifies the parameters with the greatest influence on wake circulation strength, lateral behavior, and vertical behavior, with the goal of recommending where near-future efforts on data collection and transmission technologies should be focused to implement RECAT III dynamic wake vortex separations.
4.4 Methodology

The methodology to understand wake vortex circulation behavior, wake vortex lateral and vertical behavior and the interaction between wake vortex and environmental conditions is based on Monte Carlo simulation, statistical analysis, and the derivation of probability density functions.

The analysis applied a Monte Carlo simulation approach, in conjunction with the NASA AVOSS TDAWP 2.1 model, to derive combinations of wake behavior parameters to obtain wake behavior under different conditions. NASA evaluations of fast-time models using field data measured with light detection and ranging (LIDAR) demonstrated the model TDAWP to be more accurate than other wake behavior models (Ahmad, VanValkenburg et al. 2016).

The simulation uses the Base of Aircraft Data (BADA) for modeling aircraft point mass estimates regarding speed at each altitude. The simulation assumes constant values for eddy dissipation rate (EDR), intrinsic values of Brunt-Väisälä frequency, and constant crosswind speed.

The analysis considers wake vortex lateral transport, based on possible wind conditions, as cross-flow velocity bounded by the maximum possible crosswind. To model environmental turbulence, the model uses a uniform distribution ranging from moderate to very turbulent, bounded between the typical values.

According to previous studies, the influence of environmental factors on wake turbulence is complex and nonlinear. There are many unknowns about the most frequent values of environmental turbulence for each altitude, as well as the results of the interaction between environmental factors. Consequently, there are no definite mathematical models or general conclusions about how these factors affect the wake (Xue, Xu et al. 2015).

The natural uncertainty of environmental conditions and aircraft parameters (Pruis, Delisi et al. 2016) makes it difficult to predict the exact condition of the atmosphere in which wakes will occur. As a result, a parametric approach generating multiple possible conditions for wake for each critical aircraft is appropriate for modeling wake vortex behavior.

This research expands on dynamic wake mitigation concepts and procedures. For each significant combination of environmental and aircraft-dependent parameters, the analysis derives a probability density function that can be used to compute a potential wake encounter given a specified set of input conditions. These probability density functions have been developed to show potential for a wake encounter: when an aircraft encountering a wake vortex has little altitude to recover from either an upset or a loss of lift (Proctor, Hamilton et al. 2004).
For approach operations, parameter probability density functions are combined to create wake vortex circulation curves for confidence levels of 90%, 95%, and 99%. The 95% confidence curve is used to determine the maximum circulation capacity (MCC) that the aircraft under study can withstand in today’s operations and under current separations.

4.5 Simulation Conditions

4.5.1 Simulating Environmental Factors Influencing Wake Vortex

Internal and external factors during wake encounters are complex and unpredictable. The following sections explain the incorporation of each factor into the simulation.

4.5.1.1 Brunt-Väisälä Frequency

The Brunt-Väisälä frequency is the frequency at which air oscillates in the stratified atmosphere, and it is the result of non-uniform densities among different strata of the atmosphere. Air parcels travel and at the same time oscillate within atmospheric strata of different density and humidity. The period of the oscillations made by particles of air is around 100 seconds and, typically near air boundary layers, is traveling at around 10 m/s per second (Merryfield 2016). Typical values of the Brunt-Väisälä frequency measured in the field range between 0.01 to 0.015 radians per second (s⁻¹) (Ahmad, VanValkenburg et al. 2016), where greater values indicate larger buoyancy force is acting on the wake and result in an increased wake decay rate (Hoogstraten, Visser et al. 2014).

4.5.1.2 Temperature and Air Density

Temperature and air density profiles for each altitude are based on the International Standard Atmosphere. Fixed temperature is most suitable for historical data at the airport being evaluated. This simulation requires temperature in Kelvin (K) and density in kilograms per cubic meter (kg/m³). This experiment uses standard air densities as a function of altitude, based on values from the International Standard Atmosphere: air density at a given altitude is found by linearly interpolating between the two closest values. Values for aircraft speed are specified at 50-foot increments in an internal table.

4.5.1.3 Crosswind

Crosswind is any line of steady wind that has a perpendicular component to the direction of aircraft travel. The crosswind speed values implemented for each aircraft and simulated along the entire flight path are bounded by the certified crosswind speed (CCS) for landing for each critical aircraft.
4.5.1.4 Environmental Turbulence

Environmental turbulence can be considered a population of eddies or vortices of different size and strength, which are embedded in one another and continuously changing in diameter and orbital velocity (Cushman-Roisin 2017). Based on previous studies and empirical evidence, the values of EDR selected for this simulation fall in the category of Moderate-Strong and are linearly distributed (Xue, Xu et al. 2015).

Low environmental atmosphere values represent non-disturbed wake turbulence. However, the simulation does not account for these values because wake will be disturbed when it is in contact with the ground during the in-ground-effect (Lang 2015), and the scope of this research is limited to arrival and departure operations.

Moderately weak and very weak environmental turbulence are typical for the early morning hours in the lower atmosphere, with very weak turbulence corresponding to calm conditions (Proctor, Hamilton et al. 2006) (Switzer and Proctor 2000) (Stull 1998). Table 4.1 presents the EDRs most predominant in the boundary layer: greater than $10^{-3}$ m$^2$/s$^3$. The simulation uses these values (Holzäpfel 2014).

<table>
<thead>
<tr>
<th>Category</th>
<th>ε (m$^2$/s$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Weak</td>
<td>$1.0 \times 10^{-7}$</td>
</tr>
<tr>
<td>Weak</td>
<td>$1.0 \times 10^{-5}$</td>
</tr>
<tr>
<td>Moderate</td>
<td>$1.35 \times 10^{-3}$</td>
</tr>
<tr>
<td>Moderate-Strong</td>
<td>$3.02 \times 10^{-3}$</td>
</tr>
<tr>
<td>Strong</td>
<td>$7.17 \times 10^{-3}$</td>
</tr>
<tr>
<td>Intense</td>
<td>$1.50 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

4.5.2 Simulating Aircraft Factors Influencing Wake Vortex

4.5.2.1 Aircraft Weight

Aircraft weight is a key parameter for the wake circulation strength generated by a leading aircraft, as well as for the wake strength that an aircraft can endure. It is for this reason that maximum take-off weight (MTOW) is currently the main criterion for dividing wake vortex separation categories between all operating aircraft. Aircraft weight affects the procedures for wake separations between a leading and the following aircraft (Xue, Xu et al. 2015). According to extensive data collection from FAA
consultants, landing aircraft in the Heavy group is typically at about 85% of maximum allowable landing weight (MALW) (James, Greene et al. 2015).

4.5.2.2 Aircraft Speeds

Characterizing the wake turbulence for aircraft operations under different phases of flight requires aircraft speeds on climbing and descent operations (James, Greene et al. 2015). The simulation uses aircraft speeds from BADA specifications developed and maintained by EUROCONTROL.

4.5.2.3 Aircraft Wingspan

The wingspan on the aircraft determines the capability of an aircraft to counteract the roll from a wake vortex encounter (FAA Order AC 90-23G 2014). The initial descent velocity of the wake on a generator depends on the vortex pair separation distance ($b_0$), which is $\pi/4$ times the wingspan; it is for this reason that aircraft wingspan is one of the main inputs into the simulation.

4.5.2.4 Aircraft Altitude

The altitude of the aircraft is a parameter that influences air density, air temperature, aircraft speed, and the interaction between the wake and the ground. Typical altitudes in each phase of flight, according to aircraft service ceiling and BADA, are inputs in the simulation for in-ground effect. Altitude equal to three wingspans define the in-ground effect's upper layer.

4.6 Data Analysis

A series of analyses were conducted to determine which among the independent variables of aircraft mass, temperature, wind, and environmental turbulence are the most strongly related to the dependent variables of wake strength, wake lateral position, and wake vertical position, referred to collectively as wake behavior. Two datasets were involved, with data corresponding to arrivals and data corresponding to departures. The conventional alpha level of .05 was used to determine significance ($p$).

First, a correlational analysis was performed to determine the existence and strength of any relationships. Second, a regression analysis was conducted to determine the predictive association between the independent variables and the dependent variables. Finally, a Monte Carlo simulation was performed to simulate wake behaviors based on several stochastic parameters.
A total sample of 60,000 datasets was available. In order to reduce the risk of Type I error (i.e., the chance of finding a significant result merely due to chance) due to large sample size (Field 2013); G*Power 3.1.9.2, a power and sample size calculator software, was used to calculate an appropriate sample size using parameters associated with the regression analysis. (Cohen 1988) indicates that a medium effect size and a conventional .80 power level can be used for power and sample size calculation purposes. As such, for multiple linear regression with medium effect size, an alpha of .05, a .80 power level, and four predictors, a sample of at least 108 would be appropriate (Faul, Erdfelder et al. 2009). Thus, a sample of 120 was randomly selected for the following analyses.

4.6.1 Correlation Analysis

A series of Pearson’s correlations were performed between the variables of aircraft mass, temperature, wind, environmental turbulence (EDR) and wake behavior for both arrivals and departures. The Pearson’s correlation is the appropriate analysis to perform when assessing the bivariate relationship between continuous variables (Tabachnick and Fidell 2013). Correlations (r) can range from -1.00 to 1.00, with values closer to -1.00 or 1.00 indicating stronger relationships (Field 2013). Negative coefficients indicate an inverse relationship: as one variable increases, the other decreases (Field 2013). Positive coefficients indicate a positive relationship: as one variable increases so does the other (Field 2013). Correlation coefficients will be interpreted using Cohen’s standard (Cohen 1988), where coefficients between .10 and .29 are considered small, coefficients between .30 and .49 are considered medium, and coefficients of .50 and above are considered large.

4.6.1.1 Arrivals

A level of significance of .05 was used in the correlation analysis. There is a significant correlation between the independent and dependent variables if the p-value is equal or less than the level of significance value. Each dependent variable (wake circulation strength, wake lateral position, and wake vertical position) was correlated with the study variables of interest.

4.6.1.1.1 Circulation Strength

The results for arrival wake circulation strength were significant between circulation strength and aircraft mass (r = .68, p < .001), between circulation strength and EDR (r = -.83, p < .001), and between aircraft mass and EDR (r = -.18, p = .028). The relationship between arrival wake circulation strength and aircraft mass was large and positive, indicating that increases in aircraft mass are
associated with increases in wake circulation strength. The relationship between arrival wake circulation strength and EDR was large and negative, which indicates that increases in environmental turbulence are related to decreases in wake circulation strength. Finally, the relationship between aircraft mass and EDR was small and negative, indicating that as aircraft mass increased, EDR decreased. The strongest relationship was between arrival wake circulation strength and EDR. There were no other significant relationships. Table 4.2 presents the full results of the correlations involving arrival circulation strength.

Table 4.2: Correlation Results for Circulation Strength in the Arrival Configuration Under In Ground Effect.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Circulation Strength (m²/s)</th>
<th>Aircraft Mass (kg)</th>
<th>EDR (m²/s³)</th>
<th>Wind (m/s)</th>
<th>Temperature (k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circulation</td>
<td>-</td>
<td>.68* p &lt; 0.001</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strength (m²/s)</td>
<td>.83* p &lt; 0.001</td>
<td>-.18* p = 0.028</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aircraft Mass</td>
<td>.14 p = 0.063</td>
<td>.12 p = 0.091</td>
<td>-.09 p = 0.163</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>.06 p = 0.260</td>
<td>.08 p = 0.194</td>
<td>-.03 p = 0.393</td>
<td>-.03 p = 0.381</td>
<td>-</td>
</tr>
</tbody>
</table>

*Correlation is significant at the .05 level

Wake vortex behavior when in proximity to the ground is known to experience an enhanced decay as shown in Figure 4.1; yet much is to be learned about this behavior (Proctor et al., 2000). Wake behavior presented in Figure 4.1 shows how greater atmospheric turbulence results in faster wake dissipation.
Figure 4.1: Wake Circulation Strength for A380-Class Aircraft in the Arrival Configuration Under In Ground Effect.

4.6.1.1.2 Wake Lateral Position

The only significant correlation involving arrival wake lateral position was between arrival wake lateral position and wind ($r = 1.00, p < .001$). This indicates that there is a perfect correlation between the two variables. There was no significant correlation between arrival wake lateral position and any other variable. Table 4.3 presents the results of these correlations.

Figure 4.2 shows wake lateral behavior under environmental turbulence, aircraft mass, temperature and wind variations.
Table 4.3: Correlation Results for Wake Lateral Position in the Arrival Configuration Under In Ground Effect.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Lateral Position (m)</th>
<th>Aircraft Mass (kg)</th>
<th>EDR (m²/s³)</th>
<th>Wind (m/s)</th>
<th>Temperature (k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral Position (m)</td>
<td>-</td>
<td>.13 p = 0.087</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Aircraft Mass (kg)</td>
<td>-</td>
<td>.13 p = 0.087</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>EDR (m²/s³)</td>
<td>-.09 p = 0.157</td>
<td>-.18* p = 0.028</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Wind (m/s)</td>
<td>1.00* p &lt; 0.001</td>
<td>.12 p = 0.091</td>
<td>-.09 p = 0.163</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Temperature (k)</td>
<td>-.03 p = 0.382</td>
<td>.08 p = 0.194</td>
<td>-.03 p = 0.393</td>
<td>-.03 p = 0.381</td>
<td>-</td>
</tr>
</tbody>
</table>

*Correlation is significant at the .05 level

Figure 4.2: Wake Lateral Behavior for A380-Class Aircraft in the Arrival Configuration Under In Ground Effect.

4.6.1.1.3 Wake Vertical Position

The results for arrival wake vertical position were significant for aircraft mass \((r = .84, p < .001)\), EDR \((r = - .67, p = < .001)\), and wind \((r = .16, p = .044)\). Arrival wake vertical position was strongly
positively related to aircraft mass, strongly negatively related to EDR, and weakly positively related to wind. Table 4.4 presents the results of these correlations. Figure 4.3 shows wake vertical behavior under environmental turbulence, aircraft mass, temperature and wind variations.

Table 4.4: Correlation Results for Wake Vertical Position in the Arrival Configuration Under In Ground Effect.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Vertical Position (m)</th>
<th>Aircraft Mass (kg)</th>
<th>EDR (m²/s³)</th>
<th>Wind (m/s)</th>
<th>Temperature (k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical Position</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Aircraft Mass</td>
<td>.84* p &lt; 0.001</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>EDR (m²/s³)</td>
<td>-.67* p &lt; 0.001</td>
<td>-.18* p = 0.028</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Wind (m/s)</td>
<td>.16* p = 0.094</td>
<td>.12 p = 0.091</td>
<td>-.09 p = 0.163</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Temperature (k)</td>
<td>.07 p = 0.214</td>
<td>.08 p = 0.194</td>
<td>-.03 p = 0.393</td>
<td>-.03 p = 0.381</td>
<td>-</td>
</tr>
</tbody>
</table>

*Correlation is significant at the .05 level

Figure 4.3: Wake Vertical Behavior for A380-Class Aircraft in the Arrival Configuration Under In Ground Effect.
4.6.1.2 Departures

The second set of correlations were performed using data on departure wake behaviors. Each correlation was evaluated at the .05 level. Each correlation is described below.

4.6.1.2.1 Wake Circulation Strength

Departure wake circulation strength was significantly positively correlated with aircraft mass \((r = .97, p < .001)\) and EDR \((r = -.25, p = .003)\). Wind was significantly correlated with temperature \((r = .21, p = .010)\). There was a near perfect correlation between aircraft mass and departure wake circulation strength, and a small correlation between circulation strength and EDR. Table 4.5 presents the results of these correlations. Wake behavior for departure presented in Figure 4.4 shows how greater atmospheric turbulence results in faster wake dissipation.

Table 4.5: Correlation Results for Circulation Strength in the Departure Configuration Under In Ground Effect.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Circulation Strength (m²/s)</th>
<th>Aircraft Mass (kg)</th>
<th>EDR (m²/s³)</th>
<th>Wind (m/s)</th>
<th>Temperature (k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circulation Strength (m²/s)</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aircraft Mass (kg)</td>
<td>.97* p &lt; 0.001</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EDR (m²/s³)</td>
<td>-.25* p = 0.003</td>
<td>-0.01 p = 0.442</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind (m/s)</td>
<td>-.07 p = 0.230</td>
<td>-.07 p = 0.215</td>
<td>.04 p = 0.323</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature (k)</td>
<td>-.03 p = 0.365</td>
<td>-.04 p = 0.336</td>
<td>.03 p = 0.378</td>
<td>.21* p = 0.010</td>
<td></td>
</tr>
</tbody>
</table>

*Correlation is significant at the .05 level
4.6.1.2.2 Wake Lateral Position

Departure wake lateral position was significantly positively correlated with wind ($r = 1.00, p < .001$) and temperature ($r = .21, p = .010$). There was a perfect correlation between wind and departure wake lateral position, and a small correlation between temperature and departure wake lateral position. Table 4.6 presents the results of these correlations. Figure 4.5 shows wake lateral behavior for departure under environmental turbulence, aircraft mass, temperature and wind variations.
Table 4.6: Correlation Results for Circulation Strength in the Departure Configuration Under In Ground Effect.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Lateral Position (m)</th>
<th>Aircraft Mass (kg)</th>
<th>EDR (m²/s³)</th>
<th>Wind (m/s)</th>
<th>Temperature (k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral Position (m)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Aircraft Mass (kg)</td>
<td>-.06 p = 0.269</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>EDR (m²/s³)</td>
<td>.04 p = 0.332</td>
<td>-.01 p = 0.442</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Wind (m/s)</td>
<td>1.00* p &lt; 0.001</td>
<td>-.07 p = 0.215</td>
<td>.04 p = 0.323</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Temperature (k)</td>
<td>.21* p = 0.010</td>
<td>-.04 p = 0.336</td>
<td>.03 p = 0.378</td>
<td>.21* p = 0.010</td>
<td>-</td>
</tr>
</tbody>
</table>

*Correlation is significant at the .05 level

Figure 4.5: Wake Lateral Behavior for A380-Class Aircraft in the Departure Configuration Under In Ground Effect.
4.6.1.2.3 Wake Vertical Position

Departure wake vertical position was significantly positively correlated with aircraft mass \( (r = .99, p < .001) \). This was a near perfect correlation. No other variables were significantly correlated with vertical position. Table 4.7 presents the results of these correlations.

Figure 4.6 shows wake vertical behavior for departure under environmental turbulence, aircraft mass, temperature and wind variations.

Table 4.7: Correlation Results for Circulation Strength in the Departure Configuration Under In Ground Effect.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Vertical Position (m)</th>
<th>Aircraft Mass (kg)</th>
<th>EDR ( (m^2/s^3) )</th>
<th>Wind (m/s)</th>
<th>Temperature (k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical Position (m)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Aircraft Mass (kg)</td>
<td>.99* ( p &lt; 0.001 )</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>EDR ( (m^2/s^3) )</td>
<td>-.13 ( p = 0.082 )</td>
<td>-.01 ( p = 0.442 )</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Wind (m/s)</td>
<td>-.08 ( p = 0.184 )</td>
<td>-.07 ( p = 0.215 )</td>
<td>.04 ( p = 0.323 )</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Temperature (k)</td>
<td>-.04 ( p = 0.352 )</td>
<td>-.04 ( p = 0.336 )</td>
<td>.03 ( p = 0.378 )</td>
<td>.21* ( p = 0.010 )</td>
<td>-</td>
</tr>
</tbody>
</table>

*Correlation is significant at the .05 level
Figure 4.6: Wake Vertical Behavior for A380-Class Aircraft in the Departure Configuration Under In Ground Effect.

4.6.2 Regression Analysis

To determine the predictive association between the independent variables of aircraft mass, EDR, crosswind, and temperature, and the dependent variables of circulation strength, lateral position, and vertical position wake behaviors, six multiple linear regressions were conducted. This is the appropriate analysis to perform when the research aim is to determine whether a series of continuous or categorical independent variables are significantly predictive of variability in a single continuous dependent variable (Tabachnick and Fidell 2013). The first set of multiple linear regressions were performed using arrival data, while the second was performed using departure data. The variables were entered into the model using the standard entry method, where all variables are entered at one step (Field 2013). The significance of the F statistic is used to evaluate the overall model, while the significance of the t statistic is used to evaluate each predictor. The unstandardized beta (B) may be used to interpret the predicted value of the dependent variable based on the independent variable (Tabachnick and Fidell 2013).
Before each analysis, the assumptions of the multiple linear regression, including normality, homoscedasticity, and absence of multicollinearity, were assessed. Normality was assessed through a normal P-P plot. If the plot shows data points that generally follow the diagonal normality line, the assumption is met (Tabachnick and Fidell 2013). Homoscedasticity was assessed through a scatterplot of the residuals. If the plot shows data points approximately equally distributed about zero, with no obvious cone-shaped pattern, the assumption is met (Tabachnick and Fidell 2013). The absence of multicollinearity was assessed through variance inflation factor (VIF) values. The assumption is met if VIF values are below 5.00 (Tabachnick and Fidell 2013).

4.6.2.1 Arrivals

4.6.2.1.1 Circulation Strength

First, the assumptions of the analysis were examined. A normal P-P plot (see Figure 4.7) showed data that generally followed the normality line, indicating that the assumption of normality was met. A scatterplot of the residuals (see Figure 4.8) showed no obvious pattern, with points generally randomly distributed about zero, indicating that the assumption of homoscedasticity was met. VIF values were below 5.00 (see Table 4.9), indicating that the assumption of absence of multicollinearity was met.

Figure 4.7: Normal P-P Plot for the Circulation Strength Regression. Dependent Variable Circulation Strength (m²/s).
Table 4.8: Normality Test Circulation Strength Arrival.

<table>
<thead>
<tr>
<th></th>
<th>Kolmogorov-Smirnov</th>
<th>Shapiro-Wilk</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Statistic</td>
<td>df</td>
</tr>
<tr>
<td>Circulation Strength (m²/s)</td>
<td>0.058</td>
<td>120</td>
</tr>
</tbody>
</table>

Figure 4.8: Scatterplot of the Residuals for the Regression Involving Circulation Strength.

Table 4.8 present results for normality test results where if p-value is less than or equal to alpha then data does not follow a normal distribution. In this results p-value is greater than alpha.

The results of the overall regression model involving arrival circulation strength were significant, $F(4, 115) = 1871.05$, $p < .001$, $R^2 = .98$. This indicates that the combination of independent variables significantly predicts up to 98% of the variability in arrival circulation strength. As the overall model was significant, the individual bivariate relationships were examined.

Examination of the individual predictors indicated that aircraft mass and EDR were significantly predictive of arrival circulation strength. For every one unit increase in aircraft mass, the model predicts a less than 0.00 unit increase in circulation strength. For every one unit increase in EDR, the model predicts a 2775.61 unit decrease in circulation strength. The full results of this analysis are presented in Table 4.9.
Table 4.9: Regression Results with Dependent Variable of Circulation Strength.

<table>
<thead>
<tr>
<th>Variable</th>
<th>B</th>
<th>SE</th>
<th>β</th>
<th>t</th>
<th>P</th>
<th>VIF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aircraft Mass (kg)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>14.57</td>
<td>&lt; .001</td>
<td>1.05</td>
</tr>
<tr>
<td>EDR (m²/s³)</td>
<td>-2775.61</td>
<td>44.37</td>
<td>-0.73</td>
<td>-62.56</td>
<td>&lt; .001</td>
<td>1.04</td>
</tr>
<tr>
<td>Wind (m/s)</td>
<td>0.02</td>
<td>0.03</td>
<td>0.01</td>
<td>0.56</td>
<td>.574</td>
<td>1.02</td>
</tr>
<tr>
<td>Temperature (k)</td>
<td>-0.00</td>
<td>0.01</td>
<td>-0.00</td>
<td>-0.25</td>
<td>.807</td>
<td>1.01</td>
</tr>
</tbody>
</table>

4.6.2.1.2 Wake Lateral Position

The assumptions of the analysis were examined. A normal P-P plot showed data that generally followed the normality line, indicating that the assumption of normality was met. A scatterplot of the residuals showed a cone-shaped pattern, indicating that clear heteroscedasticity was present. Some literature (Stevens 2009, Howell 2010, Tabachnick and Fidell 2013) indicate that when sample sizes are large (i.e., >50), the F statistic is robust to violations of assumptions. The results may be interpreted with caution. VIF values were below 5.00 (see Table 4.10), indicating that the assumption of absence of multicollinearity was met.

The results of the overall regression model involving wake lateral position were significant, F(4, 115) = 10586349.70, p < .001, R² = 1.00. This indicates that the combination of independent variables significantly predicts 100% of the variability in arrival circulation strength. As the overall model was significant, the individual bivariate relationships were examined.

Aircraft mass, EDR, and wind were significantly predictive of lateral position. For every one unit increase in aircraft mass, the model predicts a less than 0.00 unit increase in lateral position. For every one unit increase in EDR, the model predicts a 142.32 unit decrease in the lateral position. For every one unit increase in wind, the model predicts a 60.03 unit increase in lateral position. The full results of this analysis are presented in Table 4.10.

Table 4.10: Regression Results with Dependent Variable of Wake Lateral Position.

<table>
<thead>
<tr>
<th>Variable</th>
<th>B</th>
<th>SE</th>
<th>B</th>
<th>t</th>
<th>P</th>
<th>VIF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aircraft Mass (kg)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>14.57</td>
<td>&lt; .001</td>
<td>1.05</td>
</tr>
<tr>
<td>EDR (m²/s³)</td>
<td>-142.32</td>
<td>12.66</td>
<td>-0.00</td>
<td>-11.24</td>
<td>&lt; .001</td>
<td>1.04</td>
</tr>
<tr>
<td>Wind (m/s)</td>
<td>60.03</td>
<td>0.01</td>
<td>1.00</td>
<td>6434.44</td>
<td>&lt; .001</td>
<td>1.02</td>
</tr>
<tr>
<td>Temperature (k)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.43</td>
<td>.669</td>
<td>1.01</td>
</tr>
</tbody>
</table>
4.6.2.1.3 Wake Vertical Position

The assumptions of the analysis were examined. A normal P-P plot showed data that followed the normality line, indicating that the assumption of normality was met. A scatterplot of the residuals showed an irregular pattern, indicating that some heteroscedasticity was present. However, (Stevens 2009) and (Howell 2010) indicate that when sample sizes are large (i.e., >50), the F statistic is robust to violations of assumptions, especially when the violation is minor. VIF values were below 5.00, indicating that the assumption of absence of multicollinearity was met.

The results of the overall regression model involving wake vertical position were significant, F(4, 115) = 1439.05, p < .001, R² = .98. This indicates that the combination of independent variables significantly predicts 98% of the variability in wake vertical position. As the overall model was significant, the individual bivariate relationships were examined.

The full results of this analysis are presented in Table 4.11

Table 4.11: Regression Results with Dependent Variable of Wake Lateral Position.

<table>
<thead>
<tr>
<th>Variable</th>
<th>B</th>
<th>SE</th>
<th>β</th>
<th>t</th>
<th>p</th>
<th>VIF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aircraft Mass (kg)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.74</td>
<td>55.56</td>
<td>&lt; .001</td>
<td>1.05</td>
</tr>
<tr>
<td>EDR (m²/s³)</td>
<td>-81.99</td>
<td>2.04</td>
<td>-0.53</td>
<td>-40.13</td>
<td>&lt; .001</td>
<td>1.04</td>
</tr>
<tr>
<td>Wind (m/s)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.02</td>
<td>1.32</td>
<td>.190</td>
<td>1.02</td>
</tr>
<tr>
<td>Temperature (ºk)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.08</td>
<td>.933</td>
<td>1.00</td>
</tr>
</tbody>
</table>

4.6.2.2 Departures

4.6.2.2.1 Circulation Strength

First, the assumptions of the analysis were examined. A normal P-P plot (see Figure 4.9) showed data that closely followed the normality line, indicating that the assumption of normality was met. A scatterplot of the residuals (see Figure 4.10) showed no obvious cone-shaped pattern, indicating that the assumption of homoscedasticity was met. VIF values were below 5.00 (see Table 4.13), indicating that the assumption of absence of multicollinearity was met.
Figure 4.9: Normal P-P Plot for the Circulation Strength Regression. Dependent Variable Circulation Strength (m²/s).

If the p-value is smaller or equal than alpha of 0.05 then data does not follow a normal distribution and as seen on Table 4.12 this is not the case with circulation strength for departure.

Table 4.12: Normality Test Circulation Strength Departure.

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Kolmogorov-Smirnov</th>
<th>Shapiro-Wilk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circulation Strength (m²/s)</td>
<td>0.079</td>
<td>0.062</td>
</tr>
<tr>
<td>Circulation Strength (m²/s)</td>
<td>0.079</td>
<td>0.062</td>
</tr>
</tbody>
</table>
The results of the overall regression model involving departure circulation strength were significant, \( F(4, 115) = 5149.96, p < .001, R^2 = .99 \). This indicates that the combination of independent variables significantly predicts up to 99% of the variability in departure circulation strength. As the overall model was significant, the individual bivariate relationships were examined.

Examination of the individual predictors indicated that aircraft mass and EDR were significantly predictive of arrival wake behavior. The model predicts a less than 0.00 unit increase in circulation strength for every one unit increase in aircraft mass. The model predicts a 2398.12 unit decrease in circulation strength for every one unit increase in EDR. The full results of this analysis are presented in Table 4.13.

Table 4.13: Regression Results with Dependent Variable of Circulation Strength.

<table>
<thead>
<tr>
<th>Variable</th>
<th>B</th>
<th>SE</th>
<th>( \beta )</th>
<th>( t )</th>
<th>( P )</th>
<th>VIF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aircraft Mass (kg)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.97</td>
<td>138.58</td>
<td>&lt; .001</td>
<td>1.01</td>
</tr>
<tr>
<td>EDR (m²/s³)</td>
<td>-2398.12</td>
<td>69.40</td>
<td>-0.24</td>
<td>-34.66</td>
<td>&lt; .001</td>
<td>1.00</td>
</tr>
<tr>
<td>Wind (m/s)</td>
<td>0.07</td>
<td>0.05</td>
<td>0.01</td>
<td>1.41</td>
<td>.162</td>
<td>1.05</td>
</tr>
<tr>
<td>Temperature (k)</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>1.50</td>
<td>.138</td>
<td>1.05</td>
</tr>
</tbody>
</table>

4.6.2.2 Wake Lateral Position

The assumptions of the analysis were examined. A normal P-P plot showed data that generally followed the normality line, indicating that the assumption of normality was met. A scatterplot of the
residuals showed a cone-shaped pattern, indicating that some heteroscedasticity was present. Some experts (Stevens 2009, Howell 2010) indicate that when sample sizes are large (i.e., >50), the F statistic is relatively robust to violations of assumptions. The results may be interpreted with caution. VIF values were below 5.00 (see Table 4.14), indicating that the assumption of absence of multicollinearity was met.

The results of the overall regression model involving wake lateral position were significant, F(4, 115) = 10586349.70, p < .001, R² = 1.00. This indicates that the combination of independent variables significantly predicts 100% of the variability in arrival circulation strength. As the overall model was significant, the individual bivariate relationships were examined.

Aircraft mass, EDR, and wind were significantly predictive of lateral position. The model predicts a less than 0.00 unit increase in the lateral position for every one unit increase in aircraft mass. For every one unit increase in EDR, the model predicts a 188.54 unit decrease in the lateral position. The model predicts a 59.99 unit increase in the lateral position for every one unit increase in wind. The full results of this analysis are presented in Table 4.14.

Table 4.14: Regression Results with Dependent Variable of Wake Lateral Position.

<table>
<thead>
<tr>
<th>Variable</th>
<th>B</th>
<th>SE</th>
<th>B</th>
<th>t</th>
<th>P</th>
<th>VIF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aircraft Mass (kg)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.02</td>
<td>67.44</td>
<td>&lt; .001</td>
<td>1.01</td>
</tr>
<tr>
<td>EDR (m²/s³)</td>
<td>-188.54</td>
<td>20.32</td>
<td>-0.00</td>
<td>-9.28</td>
<td>&lt; .001</td>
<td>1.01</td>
</tr>
<tr>
<td>Wind (m/s)</td>
<td>59.99</td>
<td>0.02</td>
<td>1.00</td>
<td>4126.41</td>
<td>&lt; .001</td>
<td>1.06</td>
</tr>
<tr>
<td>Temperature (k)</td>
<td>-0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>-0.40</td>
<td>.691</td>
<td>1.05</td>
</tr>
</tbody>
</table>

4.6.2.2.3 Wake Vertical Position

The assumptions of the analysis were examined. A normal P-P plot showed data that followed the normality line, indicating that the assumption of normality was met. A scatterplot of the residuals showed an irregular pattern, indicating that clear heteroscedasticity was present. However, (Stevens 2009) and (Howell 2013) indicate that when sample sizes are large (i.e., >50), the F statistic is robust to violations of assumptions. The results should be interpreted with caution. VIF values were below 5.00 (see Table 4.15), indicating that the assumption of absence of multicollinearity was met.

The results of the overall regression model involving wake vertical position were significant, F(4, 115) = 1439.05, p < .001, R² = .98. This indicates that the combination of independent variables significantly predicts 98% of the variability in wake vertical position. As the overall model was significant, the individual bivariate relationships were examined.
Aircraft mass and EDR were significantly predictive of vertical position. For every one unit increase in aircraft mass, the model predicts a less than 0.00 unit increase in vertical position. For every one unit increase in EDR, the model predicts a 79.37 unit decrease in vertical position. The full results of this analysis are presented in Table 4.15.

Table 4.15: Regression Results with Dependent Variable of Wake Vertical Position.

<table>
<thead>
<tr>
<th>Variable</th>
<th>B</th>
<th>SE</th>
<th>β</th>
<th>t</th>
<th>P</th>
<th>VIF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aircraft Mass (kg)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.99</td>
<td>148.46</td>
<td>&lt; .001</td>
<td>1.01</td>
</tr>
<tr>
<td>EDR (m²/s³)</td>
<td>-79.37</td>
<td>4.62</td>
<td>-0.11</td>
<td>-17.17</td>
<td>&lt; .001</td>
<td>1.00</td>
</tr>
<tr>
<td>Wind (m/s)</td>
<td>-0.00</td>
<td>0.00</td>
<td>-0.01</td>
<td>-1.18</td>
<td>.239</td>
<td>1.05</td>
</tr>
<tr>
<td>Temperature (k)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.01</td>
<td>1.27</td>
<td>.208</td>
<td>1.05</td>
</tr>
</tbody>
</table>

4.7 Results Summary

This research conducted a statistical analysis of wake vortex circulation strength, lateral behavior, and vertical behavior. Results show that arrival wake circulation strength is strongly and positively correlated with aircraft mass and strongly and negatively correlated with EDR. Regression analyses indicated that increases in aircraft mass predict a negligible increase in circulation strength, and EDR predicts a decrease in circulation strength. Similarly, for departures, wake circulation strength is strongly and positively correlated with aircraft mass. However, it is only weakly and negatively correlated with EDR.

Arrival wake lateral position showed a perfect correlation with the wind, with no other significant correlations. However, the regression analysis indicated that increases in aircraft mass predict a negligible increase in arrival wake lateral position, EDR predicts decreases, and wind predicts increases. Results for departure data indicated that lateral position is perfectly correlated with wind and has a small, positive correlation with temperature. Regression results indicated that aircraft mass predicts a negligible increase in lateral position, that EDR predicts a decrease, and that wind predicts an increase. However, these results should be treated with caution due to violations of the homoscedasticity assumption.

For wake vertical position, results indicated that arrival wake vertical movement is strong, positively correlated with aircraft mass; strongly, negatively correlated with EDR; and weakly, positively correlated with wind. The regression indicated that aircraft mass predicts a negligible increase in vertical position, while EDR predicts a decrease in vertical position. Correlational results
from departure data indicated that departure wake vertical position is strongly correlated with aircraft mass and no other variable. However, a regression indicated that increases in aircraft mass predict a small increase in vertical position and that EDR predicts a decrease. However, due to violations of the homoscedasticity assumption, these results should be treated with caution.

### 4.8 Conclusion and Recommendations

This research simulated aircraft operations during arrival and departure as well as the environmental conditions in the aircraft flight path to understanding wake circulation strength, lateral and vertical behavior, and the interaction with environmental conditions, all to reduce wake vortex separations.

One of the major constraints of dynamic wake separation at airports is its dependence on real-time or near-real-time data collection and broadcasting technologies. These technologies would need to measure and report temperature, environmental turbulence, wind speed, and aircraft weight, wingspan, altitude, and speed. This data collection process will create databases for conditions and frequencies that could be used in future wake behavior research and reduce the uncertainty of some parameters, such as typical values of turbulence, especially at low altitudes and at busy airports.

Another major limitation to wake vortex mitigation is the lack of data collection of environmental turbulence and other environmental parameters (Perras, Dasey et al. 2000).

Future research could focus on simulating events based on values of EDR and aircraft weight and aircraft altitudes collected in the field to produce results that better emulate current flight operations. It could also create more simulation iterations of these parameters to produce more realistic scenarios for conditions that this research has shown to have the greatest influence on wake behavior.

The results from the recommended work could aid the assessment of the value of dynamic separations as a wake mitigation concept.

### 4.9 Acknowledgments

This research has been made possible thanks to the research contributions of the Federal Aviation Administration Wake Program, National Aeronautics and Space Administration (NASA) wake program, EUROCONTROL, Japan Aerospace Exploration Agency, Wakenet meeting members, MIT Lincoln Laboratory, and private industry research labs such as the MITRE Corporation.
4.10 Disclaimer

The contents of this material reflect the views of the author only. Neither the Federal Aviation Administration nor the United States Department of Transportation nor National Aeronautics and Space Administration makes any warranty or guarantee, or promise, expressed or implied, concerning the content or accuracy of the views expressed herein.

Any opinion, findings, and conclusion or recommendations presented herein are those of the author and do not necessarily reflect the views of the FAA or NASA.

4.11 References


5. Monte Carlo Simulation of Aircraft Operations and Environmental Conditions to Derive Maximum Circulation Capacity and Reduce In-Trail Wake Separations

5.1 Abstract

As demand approaches capacity at main hub airports, research efforts have focused on safely reducing current wake separations, which are considered a bottleneck in the effort to increase the capacity of the runway system. This research uses Monte Carlo simulations to demonstrate and quantify the potential for wake separation reductions based on discrete scenarios comprising environmental conditions, aircraft-dependent parameters, and aircraft operational capabilities. Maximum circulation capacities have been calculated based on the Federal Aviation Administration’s (FAA) proposed wake Recategorization phase II (RECAT II) 123 x 123 matrix, approach speeds have been derived from Airport Surface Detection Equipment Model X (ASDX) data, and dynamic wake separations have been calculated based on simulated conditions.

Results show that separation reductions can be obtained for aircraft such as the C750 and E170, corresponding to groups E and F in RECAT I. In RECAT III, wake time separations could be reduced by 35 seconds below RECAT II and 50 seconds below RECAT I. For all other aircraft under study, the maximum reduction in wake vortex separation is 25 seconds below proposed FAA RECAT II separations and a median of 12 seconds below FAA RECAT II.

5.2 Introduction

An aircraft in motion creates an invisible movement of air called wake turbulence, which has been shown to be dangerous to aircraft that encounter it. To avoid wake encounters, aircraft separations were developed in the 1970s, based on the technology available at that time, that allows time for wake to be dissipated and displaced from an aircraft’s path. Though there have been revisions to wake separations, they remain static.
The air transportation industry has experienced slow but continuous growth in the last 25 years. As demand approaches capacity at main hub airports, delays increase rapidly in a nonlinear relationship. With current wake separations, the capacity of the runway system remains the bottleneck in U.S. airport capacity.

Since the early 2000s, the National Aeronautics and Space Administration (NASA) Langley Research Center, in conjunction with the Federal Aviation Administration (FAA) and industry partners, has been developing systems and technologies that provide real-time observations and predictions of wake turbulence behaviors (Rutishauser 2003). The research presented in this paper uses a fast-time wake transport and decay model called NASA’s Aircraft Vortex Spacing System (AVOSS) Terminal Area Simulation System (TASS) Driven Algorithm for Wake Prediction (TDAWP), in conjunction with Monte Carlo simulation. Wake models are used to calculate the circulation capacity that each aircraft under study can endure, derive dynamic separations, and enhance the capacity of the airport system.

The dynamic wake mitigation concept proposes to discretize current wake aircraft groups by analyzing characteristics for each pair of leading and follower aircraft as well as the environment where the aircraft travel. Monte Carlo simulations with the NASA wake model were conducted to define wake hazard bounds behind the wake generator aircraft. The TDAWP model is an empirical algorithm used for real-time predictions and is based on atmospheric conditions and aircraft parameters (Cornman 2016).

5.3 Objective

The objective of this research is to develop a methodology and calculate aircraft maximum circulation capacities that could be used in dynamic separations. This study simulates aircraft operations during arrival, identify the wake capacity for the critical offender of each RECAT I group based on the maximum take-off weight (MTOW), derive dynamic wake separations, and compare dynamic separations to static separations based on RECAT I and RECAT II. This research informs the study of the possible replacement of current, static wake separations with dynamic wake separations based on a wider set of wake-related parameters.

This research aims to demonstrate and quantify the potential for wake separation reduction based on discrete scenarios comprising environmental conditions, aircraft-dependent parameters, and aircraft operational capabilities. These factors are part of the design and execution of flight simulation
experiments that generate probability density functions, calculate the maximum circulation capacity, and will lead to dynamic wake separations for each critical aircraft in the RECAT I group.

A previous research effort conducted by the National Center of Excellence for Aviation Operators (NEXTOR) universities studied and identified several promising wake mitigation concepts: wake mitigation for arrivals and departures, aircraft wake measuring and reporting for separation, simultaneous offset instrument approach (SOIA), and dynamic wake mitigation (Merryfield 2016).

This research studies dynamic wake mitigation, also known as wake Recategorization III (RECAT III), with the goal of understanding the possibility of dynamic pairwise separations that rely on environmental conditions and aircraft parameters.

5.4 Methodology

The methodology to identify the current wake capacity for each aircraft category is based on Monte Carlo constructive simulation and cumulative distribution function. This method accounts for the randomness and uncertainty of the internal factors, such as aircraft characteristics and performance, and external factors, such as environmental conditions during wake generation.

This experiment accounts for the uncertainties of environmental factors such as air density, temperature, Brunt-Väisälä frequency, cross-flow velocity, and environmental turbulence, as well as aircraft-dependent factors such as weight, speed, wingspan, and altitude.

According to previous simulation results, the greatest potential for dynamic separations will be for the leading aircraft requiring the greatest separation. These greatest offenders require large trailing separations, which in some cases are greater than typical values for runway occupancy times.

In this research, the selected greatest aircraft offenders for each RECAT I group are those that are frequently operated aircraft and have high MTOW. Manufacturer specifications are used to determine individual aircraft intrinsic characteristics such as wingspan, MTOW, and maximum allowable landing weight (MALW).

There is no publicly known wake hazard boundary for each aircraft group nor each aircraft. Without such a metric, it is impossible to determine whether a wake mitigation concept produces an acceptable reduction of wake separation. As a result, this research uses unpublished RECAT II (2017) wake separations to calculate a maximum wake circulation capacity for each aircraft group.
As identified in previous research, wake behavior is highly correlated with aircraft weight as well as environmental turbulence, eddy dissipation rate (EDR). This study’s Monte Carlo simulation includes 36,000 iterations of the weight and EDR parameters.

Environmental turbulence values considered for this analysis range from very weak to strong (Proctor, Hamilton et al. 2006) (Switzer and Proctor 2000). The aircraft weight distribution for operating aircraft used in the simulation is based on real airline data; however, for confidentiality reasons, this study does not present these values.

This study considers flights to be in the lower airspace, and subject to the in-ground-effect, when flying below the altitude of three times the aircraft wingspan (Hoogstraten, Visser et al. 2014). The Monte Carlo simulation represents both phases of flight in the terminal area: departing and arriving aircraft operations.

5.5 Monte Carlo Simulation of Wake Vortex Behavior

This research applied a Monte Carlo simulation approach, in conjunction with the NASA AVOSS TDAWP 2.1 model, to derive thousands of combinations of the wake behavior parameters. Typical NASA evaluations of fast-time models using field data measured with light detection and ranging (LIDAR) demonstrated the TDAWP model to be more accurate than other wake behavior models (Ahmad, VanValkenburg et al. 2016). First, aircraft input parameters such as an identifier (ID), wingspan, MTOW, MALW, and performance characteristics are loaded into the simulation. Second, the desired environmental conditions for each run are defined: Brunt-Väisälä frequency, air density, temperature, cross-flow velocity, and environmental turbulence.

5.5.1 Algorithm

To quantify individual cumulative distribution function profiles, the model quantifies individual aircraft performance characteristics including MTOW, MALW, wingspan, and aircraft speed profiles for climb and descent, according to BADA 3.11. The fleet representing all aircraft groups was analyzed by running the NASA model and generating wake behavior data. For each set of initial conditions, results include a series of 240 values for time (s), circulation strength left and right (m²/s), lateral position left and right (m) and vertical position left and right (m). The described wake vortex behavior is generated for each aircraft under different parameters, see Figure 5.1.
Figure 5.1: Wake Simulation Flow Diagram.
The aircraft-dependent parameters include the initial values of vortex descent velocity \((V_0)\), vortex pair separation distance \((b_0)\), and position of the aircraft. The initial atmospheric conditions include vertical profiles of either temperature or potential temperature \((\theta)\), EDR \((\varepsilon)\), and crosswind \((u)\) (Ahmad, VanValkenburg et al. 2016).

Model input depends on the initial vortex descent rate \((V_0)\), as well as on aircraft parameters of location such as latitude, longitude, and altitude along the flight path. The initial vortex descent rate is estimated from the aircraft weight, aircraft speed, air density, and the initial vortex separation \(b_0\):

\[
V_0 = \frac{\Gamma_\infty}{2\pi b_0}\tag{1}
\]

\[
V_0 = \frac{W_G}{2\pi \rho V_G b_0^2}\tag{2}
\]

Where \(\rho\) is the air density, \(V_G\) is the generator true-airspeed, and \(W_G\) is the generator weight. The initial separation distance between the vortices \(b_0\) is

\[
b_0 = \frac{\pi B_G}{4}\tag{3}
\]

where \(b_G\) is the wingspan of the generator (Robins and Delisi 2002).

The model uses base of aircraft data (BADA) for modeling aircraft trajectory regarding speed at each altitude as well as service ceiling for each aircraft. The experiment assumes constant values for EDR, Brunt-Väisälä frequency, and crosswind speed over the entire space of flight tracks.

\(V_0\), the initial descent speed of wake vortex for commercial aircraft, ranges between 1 to 2 m/s. Measurements have shown, under favorable displacing conditions, wake vortex vertical descents greater than 600 m (Holzapfel and Gerz 2012).

The simulation includes distribution of current operation landing and departing weights for the critical aircraft under study; see Table 5.1 for sample values.
Table 5.1: Sample Airbus A380-Class Aircraft APA Input File.

<table>
<thead>
<tr>
<th>Altitude (m)</th>
<th>Ground Speed (knots)</th>
<th>Aircraft Mass (kg)</th>
<th>$V_{\text{Initial}}$ (m/s)</th>
<th>EDR Value (m$^2$/s$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>106.6800</td>
<td>78.6420</td>
<td>3.6012e+05</td>
<td>1.4805</td>
<td>0.0030</td>
</tr>
<tr>
<td>106.6800</td>
<td>78.6420</td>
<td>3.6038e+05</td>
<td>1.4815</td>
<td>0.0030</td>
</tr>
<tr>
<td>106.6800</td>
<td>78.6420</td>
<td>3.6064e+05</td>
<td>1.4826</td>
<td>0.0030</td>
</tr>
<tr>
<td>106.6800</td>
<td>78.6420</td>
<td>3.6090e+05</td>
<td>1.4837</td>
<td>0.0030</td>
</tr>
</tbody>
</table>

5.5.2 Simulation Conditions

The number of simulation runs executed is between 50,000 and 60,000 aircraft operations for each aircraft studied. The average total number of operations during the year 2016 at La Guardia Airport was 186,096 operations. This is equal to 7,754 operations per runway per month according to Aviation System Performance Data (ASPM).

The aircraft selected for this simulation represents the critical aircraft for each category based on RECAT I. Table 5.2 presents the aircraft code for those aircraft that were selected for this research as well as the number of times these aircraft were operated during a typical day for the year 2014.

Table 5.2: Number of Operations for Aircraft Under Study.

<table>
<thead>
<tr>
<th>RECAT I Group</th>
<th>Aircraft Code</th>
<th>Frequency/Week</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>A380</td>
<td>679</td>
</tr>
<tr>
<td>B</td>
<td>B744</td>
<td>4,765</td>
</tr>
<tr>
<td>C</td>
<td>MD11</td>
<td>2,769</td>
</tr>
<tr>
<td>D</td>
<td>B757</td>
<td>1,647</td>
</tr>
<tr>
<td>E</td>
<td>E170</td>
<td>15,310</td>
</tr>
<tr>
<td>F</td>
<td>C750</td>
<td>7,340</td>
</tr>
</tbody>
</table>


Environmental turbulence is a key parameter to predicting wake behavior. Different EDRs represent different levels of ambient turbulence intensity. Several studies have captured and presented values of environmental turbulence during aircraft operations. Some of their results are presented below.

The investigation of the crash of American Airlines flight 587, which was induced by a wake vortex encounter, constructed an environmental turbulence profile based on the aircraft’s vertical acceleration. This research calculated that the EDR profile below 400 m (1,310 ft) indicated light
turbulence with values typical for an atmospheric boundary layer. Above the atmospheric boundary layer (altitudes greater than 400 m), the magnitude of turbulence quickly diminished to very weak intensities. Between altitudes of 535-900 m (1,750-2,950 ft), specific values for EDR ranged between 2x10^{-6} m^2/s^3 to 5x10^{-5} m^2/s^3 with an average of about 2.5x10^{-5} m^2/s^3. These very weak turbulence intensities, coupled with modest thermal stratification, imply long lifetimes for wake vortices resident in this layer (Proctor, Hamilton et al. 2004).

Another study of EDR values during airport operations is the climatology study performed by NASA and MIT Lincoln Lab at Dallas/Ft. Worth International Airport (DFW). This study showed that turbulence varies slightly during different times of the year as well as during different times of the day. This study presents a distribution of EDR exceedance measured for 40 m and 5 m above ground level. The exceedance probability is defined as the probability that the EDR will exceed a given value.

The data collected for the distribution was measured at 40 m and 5m from the ground. However, as expected, the 5-m data was heavily affected by the in-ground-effect. This is because the decay near the ground is not as strongly related to turbulence levels as it is to the destructive influence of ground friction (Perras, Dasey et al. 2000).

The altitude chosen for this simulation is 40 m, which is in accordance with the altitude at which the values of EDR used in the simulation were collected in real-life experiments. Values considered for the simulation range between moderate 1.35x10^{-3} m^2/s^3 to strong 1.50x10^{-2} m^2/s^3, with 80 percent of the values in the range moderate 1.35 x10^{-3} m^2/s^3 to strong 7.17x10^{-3} m^2/s^3.

The aircraft weight used in this simulation for each aircraft under study defines the initial circulation strength of the wake vortex. These weights are in accordance to real data collected for aircraft in the same RECAT I group.

5.6 Data Analysis and Results

5.6.1 Calculation of Maximum Circulation Capacity

Aircraft wake capacity is derived from the near-worst-case wake vortex circulation strength and decay curve, in which the 95% confidence interval is used to represent the wake circulation strength behind a leading aircraft (Tittsworth, Cheng et al. 2016).

NASA initially developed wake separations in 1970 and adjusted in the 1980s and 1990s (U.S., 1995). Aircraft separation categories were created by grouping all operating aircraft into four
categories. The main criteria for aircraft grouping were aircraft MTOW and wingspan. When aircraft approach a runway, the final segment length between the final approach fix and the runway threshold varies as a function of the common approach length. Airport Surface Detection System Model X (ASDE-X) is a technology that allows controllers to track movement at and around the airport. It merges the data of surface radar, multilateration sensors, airport surveillance radar, automatic dependent surveillance, and the terminal automation system to determine the position of and identify aircraft on final approach as well as in the airport surface (FAA 2014). Figure 5.2 shows the approach speed profile for the Boeing 747-400-class aircraft, according to real operation records.

Aircraft approach speed is needed to translate static RECAT II separations into dynamic separations based on the aircraft maximum circulation capacity. Using the ASDE-X data, the following data parameters were extracted in previous research work: (1) lift-off velocity on departure, (2) runway-threshold-crossing velocity on arrival, and (3) straight-line distance traveled from the runway threshold to the exit taxiway on arrival (Spencer 2016). Table 5.3 presents the resulting arrival approach ground speed for aircraft as determined with ASDE-X data. The relationship between approach speed and aircraft mass is presented in formulas (4) and (5).

Figure 5.2: B744 Approach Speed on Landing Profile.
Table 5.3: Approach Speeds of Follower Aircraft.

<table>
<thead>
<tr>
<th>Aircraft Code</th>
<th>Approach Speed (knots)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A380</td>
<td>148</td>
</tr>
<tr>
<td>B744</td>
<td>154</td>
</tr>
<tr>
<td>MD11</td>
<td>155</td>
</tr>
<tr>
<td>B757</td>
<td>142</td>
</tr>
<tr>
<td>E170</td>
<td>124</td>
</tr>
<tr>
<td>C750</td>
<td>125</td>
</tr>
</tbody>
</table>

*(ASDE-X 2015)*

\[
L = mg = \frac{1}{2} \rho V^2 SC_L
\]  

(4)

\[
V_{app} = \frac{2mg}{\rho SC_{L, approach}}
\]  

(5)

The derivation of circulation capacity is tied to airport operations and depends on current aircraft separation regulations as the baseline as well as on proposed RECAT II separations. These separations have proven to be safe over decades (Tittsworth, Cheng et al. 2016). They also determine the baseline for relative analyses of the safety of in-trail separation. Figure 5.3 presents the circulation strength curves for an A380-class aircraft from which circulation capacities were calculated based on proposed RECAT II separations and a 95% confidence profile. ASDE-X speed profiles for the critical follower aircraft for arrivals, and RECAT II separations.

Figure 5.3: Wake Vortex Circulation Strength Curves for A380-Class Aircraft Under 36,000 Different Dynamic Conditions.
Consistent with prior categorization efforts, those aircraft with greater MTOW and wingspan, such as the Airbus A380-class aircraft, can produce and withstand stronger wake turbulence.

One of the objectives of this study was to produce circulation strength values at various confidence levels. We selected confidence levels of 95%, 99%, and 100% to show that there is not a significant difference in values of circulation strength, except for separation times behind an A380-class aircraft greater than 180 seconds, as can be seen in Figure 5.4. The conditions for these runs are wind fixed at zero and variations of aircraft speed, mass, and EDR using NASA APA 4.5.3, with approximately 60,000 simulations.

![Figure 5.4: Circulation as a Function of Time with Confidence Levels 95%, 99%, and 100% for A380-Class Aircraft.](image)

For the simulation results shown in Figure 5.5, the 95th percentile confidence curve was selected as the foundation for circulation capacity derivation. This decision was based on current research on the topic and it allowed the use of circulation strength threshold values to derive RECAT III capacity benefits (Tittsworth, Cheng et al. 2016).

### 5.6.2 Derivation of Maximum Circulation Capacity

The 100% envelope in shows that for all Monte Carlo simulations, circulation strength at any given time will fall below this curve. The purpose of the analysis was to use circulation strength, and FAA
approved wake separations as the basis to establish credible separations beyond RECAT II. Maximum circulation capacities were calculated for each aircraft under study, to establish aircraft separations.

This research derived aircraft wake capacity from the near-worst-case wake vortex circulation strength and decay curve results are shown in Table 5.4. A 95% confidence interval, as shown in Figure 5.5, was used to represent the wake circulation strength behind an aircraft, as is consistent with current research efforts by the FAA (Tittsworth, Cheng et al. 2016).

![Wake Vortex Circulation Graph]

Figure 5.5: 95% Confidence Interval for Departure Using Current Separation and the WCC for Maximum circulation capacity (MCC) under arrival conditions for each aircraft under study was calculated to determine time separation under dynamic conditions. These results are presented in Table 5.4.

Using the maximum circulation capacity presented in Table 5.4, dynamic separations were calculated for simulation scenarios under different environmental and aircraft-dependent conditions, bounded by constraints explained in the Methodology section. The static separations in Table 5.4 represent the proposed wake separations for RECAT II. The difference in time between the dynamic separation and static separation for any given operation represents potential saved time.
Table 5.4: Maximum Circulation Capacity for RECAT II Behind A380-Class Aircraft for the Six Critical Aircraft.

<table>
<thead>
<tr>
<th>Aircraft Group</th>
<th>Aircraft Code</th>
<th>RECAT I Static Time-Based Separation (s)</th>
<th>RECAT II Static Time-Based Separation (s)</th>
<th>MCC for RECAT II (m²/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>A380</td>
<td>61</td>
<td>61 (2.5nm)</td>
<td>417</td>
</tr>
<tr>
<td>B</td>
<td>B744</td>
<td>117</td>
<td>89 (3.8nm)</td>
<td>352</td>
</tr>
<tr>
<td>C</td>
<td>B763</td>
<td>149</td>
<td>120 (5.2nm)</td>
<td>300</td>
</tr>
<tr>
<td>D</td>
<td>B752</td>
<td>177</td>
<td>150 (5.9nm)</td>
<td>261</td>
</tr>
<tr>
<td>E</td>
<td>E170</td>
<td>203</td>
<td>183 (6.3nm)</td>
<td>227</td>
</tr>
<tr>
<td>F</td>
<td>C750</td>
<td>230</td>
<td>202 (7.0nm)</td>
<td>211</td>
</tr>
</tbody>
</table>

5.6.3 Calculation of Wake Dynamic Separations

The derivation of a circulation capacity allows the dynamic separation of aircraft based on real-time, aircraft-derived data and environmental conditions. This approach depends on technology to measure current environmental conditions at destination and origin airports, as well as aircraft operational data and characteristics such as aircraft ID, weight, and flap configuration. The result of this data integration would improve capacity based on dynamic, pairwise, wake vortex aircraft separations as well as reduce flying time and fossil fuel use.

Wake dynamic separations, the focus of RECAT III, are calculated based on the proposed RECAT II static separation and the maximum circulation capacity values calculated for each aircraft under study.

5.6.4 Analysis of Wake Separations Based on Dynamic RECAT III, Static RECAT II, and Static RECAT I

Figure 5.6 represents the minimum, maximum, and median values of wake vortex separations for aircraft following an Airbus 380-class aircraft, according to RECAT I, RECAT II, and Dynamic RECAT III. As expected, RECAT I static separations values are between 10 and 25 seconds greater than the proposed values for RECAT II. For big offenders, such as the A380-class aircraft, there is
no reduction in time between RECAT I and RECAT II, and these aircraft have the maximum time value under the dynamic conditions of RECAT III.

Further separation reductions can be obtained for aircraft such as the Cessna 750-class aircraft and Embraer 170-class aircraft, which correspond to groups E and F in RECAT I.

RECAT III wake time separations could be reduced 20 seconds below RECAT II and 35 seconds below RECAT I. For all other aircraft under study, the maximum reduction in wake vortex separation is 20 seconds below proposed and a median of 12 seconds below RECAT II.

As seen in Figure 5.6, there was more variability in time when wake vortex circulation was at 212 m²/s than when it was at 420 m²/s. At wake vortex circulation of 212 m²/s, the median was at approximately 180 seconds, while most of the data fell in the lowest 25%. The RECAT II point fell within the highest 25%, while RECAT I fell above the highest 25%. This trend continued in a decreasing pattern as wake vortex circulation values increased: RECAT II remained within the highest 25%, RECAT I remained above the highest 25%, and the median value also fell. When wake vortex circulation was at 420 m²/s, the RECAT II and RECAT I, points converge. This also represents the area of lowest variability, and the area of the lowest median, with a median of approximately 55 seconds.

![Figure 5.6: Wake Vortex Separations Based on RECAT I, RECAT II, and Dynamic RECAT III Following an A380-Class Aircraft Under Unrestricted Conditions.](image-url)
Figure 5.7 shows frequencies of time separations for each aircraft under study following an Airbus A380-class aircraft, under the dynamic conditions bounded by the parameters presented in the Methodology section. A normal distribution of wake separation values in time can be observed for MCC 263, MCC 289, MCC 355, and MCC 420. However, MCC 212 and MCC 229 are negatively skewed. A normal distribution is observed when the tails on each side of the distribution are approximately symmetrical (Field, 2013). A negatively skewed distribution is observed when the left tail of the distribution is bigger and trails out farther than the right tail (Field, 2013).

![Figure 5.7: Histogram of Wake Separation Values in Time for Each Aircraft Under Study Based on Calculated MCC.](image)

5.7 Conclusions and Recommendations

The objective of this research is to simulate aircraft operations during arrival, as well as the environmental conditions in the aircraft flight path, to derive typical wake capacity for each aircraft category, all in the effort to reduce in-trail wake vortex separation.

This study has two main goals: (1) to develop a methodology to produce circulation strength values under different conditions and (2) to calculate the typical wake vortex capacities for aircraft under study that can be further used in dynamic wake separation calculations. As seen from the analysis,
wake circulation strength curves for an Airbus 380-class aircraft vary considerably at time zero and at times below 200 seconds.

Simulation results show there are several benefits of better understanding how dynamic parameters affect wake behavior intensity, location, and decay, and that there is a potential for wake separation reduction if environmental conditions at or near wake generation and development are known. Real-life experiments with separation reductions at the airport in Memphis, TN revised that airport’s legacy single-runway wake separation to improve airport capacity. The experiments produced a 20% increase in airport capacity and savings of $1.8 million in monthly fossil fuel costs by implementing changes in separation, such as RECAT I (Lang 2015).

5.7.1 Recommendations

Other phases of flight, such as those outside of the in-ground-effect, could be studied in future research. It can be inferred that lower values of EDR in the upper atmosphere would increase the duration of wake behavior. Interestingly, recent research using static separations has found that circulation strength at cruising altitude and during approach procedures to an airport have similar magnitudes. This is due to the inverse variation of flight velocity and air density, as they roughly compensate each other (Holzapfel and Gerz 2012).

Selecting critical aircraft for each aircraft class is a conservative approach to reducing wake vortex separation. When the FAA releases the 123x123 matrix of individual wake separations between all leader and follower aircraft currently operating in the national airspace, it will be possible to calculate the MCC for each aircraft. This will make possible the calculation of dynamic wake separation based on specific aircraft and environmental conditions.

Runway capacity improvement is one of the main benefits that make wake separation attractive for sustainable airports. There is a need to study possible limitations to runway capacity improvement through simulation of a real airport fleet and comparing the limitations that results from the established separation against limitations reached in RECAT II.

Airport and aircraft-specific simulations could aid the implementation of a wake dynamic separation that, in the end, could reduce airport delays, shorten final approaches to airports, and reduce fuel burn and emissions.

The complexity of implementing pairwise dynamic wake separations, such as in RECAT III, requires advanced decision support tools that can help controllers coordinate and direct arriving and departing flights. There is a need to develop reliable tools that can help the controllers in this task.
For the implementation of RECAT III, more advanced LIDAR capabilities and technologies need to be developed to capture turbulence values under all weather conditions accurately.

5.8 Acknowledgments

This research has been made possible thanks to the research contributions of the Federal Aviation Administration Wake Program, National Aeronautics and Space Administration (NASA) wake program, EUROCONTROL, Japan Aerospace Exploration Agency, Wakenet meeting members, MIT Lincoln Laboratory, and private industry research labs such as the MITRE Corporation.

5.9 Disclaimer

The contents of this material reflect the views of the author only. Neither the Federal Aviation Administration nor the United States Department of Transportation nor National Aeronautics and Space Administration makes any warranty or guarantee, or promise, expressed or implied, concerning the content or accuracy of the views expressed herein.

Any opinion, findings, and conclusion or recommendations presented herein are those of the author and do not necessarily reflect the views of the FAA or NASA.

5.10 References


6. Simulation of Runway Operations with Application of Dynamic Wake Separations to Study Runway Limitations

6.1 Abstract

This paper presents an evaluation of runway operations at Chicago O'Hare International (ORD) to estimate the impact of proposed wake vortex separation including recategorization phase II (RECAT II) and RECAT III dynamic separations.

The evaluation uses a Monte Carlo simulation model that considers arrivals and departure operations. The simulation accounts for static and dynamic wake vortex separations, aircraft fleet mix, runway occupancy times, aircraft approach speeds, aircraft wake circulation capacity, environmental conditions, and operational error buffers. Airport data considered for this analysis are based on Airport Surface Detection Equipment Model X (ASDE-X) records at ORD during a 10-month period in the year 2016. Dynamic wake separations are tailored to each unique set of conditions by using environmental and aircraft performance parameters as input and allowing aircraft to be exposed to the same wake vortex strength as in RECAT II.

The analysis shows that further reductions beyond RECAT II for aircraft pairs separated 2 nm or less is not operationally feasible. These wake separations already result in little to no wake dependency. When this is the case, the challenges in wake separation are to meet ROT and to make sure aircraft separations allow for human operational variations without resulting in aircraft turn-arounds or double-aircraft-occupancy runway violations.

6.2 Introduction

Runway capacity is critical to serving the increasing operational demands and helping airports recover from long queues created by non-favorable weather conditions that can result in airport shutdowns.

Wake separations are of major influence for runway throughput because they determine the time that the runway will be unutilized between each pair of sequential arrivals. When the separation
between arrivals is large enough, air traffic controllers may allow departures in between, but these departures also rely on wake separation standards for safety.

In the 1960’s wake vortex separations were established based on aircraft categories. The aircraft maximum takeoff weight (MTOW) is a critical parameter to estimate the strength of wakes behind the aircraft.

As research on wake behavior has evolved, the decay of wake has been recognized as an important behavior to study to decrease the minimum separation between aircraft on the same flight path.

Current research efforts led by the Federal Aviation Administration (FAA) will increase the number of aircraft groups. The research effort is studying wake vortex generation, decay and the wake handling capacity on individual aircraft. These efforts use LIDAR measurements of aircraft wake circulation strength for operations at selected airports.

This research focuses on dynamic wake separations FAA RECAT III. Dynamic wake separations account for not only the wake vortex circulation strength of each aircraft but also the aircraft configuration and environmental conditions under which the aircraft operates. Dynamic wake separations are tailored to each unique set of conditions by utilizing as input the environmental and aircraft performance parameters and allowing aircraft to be exposed to the same wake vortex strength as in FAA RECAT II.

6.3 Objective

The objective of this research is to calculate how often ROT is the limiting factor to increasing runway capacity at several U.S. airports under RECAT II and RECAT III. It also discusses implications of dynamic wake separation RECAT III implementation.

This research simulates aircraft operations during final approach utilizing RECAT II, RECAT III aircraft separations rules, and considering realistic fleet mix, runway occupancy time (ROT), operational buffers, and aircraft approach speeds (Trani, Shortle et al. 2017).

This research presents a method to estimate dynamic wake separations considering aircraft weight, atmospheric turbulence, wind speed, and temperature. These factors could be considered in airport-specific wake separations under RECAT III.

This study aims to demonstrate and quantify the potential benefits for wake separation reduction based on a simulation of RECAT III dynamic wake separations for 90% of the fleet operating at Chicago O’Hare International Airport (ORD). The simulation accounts for ROT, approach speed,
and wake circulation strength calculated from airport data recorded at Chicago O’Hare International Airport in 2016 for each aircraft under study.

6.4 Methodology

The methodology for calculating runway throughput uses Monte Carlo simulation. A computer program has been created to simulate real-world conditions of aircraft operations during arrival, and departure. The simulation accounts for static and dynamic wake vortex separations, ROTs, aircraft approach speeds, aircraft wake circulation capacity, environmental conditions, and operational error buffers.

6.4.1 Recategorization Separation Standards - RECAT I, RECAT I.5, RECAT II and RECAT III

Wake vortex categorizations are groups of aircraft with similar wake vortex generation and range capabilities. The FAA created such categorizations in the 1960s, and they remain practical and safe today.

To increase the operational efficiency of airports, especially for airports under capacity constraints, the FAA led an effort to revise legacy wake separations. These efforts increased legacy wake separations from a five-by-five matrix to a six-by-six separation matrix called RECAT I.

RECAT I was implemented at Memphis International Airport (MEM) at the end of 2012 and has expanded to Louisville International Airport (SDF), Cincinnati/Northern Kentucky International Airport (CVG), Hartsfield-Jackson Atlanta International Airport (ATL), George Bush Intercontinental Airport (IAH), and Charlotte Douglas International Airport (CLT). Table 6.1 presents FAA wake separation matrix standard for RECAT I and RECAT 1.5.

RECAT 1.5 was developed as a modification of RECAT I; its results are still being assessed. RECAT 1.5 was implemented at the beginning of 2016 at George Bush Intercontinental Airport (IAH) and continues to expand to airports such as Charlotte Douglas International Airport (CLT), John F. Kennedy International Airport (JFK), Newark Liberty International Airport (EWR), La Guardia Airport (LGA), O’Hare International Airport (ORD), and Denver International Airport (DEN) (FAA and NextGen 2016).

<table>
<thead>
<tr>
<th>Leader</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>5 nm</td>
<td>6 nm</td>
<td>7 nm</td>
<td>7 nm</td>
<td>8 nm</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>3 nm</td>
<td>4 nm</td>
<td>5 nm</td>
<td>5 nm</td>
<td>7 nm</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>3.5 nm</td>
<td>3.5 nm</td>
<td>6 nm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>5 nm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>4 nm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

On Approach, F behind E was 4 nm, now minimum radar separation (MRS)
F behind D was 5 nm, now 4 nm

This research focuses on the assessment and development of the future wake separations called: RECAT III dynamic separations.

6.4.2 Data Sources

The analysis uses detailed data of aircraft movement on the final approach, runways, and taxiways, based on Airport Surface Detection Equipment Model X (ASDE-X) to provide validity and increase operational reality of the simulation.

The ASDE-X system collects data from a variety of sources, such as surface movement radar, multilateration sensors, Automatic Dependent Surveillance-Broadcast (ADS-B), the terminal automation system, and aircraft transponders. This data allows for the calculation of aircraft approach speed, runway occupancy times, and traffic control buffers. ASDE-X data for all runways at Chicago International (ORD), for the months January to November of 2016, has been analyzed. ASDE-X Airport data was parsed for a runway exit design project (Mirmohammadsadeghi 2018).

6.4.3 Runway Fleet Mix

One of the most important factors influencing runway capacity limitations is fleet mix. The methodology for the aircraft mix selected for simulation is based on ASDE-X recordings of operating aircraft for each runway. Those aircraft that represent between 85% and 90% of operations at the runways under study are selected to represent the runway fleet mix. The simulation consists of simulating 1,000 aircraft arrivals per runway, which is equivalent to 24 hours of peak-hour operation.
at a typical runway, with ten operations every 15 minutes. Table 6.2 presents ASDE-X recorded values of fleet mix and aircraft approach speed for arrival operations to runway 09R at Chicago (ORD) International airport.

Table 6.2: Aircraft Fleet Mix at Chicago O’Hare (ORD) Runway 09R.

<table>
<thead>
<tr>
<th>Aircraft ID</th>
<th>A319</th>
<th>A320</th>
<th>B738</th>
<th>CRJ2</th>
<th>CRJ9</th>
<th>E145</th>
<th>E170</th>
<th>MD82</th>
<th>MD83</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aircraft Mix (%)</td>
<td>4</td>
<td>9</td>
<td>26</td>
<td>8</td>
<td>16</td>
<td>23</td>
<td>8</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Approach Speed (knots)</td>
<td>149</td>
<td>155</td>
<td>158</td>
<td>151</td>
<td>145</td>
<td>154</td>
<td>147</td>
<td>148</td>
<td>150</td>
</tr>
</tbody>
</table>

6.4.4 Maximum Wake Circulation Capacity (MCC)

Estimating dynamic wake separation between leader and following aircraft requires consideration of a wake vortex threshold that is known not to adversely affect an aircraft operation. This threshold considers the maximum wake vortex effect that a follower aircraft can endure at minimum wake separation standards from the wake generator aircraft, referred to as the maximum wake circulation capacity (MCC).

The methodology in this research considers the 95% confidence interval of the wake behavior cumulative density function (CDF) curves, according to FAA RECAT II wake separations. To calculate MCC, the separation distances following the two aircraft that cause the greatest and second greatest wake turbulence, respectively: the Airbus 380 type aircraft and Boeing 747-class aircraft are used. Table 6.3 presents the calculated MCC values for some of the aircraft under study (Tittsworth, Cheng et al. 2016).

Wake vortex simulations for the Airbus 380-class aircraft considers a mean aircraft mass of 394,859 kg with a standard deviation of 6,072 kg, based on operational data (Trani 2016). This mass encompasses 90% to 96% of the MALW. The Airbus 380-class aircraft has a MALW of 386,006 kg and a MTOW of 573,009 kg (Airbus 2016). Similar studies that simulated wake behavior of aircraft approaching a runway consider 85% of the MALW (Tittsworth, Cheng et al. 2016).

Wake circulation simulations for the Boeing 747-class aircraft considers a mean aircraft mass of 219,637 kg with a standard deviation of 5,382 kg, based on operational data (Trani 2016). These values represents operational landing weight values in the range of 72% to 75% of MALW. The MALW of the Boeing 747-class aircraft is 295,743 kg, and its MTOW is 396,900 kg (Boeing 2010). Figure 6.1 presents wake behavior simulation for Airbus A380 and Boeing 747 class aircraft.
Table 6.3: MCC Values for Aircraft Under Study Following an Airbus 380 and Boeing 747.

<table>
<thead>
<tr>
<th>Aircraft IDs</th>
<th>B747</th>
<th>B772</th>
<th>B763</th>
<th>DC10</th>
<th>A320</th>
<th>B737</th>
<th>MD83</th>
<th>E170</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC Group</td>
<td>B</td>
<td>B</td>
<td>C</td>
<td>C</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>E</td>
</tr>
<tr>
<td>MCC A380 (m²/s)</td>
<td>363</td>
<td>336</td>
<td>298</td>
<td>292</td>
<td>268</td>
<td>266</td>
<td>262</td>
<td>262</td>
</tr>
<tr>
<td>MCC B747 (m²/s)</td>
<td>362</td>
<td>317</td>
<td>266</td>
<td>264</td>
<td>227</td>
<td>227</td>
<td>224</td>
<td>222</td>
</tr>
</tbody>
</table>

Figure 6.1: Wake Vortex Behavior for Airbus 380 and Boeing 747 Type Aircraft.

6.4.5 Common Approach Path

The final approach fix is a point on the approach path that identifies the start of a common approach path or final segment. The common approach path is the distance between the final approach fix and the runway threshold. Analysis of ASDE-X data shows the length of the common approach segment to be 8.5 nm. This is important because this 8.5-nm distance is used to calculate the time available to schedule departures between consecutive arrival procedures. The minimum separation between arrival and departure, is considered to be 2 nm, and a buffer with a mean of 15 seconds and a standard deviation of 3 seconds (Hu 2018). Error! Reference source not found. illustrates the final approach fix point for a common approach path in a very high frequency (VHF) omnidirectional range (VOR) chart for operations at La Guardia Airport. For this study, the final approach fix was set based on ASDE-X available data.
6.4.1 Operational Buffer Times

Air traffic controllers use operational buffers to control aircraft separations. The purpose of the buffer is to guarantee that controllers do not violate minimum wake separations standards. Operational buffers account for pilot operational errors, delays in communication, ATC risk avoidance, and reaction times during pilot-controller interactions.

Operational buffer times were calculated based on ten months of operational data from ORD. The buffers were calculated by measuring inter-arrival distance separations and comparing them to RECAT 1.5 distance separation standards. Buffer are converted to time using aircraft approach speed. The buffer was calculated in the final, common approach path using a fixed distance of 8.5-nm from the runway threshold. The resulting buffer is the closest point of approach (CPA) between each pair of aircraft during the entire approach path length (Hu 2018).

During this analysis, negative buffer values may be the result of runway approach operations under Visual Flight Regulations (VFR), where aircraft-to-aircraft separations are below those of Instrument Flight Regulations (IFR) due to pilot self-separation procedures made possible in favorable environmental conditions.

![Figure 6.2: Arrival Operations on Runway 10C for the Busiest Day (September 9, 2016) of the 10 Months of ASDE-X Data Studied (Hu, 2018).](image)

To calculate operational buffer, peak-hour operations were studied using ASDE-X for runway demand of 10 or more operations in 15-minute periods (Hu, 2018). Only peak-hour periods were considered because inter-arrival separation times, and the resulting operational buffers, during non-
peak-hours buffers are longer. Figure 6.2 shows the frequency of arrival operations for the busiest day of the ten months of data available for runway 10C at ORD.

The simulation considered two types of buffers. Opening case buffers occur when the leading aircraft’s approach speed is greater than the following aircraft’s approach speed; this results in an increasing separation gap between the leading and the following aircraft. Opening case operational buffer values used in the simulation, have a mean of 15 seconds and a standard deviation of 3 seconds.

Closing case buffers occur when the following aircraft’s approach speed is greater than the leading aircraft’s speed, resulting in a decreasing separation. Closing operational buffer values used in the simulation have a mean of 20 seconds and a standard deviation of 3 seconds.

6.4.2 Runway Occupancy Times

Decreasing wake vortex separations during in the final approach segment, ROT may limit the runway capacity. Figure 6.3 illustrates runway occupancy for aircraft on the runway.

![Figure 6.3: Wake Separation and Operational Buffer on Approach.](image)

If a runway must service more aircraft, measured ROTs have to be studied to understand how much of the theoretically calculated capacity increment of RECAT II and RECAT III is operationally feasible on currently available airport infrastructures. Table 6.4 represents average ROT values for runway 09R.

Table 6.4: ROT Calculated Values for Specified Aircraft on Runway 09R at Chicago (ORD).

<table>
<thead>
<tr>
<th>Aircraft ID</th>
<th>A319</th>
<th>A320</th>
<th>B738</th>
<th>CRJ2</th>
<th>CRJ9</th>
<th>E145</th>
<th>E170</th>
<th>MD82</th>
<th>MD83</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROT (s)</td>
<td>58</td>
<td>57</td>
<td>57</td>
<td>55</td>
<td>60</td>
<td>53</td>
<td>54</td>
<td>56</td>
<td>57</td>
</tr>
</tbody>
</table>
6.4.3 Environmental and Aircraft Parameters

Environmental and aircraft parameters are key factors in RECAT III dynamic separation calculations. These calculations vary environmental factors such as temperature, crosswind speeds, and environmental turbulence every 15 minutes. Values for a temperature range between 283 and 299 Kelvin, values for crosswind speeds range between 0 and 12.86 m/s, and EDR values follow the distribution shown in Figure 6.4 which considers values of EDR in the in-ground-effect measured at Dallas Fort Worth International Airport (Perras, Dasey et al. 2000).

![Figure 6.4: EDR Distribution of Exceedance Probabilities for In-Ground-Effect.](image)

The EDR distribution is in accordance with the in-ground-effect altitude where values considered for the simulation range between moderate $1.35 \times 10^{-3} \text{ m}^2/\text{s}^3$ to intense $1.50 \times 10^{-2} \text{ m}^2/\text{s}^3$, with 80 percent of the values in the range moderate $1.35 \times 10^{-3} \text{ m}^2/\text{s}^3$ to strong $7.17 \times 10^{-3} \text{ m}^2/\text{s}^3$ (Proctor, Hamilton et al. 2006) (Switzer and Proctor 2000).

In this research, aircraft operational performance is simulated using the Base of Aircraft Data (BADA), an aircraft performance model developed and maintained by EUROCONTROL in cooperation with aircraft manufacturers and airlines. The BADA database has been designed for simulation and aircraft trajectory prediction. The BADA performance model is based on the Total
Energy Model, which equates the forces acting on the aircraft with the rate of increase in potential and kinetic energy (EUROCONTROL 2016).

Aircraft weight, a critical parameter of wake initial circulation strength, is simulated based on empirical operational data for typical airline operations.

6.5 Monte Carlo Simulation of Runway Operations for Arrivals with Inter-Arrival Departures

6.5.1 Algorithm

Figure 6.5 presents the Monte Carlo simulation flowchart. The first step in the algorithm for the computer program is to load previously calculated parameters, such as runway fleet mix, aircraft-wake generated behavior, wake circulation capacity of each aircraft, approach speeds, buffer times, and ROTs.

An outer simulation loop is used to simulate runway operations for specified numbers of arrivals and specified fleet mix. Another outer simulation loop is used to simulate each aircraft pair arriving at the runway, up to the number of arrival procedures to be simulated. In this step, environmental conditions are changed every 15 minutes and aircraft weight is unique for each operation.

Inside the loop, the computer program determines if each pair of aircraft approaching the runway belongs to an opening or closing case. The case is important because it determines which operational buffer will be applied by air traffic controllers. At this stage, the program identifies the circulation strength of the follower, identifies time separation according to minimum radar separation for future validation, and calculates the mass of the leading aircraft according to mass distribution.

The program then calls the function that interpolates the value of dynamic separation according to aircraft mass, environmental turbulence, wind speed, temperature, and wake circulation capacity for the follower and, consequently, the aircraft pair.
Select airport and runway for study

Load aircraft performance data

Load aircraft operational data, ROT, approach speed, MCC

Load runway fleet mix

Arrivals only operations

Departures with 100% arrival priority

Departures only

Generate arrival

Define environmental conditions (start clock)

Define leading and following aircraft

Leader/Follower

Leader

Define aircraft weight and speed

Simulation wake behavior based on NASA model

Define MCC

Calculate RECAT III dynamic separations

\[
\text{DWS} + \text{buffer} \geq \text{ROT} \\
\text{DWS} + \text{buffer} < \text{ROT}
\]

\[
\text{WS} = \text{DWS} + \text{buffer} \\
\text{WS} = \text{ROT (leader)} + \text{buffer} \\
\text{Add WS to the clock} \\
\text{Check for inter-arrival departure}
\]

\[
\text{WS} = \text{ROT} \\
\text{Add WS to the clock} \\
\text{Check for inter-arrival departure}
\]
Operational rules are applied to guarantee that results are operationally feasible. If the calculated dynamic wake separation for the follower aircraft is less than the leading aircraft’s ROT, then dynamic separation is adjusted to ROT plus the controller-applied buffer.

Between each pair of successive arrivals, the program checks for possible departure procedures by calculating the time it will take for next arriving aircraft to reach the runway threshold and subtracting the regulation standard for possible minimum separation between arriving and departing aircraft.

6.5.2 Simulation Conditions

The lifetime of the vortex depends on its initial strength, which depends on aircraft weight and wingspan as well as the ambient weather conditions. It is for this reason that the simulation changes environmental conditions every fifteen minutes and aircraft weight in every operation (Proctor, Hamilton et al. 2004).

In this simulation, the dynamic wake separation required for a follower aircraft is calculated by using the National Aeronautics and Space Administration (NASA) Aircraft Vortex Spacing System (AVOSS) Prediction Algorithm (APA) model. This model is a semi-empirical wake behavior model developed by NASA that predicts wake decay as a function of atmospheric turbulence and stratification.

The number of arrival operations simulated is one thousand. Departures are launched in between successive arrivals if the wake separation gap for each pair of aircraft is larger than wake minimum separation standards. The simulation considers 2-nm plus an additional buffer to be the minimum separation between arriving and departing aircraft.
Simulated conditions for ROT and approach speeds are in accordance with the runway under study and follow the distribution according to the ASDE-X data studied. The common approach path length is considered to be 8.5 nm.

6.6 Data Analysis and Results Based on RECAT II and Dynamic RECAT III

In the analysis of the results, each runway end is considered separately, according to its unique aircraft fleet mix and the runway occupancy time of each aircraft. Those aircraft that represent 85% to 95% of the total operations at that runway are selected. The average approach speed for the 8.5-nm final approach segment for each aircraft is calculated and used for simulation. Table 6.5 presents the calculated values of MCC and approach speed for all aircraft under study when the Airbus 380-class aircraft is considered the critical leading aircraft.

Table 6.5: MCC for Aircraft Studied, with Critical Leader A380-Class Aircraft.

<table>
<thead>
<tr>
<th>Follower</th>
<th>Approach Speed (knots)</th>
<th>RECAT II Time (s)</th>
<th>RECAT II Distance (nm)</th>
<th>MCC 95th pct. (m²/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A388</td>
<td>148</td>
<td>61</td>
<td>2.5</td>
<td>418</td>
</tr>
<tr>
<td>A319</td>
<td>150</td>
<td>149</td>
<td>6.2</td>
<td>263</td>
</tr>
<tr>
<td>A320</td>
<td>154</td>
<td>145</td>
<td>6.2</td>
<td>268</td>
</tr>
<tr>
<td>B737</td>
<td>153</td>
<td>146</td>
<td>6.2</td>
<td>266</td>
</tr>
<tr>
<td>B738</td>
<td>159</td>
<td>145</td>
<td>6.4</td>
<td>268</td>
</tr>
<tr>
<td>B744</td>
<td>162</td>
<td>84</td>
<td>3.8</td>
<td>363</td>
</tr>
<tr>
<td>B752</td>
<td>152</td>
<td>139</td>
<td>5.9</td>
<td>275</td>
</tr>
<tr>
<td>B763</td>
<td>154</td>
<td>122</td>
<td>5.2</td>
<td>298</td>
</tr>
<tr>
<td>B772</td>
<td>155</td>
<td>98</td>
<td>4.2</td>
<td>336</td>
</tr>
<tr>
<td>CRJ2</td>
<td>152</td>
<td>152</td>
<td>6.4</td>
<td>259</td>
</tr>
<tr>
<td>CRJ9</td>
<td>153</td>
<td>151</td>
<td>6.4</td>
<td>261</td>
</tr>
<tr>
<td>DC10</td>
<td>151</td>
<td>126</td>
<td>5.3</td>
<td>292</td>
</tr>
<tr>
<td>E120</td>
<td>145</td>
<td>173</td>
<td>7</td>
<td>237</td>
</tr>
<tr>
<td>E135</td>
<td>153</td>
<td>150</td>
<td>6.4</td>
<td>262</td>
</tr>
<tr>
<td>E145</td>
<td>155</td>
<td>149</td>
<td>6.4</td>
<td>263</td>
</tr>
<tr>
<td>E170</td>
<td>151</td>
<td>150</td>
<td>6.3</td>
<td>262</td>
</tr>
<tr>
<td>E190</td>
<td>156</td>
<td>146</td>
<td>6.3</td>
<td>266</td>
</tr>
<tr>
<td>MD82</td>
<td>153</td>
<td>151</td>
<td>6.4</td>
<td>261</td>
</tr>
<tr>
<td>MD83</td>
<td>153</td>
<td>150</td>
<td>6.4</td>
<td>262</td>
</tr>
</tbody>
</table>

Values presented in table are simulation based. These values do not represent the views of the FAA.
The runway occupancy for aircraft operating on the runway is the average ROT, in seconds, to the hold bar; and the average approach speed, is the ground speed in knots, from the fix approach point to the runway threshold; for the 8.5-nm final approach path.

The longitudinal separation between each pair of leading and following aircraft defaults to ROT in seconds if RECAT II separation in seconds plus the operational buffer is less than ROT (RECAT II + Buffer < ROT; ROT). Table 6.6 presents the calculated values of MCC and approach speed for all aircraft under study when the Boeing 747 400-class aircraft is considered the critical leading aircraft.

Table 6.6: MCC for Aircraft Studied, with Critical Leader B747 400 Class Aircraft.

<table>
<thead>
<tr>
<th>Leader B744</th>
<th>Follower</th>
<th>Approach Speed (knots)</th>
<th>RECAT II Time (s)</th>
<th>RECAT II Distance (nm)</th>
<th>MCC 95th pctl. (m²/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A388</td>
<td>148</td>
<td>49</td>
<td>2</td>
<td>343</td>
<td></td>
</tr>
<tr>
<td>A319</td>
<td>150</td>
<td>108</td>
<td>4.5</td>
<td>227</td>
<td></td>
</tr>
<tr>
<td>A320</td>
<td>154</td>
<td>108</td>
<td>4.6</td>
<td>227</td>
<td></td>
</tr>
<tr>
<td>B737</td>
<td>153</td>
<td>108</td>
<td>4.6</td>
<td>227</td>
<td></td>
</tr>
<tr>
<td>B738</td>
<td>159</td>
<td>107</td>
<td>4.7</td>
<td>228</td>
<td></td>
</tr>
<tr>
<td>B744</td>
<td>162</td>
<td>44</td>
<td>2</td>
<td>362</td>
<td></td>
</tr>
<tr>
<td>B752</td>
<td>152</td>
<td>99</td>
<td>4.2</td>
<td>239</td>
<td></td>
</tr>
<tr>
<td>B763</td>
<td>154</td>
<td>82</td>
<td>3.5</td>
<td>266</td>
<td></td>
</tr>
<tr>
<td>B772</td>
<td>155</td>
<td>58</td>
<td>2.5</td>
<td>317</td>
<td></td>
</tr>
<tr>
<td>CRJ2</td>
<td>152</td>
<td>112</td>
<td>4.7</td>
<td>222</td>
<td></td>
</tr>
<tr>
<td>CRJ9</td>
<td>153</td>
<td>111</td>
<td>4.7</td>
<td>223</td>
<td></td>
</tr>
<tr>
<td>DC10</td>
<td>151</td>
<td>83</td>
<td>3.5</td>
<td>264</td>
<td></td>
</tr>
<tr>
<td>E120</td>
<td>145</td>
<td>124</td>
<td>5</td>
<td>208</td>
<td></td>
</tr>
<tr>
<td>E135</td>
<td>153</td>
<td>110</td>
<td>4.7</td>
<td>224</td>
<td></td>
</tr>
<tr>
<td>E145</td>
<td>155</td>
<td>110</td>
<td>4.7</td>
<td>224</td>
<td></td>
</tr>
<tr>
<td>E170</td>
<td>151</td>
<td>112</td>
<td>4.7</td>
<td>222</td>
<td></td>
</tr>
<tr>
<td>E190</td>
<td>156</td>
<td>109</td>
<td>4.7</td>
<td>226</td>
<td></td>
</tr>
<tr>
<td>MD82</td>
<td>153</td>
<td>111</td>
<td>4.7</td>
<td>223</td>
<td></td>
</tr>
<tr>
<td>MD83</td>
<td>153</td>
<td>110</td>
<td>4.7</td>
<td>224</td>
<td></td>
</tr>
</tbody>
</table>

Values presented in table are simulation based. These values do not represent the views of the FAA.

Table 6.7 presents the calculated values of MCC, approach speed and RECAT II time and distance separations for all aircraft under study when the Boeing 737 800-class aircraft is considered the critical leading aircraft.
Table 6.7: MCC for Aircraft Studied, with Critical Leader B737 800-class Aircraft.

<table>
<thead>
<tr>
<th>Follower</th>
<th>Approach Speed (knots)</th>
<th>RECAT II Time (s)</th>
<th>RECAT II Distance (nm)</th>
<th>MCC 95(^{th}) pctl. (m(^2)/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A388</td>
<td>148</td>
<td>-</td>
<td>0</td>
<td>196.5</td>
</tr>
<tr>
<td>A319</td>
<td>151</td>
<td>48</td>
<td>2</td>
<td>174.3</td>
</tr>
<tr>
<td>A320</td>
<td>156</td>
<td>46</td>
<td>2</td>
<td>175.2</td>
</tr>
<tr>
<td>B737</td>
<td>155</td>
<td>46</td>
<td>2</td>
<td>175.2</td>
</tr>
<tr>
<td>B738</td>
<td>161</td>
<td>45</td>
<td>2</td>
<td>175.6</td>
</tr>
<tr>
<td>B744</td>
<td>165</td>
<td>-</td>
<td>0</td>
<td>196.5</td>
</tr>
<tr>
<td>B752</td>
<td>152</td>
<td>47</td>
<td>2</td>
<td>174.7</td>
</tr>
<tr>
<td>B763</td>
<td>157</td>
<td>46</td>
<td>2</td>
<td>175.2</td>
</tr>
<tr>
<td>B772</td>
<td>159</td>
<td>-</td>
<td>0</td>
<td>196.5</td>
</tr>
<tr>
<td>CRJ2</td>
<td>154</td>
<td>47</td>
<td>2</td>
<td>174.7</td>
</tr>
<tr>
<td>CRJ9</td>
<td>153</td>
<td>47</td>
<td>2</td>
<td>174.7</td>
</tr>
<tr>
<td>DC10</td>
<td>151</td>
<td>48</td>
<td>2</td>
<td>174.3</td>
</tr>
<tr>
<td>E120</td>
<td>145</td>
<td>50</td>
<td>2</td>
<td>173.6</td>
</tr>
<tr>
<td>E135</td>
<td>154</td>
<td>47</td>
<td>2</td>
<td>174.7</td>
</tr>
<tr>
<td>E145</td>
<td>155</td>
<td>47</td>
<td>2</td>
<td>174.7</td>
</tr>
<tr>
<td>E170</td>
<td>153</td>
<td>47</td>
<td>2</td>
<td>174.7</td>
</tr>
<tr>
<td>E190</td>
<td>156</td>
<td>46</td>
<td>2</td>
<td>175.2</td>
</tr>
<tr>
<td>MD82</td>
<td>155</td>
<td>46</td>
<td>2</td>
<td>175.2</td>
</tr>
<tr>
<td>MD83</td>
<td>157</td>
<td>46</td>
<td>2</td>
<td>175.2</td>
</tr>
</tbody>
</table>

Values presented in table are simulation based. These values do not represent the views of the FAA.

6.6.1 ORD Runway 09L

The aircraft operating on runway end 09L predominantly belong to groups D and E in the FAA RECAT 1.5 wake matrix. These aircraft have similar weight carrying capabilities, MCC, and wake generation capabilities. For this reason, separations between leaders and followers for this runway fall in the 2-nm range, meaning that there is no wake influence, or little, between these aircraft pairs. Table 6.9 presents wake separation values proposed by the FAA in RECAT II, and Table 6.8 presents calculated values of ROT and approach speed for each aircraft studied on this runway.
Table 6.8: Runway and Aircraft Parameters for ORD 09L.

<table>
<thead>
<tr>
<th>Aircraft ID</th>
<th>A319</th>
<th>A320</th>
<th>B737</th>
<th>B738/ B739</th>
<th>CRJ2</th>
<th>CRJ9/ CRJ7</th>
<th>E135</th>
<th>E145</th>
<th>E170</th>
<th>MD83</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fleet Mix (%)</td>
<td>5</td>
<td>8</td>
<td>2</td>
<td>20</td>
<td>10</td>
<td>15</td>
<td>3</td>
<td>24</td>
<td>11</td>
<td>2</td>
</tr>
<tr>
<td>Frequency</td>
<td>1736</td>
<td>2966</td>
<td>670</td>
<td>5466</td>
<td>3978</td>
<td>834</td>
<td>1122</td>
<td>9316</td>
<td>4376</td>
<td>596</td>
</tr>
<tr>
<td>ROT (s)</td>
<td>60</td>
<td>58</td>
<td>62</td>
<td>58</td>
<td>64</td>
<td>59</td>
<td>57</td>
<td>57</td>
<td>58</td>
<td>58</td>
</tr>
<tr>
<td>RECAT II following B738 (s)</td>
<td>47</td>
<td>46</td>
<td>46</td>
<td>44</td>
<td>46</td>
<td>46</td>
<td>46</td>
<td>46</td>
<td>46</td>
<td>46</td>
</tr>
<tr>
<td>RECAT II following B738 (nm)</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Approach Ground Speed (knots)</td>
<td>154</td>
<td>158</td>
<td>157</td>
<td>163</td>
<td>155</td>
<td>157</td>
<td>156</td>
<td>158</td>
<td>155</td>
<td>157</td>
</tr>
</tbody>
</table>

*RECAT II(t) = (RECAT II(nm)/Vapp(knots))*3600

Table 6.9: Recategorization II Wake Separation FAA Proposed Matrix for ORD 09L.

<table>
<thead>
<tr>
<th>Leader</th>
<th>A320</th>
<th>A319</th>
<th>B738</th>
<th>B737</th>
<th>MD83</th>
<th>E170</th>
<th>CRJ9</th>
<th>CRJ2</th>
<th>E135</th>
<th>E145</th>
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<td>D</td>
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</tr>
<tr>
<td>MD83</td>
<td>D</td>
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</tbody>
</table>

The MCC for all aircraft operating on runway 09L is near 200 m²/s, as shown in Table 6.5, and the wake behavior generated by the Boeing 737 800 series type aircraft, the greatest offender of all aircraft that operate on this runway, is shown in Figure 6.6 with an initial circulation value of 200 m²/s.

Wake circulation for Boeing 737 800-class aircraft considers a mean aircraft mass of 49,781 kg with a standard deviation of 851, based on operational data; this represents operational landing weight values in the range of 74% to 76% of MALW. The Boeing 737 800-class aircraft has a MALW of 66,362 kg and an MTOW of 79,017 kg.

From this analysis, it is clear that if dynamic separation were to be applied for aircraft pairs selected for runway 09R, ROT would be the determining factor for all aircraft separations. Table 6.10 presents
the percentage of aircraft operations that would be restricted by ROT if RECAT II and RECAT III wake separation reductions were to be implemented.

![Wake Vortex Behavior for Boeing 737-800-Class Aircraft](image)

Figure 6.6: Wake Vortex Behavior for Boeing 737-800-Class Aircraft.

<table>
<thead>
<tr>
<th></th>
<th>RECAT II</th>
<th>RECAT III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of arrivals restricted by ROT</td>
<td>11</td>
<td>69</td>
</tr>
</tbody>
</table>

*Critical aircraft is B738*

6.6.2 ORD Runway 09R

Aircraft operating on runway end 09R predominantly belong to groups D and E in the FAA RECAT 1.5 wake matrix. These aircraft have similar weight carrying capabilities, MCC, and wake generation capabilities. For this reason, separations between leaders and followers for this runway fall in the 2-nm range, meaning that there is little to no wake influence, between these aircraft pairs. Table 6.12 presents wake separation values proposed by the FAA in RECAT II, and Table 6.11 presents calculated values of ROT and approach speed for each aircraft studied on this runway.
Table 6.11: Runway and Aircraft Parameters for ORD 09R.

<table>
<thead>
<tr>
<th>Aircraft ID</th>
<th>A319</th>
<th>A320</th>
<th>B738/ B739</th>
<th>CRJ2</th>
<th>CRJ9/ CRJ7</th>
<th>E145</th>
<th>E170</th>
<th>MD82</th>
<th>MD83</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fleet Mix (%)</td>
<td>4</td>
<td>9</td>
<td>26</td>
<td>8</td>
<td>16</td>
<td>23</td>
<td>8</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Frequency</td>
<td>88</td>
<td>181</td>
<td>360</td>
<td>161</td>
<td>329</td>
<td>490</td>
<td>173</td>
<td>51</td>
<td>73</td>
</tr>
<tr>
<td>ROT (s)</td>
<td>58</td>
<td>57</td>
<td>57</td>
<td>55</td>
<td>60</td>
<td>53</td>
<td>54</td>
<td>56</td>
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<tr>
<td>Approach Ground Speed (knots)</td>
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<td>155</td>
<td>158</td>
<td>151</td>
<td>145</td>
<td>154</td>
<td>147</td>
<td>148</td>
<td>150</td>
</tr>
</tbody>
</table>

Table 6.12: Recategorization II Wake Separation FAA Proposed Matrix for ORD 09R.

<table>
<thead>
<tr>
<th>Leader</th>
<th>A320</th>
<th>A319</th>
<th>B738</th>
<th>MD83</th>
<th>MD82</th>
<th>E170</th>
<th>CRJ9</th>
<th>CRJ2</th>
<th>E145</th>
</tr>
</thead>
<tbody>
<tr>
<td>A320</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>E</td>
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<td>CRJ9</td>
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</tbody>
</table>

The MCC for all aircraft operating in runway 09R is near 200 m²/s, as shown in Table 6.5, and the wake behavior generated by the B737 800-class aircraft, the greatest offender of all aircraft that operate on this runway, is shown in Figure 6.6, with an initial circulation value of 200 m²/s. From this figure, it is clear that if dynamic separation were to be applied to such aircraft pairs, ROT would be the determining factor for all aircraft separations. Table 6.13 presents the percentage of aircraft operations that would be restricted by ROT if RECAT II and RECAT III wake separation reductions were to be implemented.

Table 6.13: Percentage of RECAT II and RECAT III Operations Limited by ROT for Runway 09R.

<table>
<thead>
<tr>
<th>RECAT II</th>
<th>RECAT III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of arrivals restricted by ROT</td>
<td>2</td>
</tr>
</tbody>
</table>

* Critical aircraft is B738
6.6.3 ORD Runway 10C

For runway end 10C, 8% of operations are for aircraft in groups B and C, such as Boeing 744, Boeing 772, and Boeing 763 from RECAT 1.5, for which wake separations are from 0-2nm. In the FAA RECAT 1.5 wake matrix, 92% of operations belong to groups D and E, with separations from 2-4.6 nm. For this reason, 5%-6% of operations are not restricted by ROT. Table 6.15 presents values of wake separation proposed by the FAA in RECAT II, and Table 6.14 presents calculated ROT values, and approach speed for each aircraft studied on this runway.

Table 6.14: Runway and Aircraft Parameters for ORD 10C.

<table>
<thead>
<tr>
<th>Aircraft ID</th>
<th>A319</th>
<th>A320/ A321</th>
<th>B737</th>
<th>B738/ B739</th>
<th>B744</th>
<th>B763</th>
<th>B772</th>
<th>CRJ2</th>
<th>CRJ9/ CRJ7</th>
<th>E135</th>
<th>E145</th>
<th>E170</th>
<th>MD82</th>
<th>MD83</th>
</tr>
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<tbody>
<tr>
<td>Fleet Mix (%)</td>
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<td>Approach Ground Speed (knots)</td>
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Table 6.15: Recategorization II Wake Separation FAA Proposed Matrix for ORD 10C.

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<th>B763</th>
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<th>B737</th>
<th>MD83</th>
<th>MD82</th>
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</tr>
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</tbody>
</table>

Note: *No effect.
The maximum circulation capacity for all aircraft operating on runway 10C are shown in Table 6.5. The wake behavior generated by the Boeing 747 400-class aircraft, the greatest offender on this runway, with an initial circulation value of 450 m$^2$/s, is shown in Figure 6.1. Table 6.16 presents the percentage of aircraft operations that would be restricted by ROT if RECAT II and RECAT III wake separation reductions were to be implemented.

Table 6.16: Operations Restricted by ROT in RECAT II and RECAT III for Runway 10C.

<table>
<thead>
<tr>
<th></th>
<th>RECAT II</th>
<th>RECAT III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of arrivals restricted by ROT</td>
<td>8</td>
<td>95</td>
</tr>
</tbody>
</table>

* Critical aircraft is B744

6.6.4 ORD Runway 10L

For runway end 10 L, 11% of operations are for aircraft in group B, such as Boeing 744 and Boeing 772, from RECAT 1.5 classifications, for which wake separations are from 0-2 nm. In the FAA RECAT 1.5 wake matrix, 89% of operations belong to groups D and E, with separations from 2-4.7 nm. For this reason, 12% of operations are not restricted by ROT. Table 6.18 presents values of wake separation proposed by the FAA in RECAT II, and Table 6.17 presents calculated values of ROT and approach speed for each aircraft studied on this runway.

Table 6.17: Runway and Aircraft Parameters for ORD 10L.

<table>
<thead>
<tr>
<th>Aircraft ID</th>
<th>A319</th>
<th>A320/ A321</th>
<th>B737</th>
<th>B738/ B739</th>
<th>B744/ B748</th>
<th>B752/ B753</th>
<th>B772</th>
<th>CRJ9/ CRJ7</th>
<th>DC10</th>
<th>E145</th>
<th>E170</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fleet Mix (%)</td>
<td>3</td>
<td>26</td>
<td>3</td>
<td>35</td>
<td>8</td>
<td>6</td>
<td>3</td>
<td>4</td>
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<td>75</td>
<td>84</td>
<td>50</td>
<td>109</td>
<td>132</td>
</tr>
<tr>
<td>ROT (s)</td>
<td>78</td>
<td>75</td>
<td>81</td>
<td>76</td>
<td>82</td>
<td>73</td>
<td>82</td>
<td>81</td>
<td>66</td>
<td>72</td>
<td>75</td>
</tr>
<tr>
<td>Approach Ground Speed (knots)</td>
<td>150</td>
<td>161</td>
<td>155</td>
<td>162</td>
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<td>150</td>
<td>159</td>
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</table>
Table 6.18: Recategorization II Wake Separation FAA Proposed Matrix for ORD 10L.

<table>
<thead>
<tr>
<th>Leader</th>
<th>B744</th>
<th>B772</th>
<th>DC10</th>
<th>B752</th>
<th>A320</th>
<th>A319</th>
<th>B738</th>
<th>B737</th>
<th>E170</th>
<th>CRJ9</th>
<th>E145</th>
</tr>
</thead>
<tbody>
<tr>
<td>Follower</td>
<td>B</td>
<td>B</td>
<td>C</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>E</td>
<td>E</td>
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<td>B744</td>
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<td>4.6</td>
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<td>4.6</td>
<td>4.7</td>
<td>4.7</td>
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</tr>
<tr>
<td>B772</td>
<td>2</td>
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<td>4.8</td>
<td>4.7</td>
<td>4.7</td>
<td>4.7</td>
</tr>
<tr>
<td>DC10</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2.8</td>
<td>3.1</td>
<td>3.1</td>
<td>3.1</td>
<td>3.2</td>
<td>3.2</td>
<td>3.2</td>
<td>3.2</td>
</tr>
<tr>
<td>B752</td>
<td>D</td>
<td>*</td>
<td>*</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>A320</td>
<td>D</td>
<td>*</td>
<td>*</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
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</tr>
<tr>
<td>A319</td>
<td>D</td>
<td>*</td>
<td>*</td>
<td>2</td>
<td>2</td>
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<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
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</tr>
<tr>
<td>B738</td>
<td>D</td>
<td>*</td>
<td>*</td>
<td>2</td>
<td>2</td>
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<tr>
<td>B737</td>
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</tr>
<tr>
<td>E170</td>
<td>E</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>CRJ9</td>
<td>E</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
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<td>2</td>
<td>2</td>
</tr>
<tr>
<td>E145</td>
<td>E</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Note: *No effect.

The maximum circulation capacity for all aircraft operating on runway 10L are shown in Table 6.5, and the wake behavior generated by the B747 400-class aircraft, the greatest offender of all aircraft that operate on this runway, with an initial circulation value of 450 m2/s, is shown in Figure 6.1. Table 6.19 presents the percentage of aircraft operations that would be restricted by ROT if RECAT II and RECAT III wake separation reductions were to be implemented.

Table 6.19: Percentage of RECAT II and RECAT III Operations Limited by ROT for Runway 10L.

| RECAT II | Percentage of arrivals restricted by ROT | 87 |
| RECAT III | *Percentage of arrivals restricted by ROT | 89 |

* Critical aircraft is B744

6.6.5 ORD Runway 10R

Runway end 10R is predominantly operated by aircraft that belong to groups D and E in the FAA RECAT 1.5 wake matrix. These aircraft have similar weight carrying capabilities, maximum circulation capacity, and wake generation capabilities behavior. For this reason, separations between leaders and followers in this runway fall in the 2-nm meaning that there is little to no wake influence between these aircraft pairs.
Table 6.20: Runway and Aircraft Parameters for ORD 10R.

<table>
<thead>
<tr>
<th>Aircraft ID</th>
<th>A319</th>
<th>A320/ A321</th>
<th>B738/ B739</th>
<th>CRJ2</th>
<th>CRJ9/ CRJ7</th>
<th>E135</th>
<th>E145</th>
<th>E170</th>
<th>MD82</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fleet Mix (%)</td>
<td>5</td>
<td>12</td>
<td>14</td>
<td>5</td>
<td>16</td>
<td>3</td>
<td>26</td>
<td>18</td>
<td>2</td>
</tr>
<tr>
<td>Frequency</td>
<td>558</td>
<td>959</td>
<td>1752</td>
<td>611</td>
<td>1789</td>
<td>371</td>
<td>3102</td>
<td>1267</td>
<td>189</td>
</tr>
<tr>
<td>ROT (s)</td>
<td>58</td>
<td>58</td>
<td>56</td>
<td>54</td>
<td>56</td>
<td>52</td>
<td>53</td>
<td>54</td>
<td>56</td>
</tr>
<tr>
<td>Approach Ground Speed (knots)</td>
<td>155</td>
<td>159</td>
<td>163</td>
<td>156</td>
<td>157</td>
<td>161</td>
<td>160</td>
<td>157</td>
<td>148</td>
</tr>
</tbody>
</table>

Table 6.21: Recategorization II Wake Separation FAA Proposed Matrix for ORD 10R.

<table>
<thead>
<tr>
<th>Leader</th>
<th>A320</th>
<th>A319</th>
<th>B738</th>
<th>MD82</th>
<th>E170</th>
<th>CRJ9</th>
<th>CRJ2</th>
<th>E135</th>
<th>E145</th>
</tr>
</thead>
<tbody>
<tr>
<td>A320</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
</tr>
<tr>
<td>A319</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
</tr>
<tr>
<td>B738</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
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<tr>
<td>MD82</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
</tr>
<tr>
<td>E170</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
</tr>
<tr>
<td>CRJ9</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
</tr>
<tr>
<td>CRJ2</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
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<tr>
<td>E135</td>
<td>E</td>
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<td>E</td>
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<td>E145</td>
<td>E</td>
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<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
</tr>
</tbody>
</table>

Table 6.21 presents values of wake separation proposed by the FAA in RECAT II, and Table 6.20 presents calculated values of ROT and approach speed for each aircraft studied on this runway. Table 6.22 presents the percentage of aircraft operations that would be restricted by ROT if RECAT II and RECAT III wake separation reductions were to be implemented.

Table 6.22: Percentage of RECAT II and RECAT III Operations Limited by ROT for Runway 10R.

<table>
<thead>
<tr>
<th>RECAT II</th>
<th>RECAT III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of arrivals restricted by ROT</td>
<td>2</td>
</tr>
</tbody>
</table>

* Critical aircraft is B738

6.6.6 ORD Runway 22R

For Runway end 22R, 5% of operations are for B772 and DC10 aircraft in group B and C from RECAT 1.5 classifications for which wake separations are from 3-nm to 0 nm. 95% of operations
belong to groups D and E in the FAA RECAT 1.5 wake matrix with separations from 4.8 nm- 2nm. For this reason, 4% of operations are not restricted by ROT.

Table 6.23: Runway and Aircraft Parameters for ORD 22R.

<table>
<thead>
<tr>
<th>Aircraft ID</th>
<th>A319</th>
<th>A320/ A321</th>
<th>B738/ B739</th>
<th>B752/ B753</th>
<th>B772</th>
<th>CRJ2</th>
<th>CRJ9/ CRJ7</th>
<th>DC10</th>
<th>E145</th>
<th>E170</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fleet Mix (%)</td>
<td>3</td>
<td>23</td>
<td>35</td>
<td>6</td>
<td>3</td>
<td>4</td>
<td>8</td>
<td>2</td>
<td>11</td>
<td>4</td>
</tr>
<tr>
<td>Frequency</td>
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<td>259</td>
<td>395</td>
<td>54</td>
<td>63</td>
<td>79</td>
<td>101</td>
<td>45</td>
<td>202</td>
<td>76</td>
</tr>
<tr>
<td>ROT (s)</td>
<td>57</td>
<td>62</td>
<td>64</td>
<td>77</td>
<td>71</td>
<td>53</td>
<td>52</td>
<td>81</td>
<td>51</td>
<td>55</td>
</tr>
<tr>
<td>Approach Ground Speed (knots)</td>
<td>146</td>
<td>152</td>
<td>157</td>
<td>150</td>
<td>157</td>
<td>144</td>
<td>143</td>
<td>157</td>
<td>146</td>
<td>138</td>
</tr>
</tbody>
</table>

Table 6.24: Recategorization II Wake Separation FAA Proposed Matrix for ORD 22R.

<table>
<thead>
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<th>Leader</th>
<th>B772</th>
<th>DC10</th>
<th>B752</th>
<th>A320</th>
<th>A319</th>
<th>B738</th>
<th>E170</th>
<th>CRJ9</th>
<th>CRJ2</th>
<th>E145</th>
</tr>
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<td>4.6</td>
<td>4.8</td>
<td>4.7</td>
<td>4.7</td>
<td>4.7</td>
</tr>
<tr>
<td>DC10</td>
<td>C</td>
<td>2</td>
<td>2</td>
<td>2.8</td>
<td>3.1</td>
<td>3.1</td>
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<td>3.2</td>
<td>3.2</td>
<td>3.2</td>
</tr>
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<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>A320</td>
<td>D</td>
<td>*</td>
<td>2</td>
<td>2</td>
<td>2</td>
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<td>2</td>
<td>2</td>
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<tr>
<td>B738</td>
<td>D</td>
<td>*</td>
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<td>2</td>
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<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>E170</td>
<td>E</td>
<td>*</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>CRJ9</td>
<td>E</td>
<td>*</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>CRJ2</td>
<td>E</td>
<td>*</td>
<td>2</td>
<td>2</td>
<td>2</td>
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</tr>
<tr>
<td>E145</td>
<td>E</td>
<td>*</td>
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<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Note: *No effect.

Table 6.24 presents values of wake separation proposed by the FAA in RECAT II, and Table 6.23 presents calculated values of ROT and approach speed for each aircraft studied on this runway. Table 6.25 presents the percentage of aircraft operations that would be restricted by ROT if RECAT II and RECAT III wake separation reductions were to be implemented.

Table 6.25: Percentage of RECAT II and RECAT III Operations Limited by ROT for Runway 22R.

<table>
<thead>
<tr>
<th>RECAT II</th>
<th>Percentage of arrivals restricted by ROT</th>
<th>24</th>
</tr>
</thead>
<tbody>
<tr>
<td>RECAT III</td>
<td>*Percentage of arrivals restricted by ROT</td>
<td>94</td>
</tr>
</tbody>
</table>

* Critical aircraft is B772
6.6.7 ORD Runway 27L

Runway end 27L is predominantly operated by aircraft that belong to groups D and E in the FAA RECAT 1.5 wake matrix. These aircraft have similar weight carrying capabilities, maximum circulation capacity, and wake generation capabilities behavior. For this reason, separations between leaders and followers in this runway fall in the 2-nm meaning that there is little to no wake influence between these aircraft pairs.

Table 6.26: Runway and Aircraft Parameters for ORD 27L.

<table>
<thead>
<tr>
<th>Aircraft ID</th>
<th>A319</th>
<th>A320/A321</th>
<th>B738/B739</th>
<th>CRJ2</th>
<th>CRJ9/CRJ7</th>
<th>E135</th>
<th>E145</th>
<th>E170</th>
<th>MD83</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fleet Mix (%)</td>
<td>5</td>
<td>14</td>
<td>23</td>
<td>6</td>
<td>15</td>
<td>2</td>
<td>22</td>
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</tr>
<tr>
<td>Frequency</td>
<td>3808</td>
<td>7422</td>
<td>11984</td>
<td>4317</td>
<td>10355</td>
<td>1603</td>
<td>16725</td>
<td>8190</td>
<td>1464</td>
</tr>
<tr>
<td>ROT (s)</td>
<td>54</td>
<td>55</td>
<td>55</td>
<td>49</td>
<td>52</td>
<td>48</td>
<td>53</td>
<td>51</td>
<td>54</td>
</tr>
<tr>
<td>Approach Ground Speed (knots)</td>
<td>148</td>
<td>152</td>
<td>156</td>
<td>150</td>
<td>150</td>
<td>152</td>
<td>152</td>
<td>150</td>
<td>151</td>
</tr>
</tbody>
</table>

Table 6.27: Recategorization II Wake Separation FAA Proposed Matrix for ORD 27L.

<table>
<thead>
<tr>
<th>Leader</th>
<th>A320</th>
<th>A319</th>
<th>B738</th>
<th>MD83</th>
<th>E170</th>
<th>CRJ9</th>
<th>CRJ2</th>
<th>E135</th>
<th>E145</th>
</tr>
</thead>
<tbody>
<tr>
<td>A320</td>
<td>D</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
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<td>A319</td>
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<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>B738</td>
<td>D</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
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<tr>
<td>MD83</td>
<td>D</td>
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<td>E170</td>
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<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>CRJ9</td>
<td>E</td>
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<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
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</tr>
<tr>
<td>CRJ2</td>
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<td>2</td>
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<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 6.26 presents calculated values of ROT and approach speed for each aircraft studied on this runway and Table 6.27 presents values of wake separation proposed by the FAA in RECAT II. Table 6.28 presents the percentage of aircraft operations that would be restricted by ROT if RECAT II and RECAT III wake separation reductions were to be implemented.
Table 6.28: Percentage of RECAT II and RECAT III Operations Limited by ROT for Runway 27L.

<table>
<thead>
<tr>
<th>RECAT II</th>
<th>RECAT III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of arrivals restricted by ROT</td>
<td>Percentage of arrivals restricted by ROT</td>
</tr>
<tr>
<td>1</td>
<td>49</td>
</tr>
</tbody>
</table>

*Critical aircraft is B738*

6.6.8 ORD Runway 27R

Runway end 27R is predominantly operated by aircraft that belong to groups D and E in the FAA RECAT 1.5 wake matrix. These aircraft have similar weight carrying capabilities, maximum circulation capacity, and wake generation capabilities behavior. For this reason, separations between leaders and followers in this runway fall in the 2-nm meaning that there is little to no wake influence between these aircraft pairs. Table 6.29 presents calculated values of ROT and approach speed for each aircraft studied on this runway. Table 6.30 presents values of wake separation proposed by the FAA in RECAT II.

Table 6.29: Runway and Aircraft Parameters for ORD 27R.

<table>
<thead>
<tr>
<th>Aircraft ID</th>
<th>A319</th>
<th>A320</th>
<th>B738/B739</th>
<th>CRJ2</th>
<th>CRJ9/CRJ7</th>
<th>E135</th>
<th>E145</th>
<th>E170</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fleet Mix (%)</td>
<td>5</td>
<td>8</td>
<td>14</td>
<td>11</td>
<td>22</td>
<td>4</td>
<td>26</td>
<td>10</td>
</tr>
<tr>
<td>Frequency</td>
<td>1962</td>
<td>3332</td>
<td>5682</td>
<td>4449</td>
<td>5217</td>
<td>1415</td>
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<td>4018</td>
</tr>
<tr>
<td>ROT (s)</td>
<td>59</td>
<td>57</td>
<td>57</td>
<td>58</td>
<td>58</td>
<td>56</td>
<td>56</td>
<td>58</td>
</tr>
<tr>
<td>Approach Ground Speed (knots)</td>
<td>149</td>
<td>154</td>
<td>158</td>
<td>151</td>
<td>152</td>
<td>153</td>
<td>155</td>
<td>151</td>
</tr>
</tbody>
</table>

Table 6.30: Recategorization II Wake Separation FAA Proposed Matrix for ORD 27R.

<table>
<thead>
<tr>
<th>Leader</th>
<th>A320</th>
<th>A319</th>
<th>B738</th>
<th>E170</th>
<th>CRJ9</th>
<th>CRJ2</th>
<th>E135</th>
<th>E145</th>
</tr>
</thead>
<tbody>
<tr>
<td>A320</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
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<tr>
<td>A319</td>
<td>D</td>
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<td>2</td>
<td>2</td>
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</tr>
<tr>
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<td>2</td>
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<td>2</td>
</tr>
<tr>
<td>E170</td>
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<td>2</td>
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<td>2</td>
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<td>2</td>
<td>2</td>
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</tr>
<tr>
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<td>E</td>
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<td>2</td>
</tr>
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<td>CRJ2</td>
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<td>2</td>
<td>2</td>
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<tr>
<td>E135</td>
<td>E</td>
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<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
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</tr>
<tr>
<td>E145</td>
<td>E</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>
Error! Not a valid bookmark self-reference, presents the percentage of aircraft operations that would be restricted by ROT if RECAT II and RECAT III wake separation reductions were to be implemented.

Table 6.31: Percentage of RECAT II and RECAT III Operations Limited by ROT for Runway 27R.

<table>
<thead>
<tr>
<th></th>
<th>RECAT II</th>
<th>RECAT III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of arrivals restricted by ROT</td>
<td>2</td>
<td>73</td>
</tr>
</tbody>
</table>

*Critical aircraft is B738

6.6.9 ORD Runway 28C

For Runway end 28C, 10% of operations are for Boeing 744, Boeing 772 and Boeing 763 aircraft in group B and C from RECAT 1.5 classifications for which wake separations are from 3.5-nm to 0 nm. 90% of operations belong to groups D and E in the FAA RECAT 1.5 wake matrix with separations from 4.8 nm-2nm. For this reason, 13% of operations are not restricted by ROT.

Table 6.32: Runway and Aircraft Parameters for ORD 28C.

<table>
<thead>
<tr>
<th>Aircraft ID</th>
<th>A319</th>
<th>A320/ A321</th>
<th>B737</th>
<th>B738/ B739</th>
<th>B744/ B748</th>
<th>B763</th>
<th>B772</th>
<th>CRJ2</th>
<th>CRJ9/ CRJ7</th>
<th>E135</th>
<th>E145</th>
<th>E170</th>
<th>MD83/ MD82</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fleet Mix (%)</td>
<td>4</td>
<td>10</td>
<td>1</td>
<td>20</td>
<td>6</td>
<td>4</td>
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<td>14</td>
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<td>Frequency</td>
<td>1573</td>
<td>3394</td>
<td>605</td>
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<td>1703</td>
<td>1625</td>
<td>1792</td>
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<td>766</td>
<td>7733</td>
<td>3513</td>
<td>1347</td>
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<tr>
<td>ROT (s)</td>
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<td>58</td>
<td>56</td>
<td>57</td>
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<td>60</td>
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<td>53</td>
<td>54</td>
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<td>Approach Ground Speed (knots)</td>
<td>146</td>
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<td>155</td>
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<td>151</td>
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<td>147</td>
<td>148</td>
<td>149</td>
<td>150</td>
<td>147</td>
<td>149</td>
</tr>
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</table>
Table 6.33: Recategorization II Wake Separation FAA Proposed Matrix for ORD 28C.

<table>
<thead>
<tr>
<th>Leader</th>
<th>B744</th>
<th>B772</th>
<th>B763</th>
<th>A320</th>
<th>A319</th>
<th>B738</th>
<th>B737</th>
<th>MD83</th>
<th>E170</th>
<th>CRJ9</th>
<th>CRJ2</th>
<th>E135</th>
<th>E145</th>
</tr>
</thead>
<tbody>
<tr>
<td>B744</td>
<td>B</td>
<td>2</td>
<td>2.4</td>
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<td>4.5</td>
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</tr>
</tbody>
</table>

Note: *No effect.

Table 6.33 presents values of wake separation proposed by the FAA in RECAT II, and Table 6.32 presents calculated values of ROT and approach speed for each aircraft studied on this runway. Table 6.34 presents the percentage of aircraft operations that would be restricted by ROT if RECAT II and RECAT III wake separation reductions were to be implemented.

Table 6.34: Percentage of RECAT II and RECAT III Operations Limited by ROT for Runway 28C.

<table>
<thead>
<tr>
<th>RECAT II</th>
<th>Percentage of arrivals restricted by ROT</th>
<th>13</th>
</tr>
</thead>
<tbody>
<tr>
<td>RECAT III</td>
<td>*Percentage of arrivals restricted by ROT</td>
<td>87</td>
</tr>
</tbody>
</table>

* Critical aircraft is B744

6.6.10 ORD Runway 28R

For Runway end 28R, 13% of operations are for Boeing 744, Boeing 772 and McDonnell Douglas 10 aircraft in group B and C from RECAT 1.5 classifications for which wake separations are from 3.5 nm to 0 nm. 87% of operations belong to groups D and E in the FAA RECAT 1.5 wake matrix with separations from 4.8 nm- 2nm. For this reason, 18% of operations are not restricted by ROT.
Table 6.35: Runway and Aircraft Parameters for ORD 28R.

<table>
<thead>
<tr>
<th>Aircraft ID</th>
<th>A319</th>
<th>A320/ A321</th>
<th>B737</th>
<th>B738/ B739</th>
<th>B744/ B748</th>
<th>B752/ B753</th>
<th>B772</th>
<th>CRJ2</th>
<th>CRJ9/ CRJ7</th>
<th>DC10</th>
<th>E145</th>
<th>E170</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fleet Mix (%)</td>
<td>2</td>
<td>18</td>
<td>30</td>
<td>18</td>
<td>5</td>
<td>5</td>
<td>2</td>
<td>4</td>
<td>7</td>
<td>6</td>
<td>3</td>
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<tr>
<td>Frequency</td>
<td>49</td>
<td>287</td>
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<td>107</td>
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<td>79</td>
<td>134</td>
<td>115</td>
<td>68</td>
<td>49</td>
</tr>
<tr>
<td>ROT (s)</td>
<td>67</td>
<td>67</td>
<td>67</td>
<td>86</td>
<td>71</td>
<td>71</td>
<td>61</td>
<td>65</td>
<td>88</td>
<td>60</td>
<td>62</td>
<td>67</td>
</tr>
<tr>
<td>Approach Ground Speed (knots)</td>
<td>139</td>
<td>147</td>
<td>161</td>
<td>163</td>
<td>134</td>
<td>127</td>
<td>160</td>
<td>141</td>
<td>154</td>
<td>132</td>
<td>156</td>
<td>139</td>
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</tbody>
</table>

Table 6.36: Recategorization II Wake Separation FAA Proposed Matrix for ORD 28R.

<table>
<thead>
<tr>
<th>Leader</th>
<th>B744</th>
<th>B772</th>
<th>DC10</th>
<th>B752</th>
<th>A320</th>
<th>A319</th>
<th>B738</th>
<th>E170</th>
<th>CRJ9</th>
<th>CRJ2</th>
<th>E145</th>
</tr>
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<tbody>
<tr>
<td>B744</td>
<td>B</td>
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<td>2.4</td>
<td>B</td>
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</tr>
<tr>
<td>DC10</td>
<td>C</td>
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</tr>
<tr>
<td>E170</td>
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</tr>
<tr>
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<td>E</td>
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</tr>
<tr>
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<td>E</td>
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<td>2</td>
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<tr>
<td>E145</td>
<td>E</td>
<td>*</td>
<td>*</td>
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<td>2</td>
<td>2</td>
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</tr>
</tbody>
</table>

Note: *No effect.

Table 6.36 presents values of wake separation proposed by the FAA in RECAT II, and Table 6.35 presents calculated values of ROT and approach speed for each aircraft studied on this runway. Table 6.37 presents the percentage of aircraft operations that would be restricted by ROT if RECAT II and RECAT III wake separation reductions were to be implemented.

Table 6.37: Percentage of RECAT II and RECAT III Operations Limited by ROT for Runway 28R.

<table>
<thead>
<tr>
<th>RECAT II</th>
<th></th>
<th>RECAT III</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of arrivals restricted by ROT</td>
<td>53</td>
<td>*Percentage of arrivals restricted by ROT</td>
<td>83</td>
</tr>
</tbody>
</table>

*Critical aircraft is B744*
6.7 Conclusions and Recommendations

The objective of this research is to simulate aircraft operations during arrival, as well as the environmental conditions in the aircraft flight path, to derive dynamic wake separations RECAT III and compare separations values with FAA proposed static separations RECAT II to evaluate possible gains and feasibility of operation and implementation of RECAT III.

For this, Chicago ORD unique fleet mix, ROT, approach speed and operational buffers data for each runway end under study is used to calculate potential capacity benefits if wake RECAT III were to be implemented and the percentage of operations that are not restricted by ROT.

As seen from the analysis, further reductions beyond RECAT II for those aircraft pairs that are separated 2-nm or below is not operationally feasible. Wake separations of two nautical miles or below already implies no wake dependency between the aircraft pair, this can be inferred by ROT and RECAT II-time separations. When this is the case, the challenges in wake separation are to meet ROT and to make sure the aircraft separations allows for human operational errors without resulting in aircraft turn-arounds or double aircraft occupancy runway violations.

6.8 Acknowledgments

This research has been made possible thanks to the research contributions of the Federal Aviation Administration Wake Program, National Aeronautics and Space Administration (NASA) wake program, EUROCONTROL, Japan Aerospace Exploration Agency, Wakenet meeting members, MIT Lincoln Laboratory, and private industry research labs such as the MITRE Corporation.

6.9 Disclaimer

The contents of this material reflect the views of the author only. Neither the Federal Aviation Administration nor the United States Department of Transportation nor the National Aeronautics and Space Administration makes any warranty or guarantee, or promise, expressed or implied, concerning the content or accuracy of the views expressed herein.

Any opinion, findings, and conclusion or recommendations presented herein are those of the author and do not necessarily reflect the views of the FAA or NASA.
6.10 References


7. Simulation and Modeling of Aircraft Operations to Evaluate Dynamic Aircraft Separations with Runway Limitations

7.1 Abstract

This study analyzes how much of the aircraft-to-aircraft separation reductions that result from the Federal Aviation Administration’s (FAA) proposed wake recategorization phase II (RECAT II) and RECAT III dynamic wake separations can translate to an operational airport capacity increase at current airport infrastructures. This percentage of arrivals restricted by runway occupancy time (ROT) between RECAT II and RECAT III is compared and analyzed. The study examines each runway that is operated under capacity constraints at Denver International Airport (DEN) and at LaGuardia Airport (LGA).

This simulation uses a Monte Carlo approach to calculate the dynamic wake separation required for a follower aircraft by using the National Aeronautics and Space Administration (NASA) Aircraft Vortex Spacing System (AVOSS) Prediction Algorithm (APA) model, a semi-empirical wake behavior model that predicts wake decay as a function of atmospheric turbulence and stratification.

This study simulates steady-state operations for 1,000 arrivals per runway, resulting in more than 24 hours of operation at capacity. The simulation injects departures in between arrivals when aircraft wake separation distances comply with regulations.

Dynamic wake separations account for not only the wake vortex circulation strength of each individual aircraft but also the aircraft condition and environmental parameters under which the aircraft operates.

In the simulation, each runway is operated independently, and priority has been given to arrival procedures. A heuristic algorithm assigns sequences of arrivals and departures to traffic while enforcing wake separation regulations.

Results indicate that further reducing wake separations distances from the proposed RECAT II static matrix, of 2 nm and less, shifts the operational bottleneck from the airspace to the final approach
segment. Consequently, given current values of aircraft ROT, the airport runway becomes the limiting factor for inter-arrival separations.

7.2 Introduction

Federal Aviation Administration (FAA) initiatives are developing new platforms that create procedures, technologies, and capabilities that enable a safe and more efficient next generation (NextGen) of airports. NextGen is an FAA program with the goal of improving the safety, efficiency, predictability, capacity, and resilience of the air transportation industry. Aircraft wake vortex has been identified as a major challenge for the NextGen program, specifically to the sustainable development of the safety and capacity of the airport system (Holzapfel and Gerz 2012).

Wake vortex research has identified a promising concept for wake mitigation called dynamic wake separation. This concept considers live aircraft conditions, such as aircraft weight, speed, and altitude, and environmental parameters, such as environmental turbulence, air density, temperature, and crosswind, of each aircraft in operation. This information is used to derive dynamic wake separations between aircraft arriving or departing a runway. Not only would this concept minimize the impact of disruptions from weather, but it would also make aircraft wake separations more efficient while still satisfying current safety requirements.

Previous research has derived the maximum wake circulation capacities (MCC) that an aircraft can safely endure without disturbing flight operations as well as the bounds of possible wake separation reductions based on proposed FAA RECAT II wake separations.

This study simulates arriving aircraft operations at Denver International Airport (DEN) and La Guardia Airport (LGA). It accounts for real-world recorded conditions, such as the aircraft fleet operating at that runway, the approach speed for aircraft on the final approach segment the buffer times used by controllers to manage human and operational errors, and the time for each aircraft to clear the runway.

7.3 Objective

The objective of this research is to calculate the percentage of time that dynamic wake separations are limited by runway occupancy time (ROT). Fully implementing RECAT III dynamic wake separations will require major system changes regarding air traffic control computer dependency and aircraft
equipage. Looking into ROT limitations will help us understand the percentage of actual possible operational gains provided by RECAT III if the FAA proceeds with the implementation phase of current airport infrastructures.

This study analyzes how much of the aircraft-to-aircraft separation reductions that result from relating aircraft and environmental parameters to wake behavior can translate to an operational airport capacity increase under current airport infrastructure. The study examines each runway end that is operated under capacity constraints at DEN and at LGA.

This study also intends to identify future research needs and gaps to understand the implications of reduced wake separations to the airport system. To achieve a safe and sustainable operational airport capacity increase, the implications of and effects on other processes of the system need to be recognized.

7.4 Methodology

The methodology for calculating runway throughput for the airport runways under study is based on a Monte Carlo constructive simulation of runway operation procedures. For this research, a computer program was developed to simulate aircraft on final approach under real-world conditions for aircraft parameters and environmental factors.

The simulation generates a randomized traffic schedule that keeps the pressure on the runway. The traffic sample reflects an airport’s mix of aircraft types and generates traffic so that there is a constant demand on the runway system. As aircraft enter the final approach fix (FAF), which is a point of conversion for aircraft approaching the same runway, the simulation assigns aircraft parameters and environmental conditions and predicts wake vortex behavior. Based on this unique set of conditions and the follower aircraft MCC, the simulation calculates wake separation for the follower aircraft and reports it to the ATC.

The air traffic control, which the simulation represents with a module, then compares the median ROT value for the leader aircraft, plus an operational time buffer, with the time that it will take the current leader to clear the runway. The air traffic control then enforces the safest separation, which is the larger separation of the two calculations.

This procedure accounts for static and dynamic wake vortex separations; ROTs; aircraft approach speeds; MCC; environmental conditions such as air density, crosswind, temperature, environmental
turbulence, and Brunt–Väisälä frequency; and human operational error buffers. Figure 7.1 illustrates wake vortex separation simulation.

Figure 7.1: Wake Vortex Separation.

The simulation uses aircraft that represent 85% or more of the total operations at the studied runway ends. For all runway ends under study, fewer than ten unique aircraft comply with the criteria, though 14 aircraft were selected for runway end 17R at DEN, representing 75% of its total operations.

This simulation calculated the dynamic wake separation required for a follower aircraft by using the National Aeronautics and Space Administration (NASA) Aircraft Vortex Spacing System (AVOSS) Prediction Algorithm (APA) model, a semi-empirical wake behavior model that predicts wake decay as a function of atmospheric turbulence and stratification.

The system simulates steady-state operations for 1,000 arrivals per runway, resulting in more than 24 hours of operation at capacity. The system injects departures in between arrivals when aircraft wake separation distances comply with regulations.

In the simulation, each runway is operated independently, and priority has been given to arrival procedures. A heuristic algorithm assigns runways and sequences of arrivals and departures to traffic while enforcing FAA regulations. The simulation records the average throughput achieved by each runway.

The simulation uses parameters such as aircraft frequency, ROT, and approach speed according to values recorded on Airport Surface Detection Equipment Model X (ASDE-X). Records with empty values for either the ROT or the approach speed, as well as ROT values greater than 150 seconds, have been filtered.

The EDR distribution is in accordance with the in-ground-effect altitude where values considered for the simulation range between moderate $1.35 \times 10^3 \text{ m}^2/\text{s}^3$ to intense $1.50 \times 10^2 \text{ m}^2/\text{s}^3$, with 80 percent
of the values in the range moderate $1.35 \times 10^{-3}$ m$^2$/s$^3$ to strong $7.17 \times 10^{-3}$ m$^2$/s$^3$ (Proctor, Hamilton et al. 2006) (Switzer and Proctor 2000). This range to represents typical EDR values in the lower atmosphere (Perras, Dasey et al. 2000).

These calculations vary environmental factors such as temperature, crosswind speeds, and environmental turbulence every 15 minutes. Values for a temperature range between 283 and 299 Kelvin and values for crosswind speeds range between 0 m/s and 12.86 m/s. Air density is based on the international standard atmosphere, and aircraft performance is based on Base of Aircraft Data (BADA). Aircraft weight is based on typical real-world aircraft weight recorded for arrivals and departures for each aircraft.

The approach to calculating the percentage of operations restricted by ROT, accounting for the buffer, does the following:

If operational wake separation between leader and follower (wake separation plus operational buffer) is less than the ROT of the leader aircraft, then the system adjusts the separation to ROT plus buffer and records this instance as ROT restricted; otherwise, it uses operational wake separation.

The selected airports for this study are DEN and LGA. Runway ends studied for each airport are those runways that operate under capacity constraints, defined in this study as a demand greater than ten aircraft operations per 15-minute period.

7.4.1 Denver International Airport (DEN)

The airfield at DEN consists of six runways configured as two sets of parallel runways oriented in the north-south direction and two crosswind runways oriented in an east-west direction. Runway 16R-34L is the longest commercial runway in the United States at 16,000 feet (Denver-Dept.-Aviation 2012).

DEN operates with an aircraft flow that is generally north-south, with arrivals occurring on one side of the central terminal area and departures on the other side. East-west runways provide crosswind capability and additional capacities for servicing arriving and departing aircraft when winds permit.

Figure 7.2 shows real aircraft arrival tracks during the 24-hour period on August 23, 2016. This is the busiest day in the three months analyzed—January, July, and August—based on the available ASDE-X data of 994 arrivals. According to the real-world operational data studied, a final approach segment of 6 nm has been considered.
Figure 7.2: Arrival Operations at Denver International Airport for a 24-Hour Period.

7.4.2 La Guardia Airport (LGA)

The airfield at LGA consists of two intersecting runways: runway 13/31 with a length of 7,003 feet and runway 04/22 with a length if 7,001 feet. The airport elevation is sea level. Runways at LGA have aircraft weight limitations that are related the runway structural construction (FAA-Capacity-Profiles 2014).

Figure 7.3 shows aircraft arrival tracks during a 24-hour period on January 19, 2016. This is the busiest day in the four months of ASDE-X data available (January, February, July, and September);
621 arrivals were studied. According to available data, the length of final approach segment was set to 6 nm. Departures were not studied due to lack of ASDE-X departure data for LGA.

Figure 7.3: Arrival Operations at La Guardia Airport Arrivals for a 24-Hour Period.

7.5 Results

The analysis of the results considers each runway end separately, according to its unique aircraft fleet mix and the ROT of each aircraft. Those aircraft that represent 85% to 95% of the total operations at that runway are selected. The average approach speed for each aircraft over the 6-nm final approach path is calculated and used for simulation. Table 7.1 presents the calculated values of MCC and approach speed for all aircraft under study when the Airbus 380-class aircraft is the leading aircraft.

The number of arrival operations simulated is 1,000 operations. Departures are launched in between successive arrivals if the wake gap for each pair of aircraft is larger than wake minimum separation standards. The simulation assumes 2-nm plus an additional buffer to be the minimum separation between arriving and departing aircraft.
Table 7.1: MCC for Aircraft Studied, with Airbus 380-Class Aircraft as the Critical Aircraft in the National Airspace.

<table>
<thead>
<tr>
<th>Follower</th>
<th>Approach Speed</th>
<th>RECAT II Time (s)</th>
<th>RECAT II Distance (nm)</th>
<th>MCC 95th pctl (m²/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A388</td>
<td>148</td>
<td>61</td>
<td>2.5</td>
<td>418</td>
</tr>
<tr>
<td>A319</td>
<td>150</td>
<td>149</td>
<td>6.2</td>
<td>263</td>
</tr>
<tr>
<td>A320</td>
<td>154</td>
<td>145</td>
<td>6.2</td>
<td>268</td>
</tr>
<tr>
<td>B737</td>
<td>153</td>
<td>146</td>
<td>6.2</td>
<td>266</td>
</tr>
<tr>
<td>B738</td>
<td>159</td>
<td>145</td>
<td>6.4</td>
<td>268</td>
</tr>
<tr>
<td>B744</td>
<td>162</td>
<td>84</td>
<td>3.8</td>
<td>363</td>
</tr>
<tr>
<td>B752</td>
<td>152</td>
<td>139</td>
<td>5.9</td>
<td>275</td>
</tr>
<tr>
<td>B763</td>
<td>154</td>
<td>122</td>
<td>5.2</td>
<td>298</td>
</tr>
<tr>
<td>B772</td>
<td>155</td>
<td>98</td>
<td>4.2</td>
<td>336</td>
</tr>
<tr>
<td>CRJ2</td>
<td>152</td>
<td>152</td>
<td>6.4</td>
<td>259</td>
</tr>
<tr>
<td>CRJ9</td>
<td>153</td>
<td>151</td>
<td>6.4</td>
<td>261</td>
</tr>
<tr>
<td>DC10</td>
<td>151</td>
<td>126</td>
<td>5.3</td>
<td>292</td>
</tr>
<tr>
<td>E120</td>
<td>145</td>
<td>173</td>
<td>7</td>
<td>237</td>
</tr>
<tr>
<td>E135</td>
<td>153</td>
<td>150</td>
<td>6.4</td>
<td>262</td>
</tr>
<tr>
<td>E145</td>
<td>155</td>
<td>149</td>
<td>6.4</td>
<td>263</td>
</tr>
<tr>
<td>E170</td>
<td>151</td>
<td>150</td>
<td>6.3</td>
<td>262</td>
</tr>
<tr>
<td>E190</td>
<td>156</td>
<td>146</td>
<td>6.3</td>
<td>266</td>
</tr>
<tr>
<td>MD82</td>
<td>153</td>
<td>151</td>
<td>6.4</td>
<td>261</td>
</tr>
<tr>
<td>MD83</td>
<td>153</td>
<td>150</td>
<td>6.4</td>
<td>262</td>
</tr>
</tbody>
</table>

Values presented in table are simulation based. These values do not represent the views of the FAA.

Simulated conditions for ROT and approach speeds are in accordance with the runway under study and follow the distribution according to the ASDE-X data studied. The common approach path length is considered to be 6 nm.

The runway occupancy for aircraft operating on the runway is the average ROT, in seconds, to the hold bar; the average approach speed is the ground speed in knots from the FAF to the runway threshold for the 8.5-nm final approach path.

7.5.1 Results for Denver International Airport

7.5.1.1 Runway End 16L

The aircraft operating on runway end 16L predominantly belong to groups D and E in the FAA RECAT 1.5 wake matrix. These aircraft have similar weight carrying capabilities, MCC, and wake generation capabilities. For this reason, RECAT II separations between leaders and followers for this runway fall in the 2-nm range, as shown in Table 7.2. Wake separations of 2-nm represent little to no
wake influence between these aircraft pairs. Table 7.3 presents calculated values of ROT and approach 
speed for each aircraft studied on this runway.

Table 7.2: RECAT II Wake Separation FAA Proposed Matrix for DEN 16L.

<table>
<thead>
<tr>
<th>Leader</th>
<th>A320</th>
<th>A319</th>
<th>B738</th>
<th>B737</th>
<th>E170</th>
<th>CRJ9</th>
<th>CRJ2</th>
</tr>
</thead>
<tbody>
<tr>
<td>A320</td>
<td>D</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>A319</td>
<td>D</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>B738</td>
<td>D</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>B737</td>
<td>D</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>E170</td>
<td>D</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>CRJ9</td>
<td>D</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>CRJ2</td>
<td>E</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 7.3: Runway and Aircraft Parameters for DEN 16L.

<table>
<thead>
<tr>
<th>Aircraft ID</th>
<th>A319</th>
<th>A320/A321</th>
<th>B737</th>
<th>B738/B739</th>
<th>CRJ2</th>
<th>CRJ9/CRJ7</th>
<th>E170</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fleet Mix (%)</td>
<td>12</td>
<td>20</td>
<td>18</td>
<td>23</td>
<td>14</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>Approach Ground Speed (knots)</td>
<td>159</td>
<td>164</td>
<td>161</td>
<td>171</td>
<td>160</td>
<td>157</td>
<td>159</td>
</tr>
<tr>
<td>ROT (s)</td>
<td>65</td>
<td>66</td>
<td>65</td>
<td>65</td>
<td>61</td>
<td>66</td>
<td>63</td>
</tr>
</tbody>
</table>

The MCC for all aircraft operating on runway 16L is near 200 m2/s, as shown in Table 7.1, and 
the wake behavior generated by the Boeing 737 800-class aircraft, the critical aircraft studied for this 
runway, is shown in Figure 7.4 with an initial circulation value of 200 m2/s.

Wake circulation for the Boeing 737 800-class aircraft considers a mean aircraft mass of 49,781 kg 
with a standard deviation of 851 kg, based on operational data. This represents operational landing 
weight values in the range of 74% to 76% of MALW. The Boeing 737 800-class aircraft has a MALW 
of 66,362 kg and an MTOW of 79,017 kg.
From this analysis, it is clear that if dynamic separation were to be applied for aircraft pairs selected for runway 16L, ROT would be the determining factor for at least 48 percent of all aircraft separations in RECAT III. This can be seen in Table 7.4.

Table 7.4: Percentage of RECAT II and RECAT III Operations Limited by ROT for DEN 16L.

<table>
<thead>
<tr>
<th></th>
<th>RECAT II</th>
<th>RECAT III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of arrivals restricted by ROT</td>
<td>6</td>
<td>48</td>
</tr>
</tbody>
</table>

* Critical aircraft is B737-800

7.5.1.2 Runway End 16R

Runway end 16R is predominantly operated by aircraft that belong to groups D and E in the FAA RECAT 1.5 wake matrix. These aircraft have similar weight carrying capabilities, MCC, and wake generation capabilities. For this reason, separations between leaders and followers in this runway fall in the 2-nm range, meaning that there is little to no wake influence between these aircraft pairs. Table 7.5 presents calculated values of ROT and approach speed for each aircraft studied on this runway. Values of ROT on this runway are higher than the average values of ROT for any of the studied runways at DEN. Figure 7.5, Figure 7.6, and Figure 7.7 present the ROT distribution for the Boeing 737, Airbus 319, and Canada Regional Jet 200.
Table 7.5: Runway and Aircraft Parameters for DEN 16R.

<table>
<thead>
<tr>
<th>Aircraft ID</th>
<th>A319</th>
<th>A320/A321</th>
<th>B737</th>
<th>B738/B739</th>
<th>B752/B753</th>
<th>CRJ2</th>
<th>CRJ9/CRJ7</th>
<th>DH8D</th>
<th>E145</th>
<th>E170</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fleet Mix (%)</td>
<td>11</td>
<td>14</td>
<td>16</td>
<td>21</td>
<td>2</td>
<td>17</td>
<td>13</td>
<td>1</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Approach Ground Speed (knots)</td>
<td>159</td>
<td>164</td>
<td>160</td>
<td>170</td>
<td>158</td>
<td>160</td>
<td>160</td>
<td>150</td>
<td>161</td>
<td>158</td>
</tr>
<tr>
<td>ROT (s)</td>
<td>78</td>
<td>78</td>
<td>77</td>
<td>76</td>
<td>80</td>
<td>74</td>
<td>75</td>
<td>69</td>
<td>71</td>
<td>74</td>
</tr>
</tbody>
</table>

Figure 7.5: Runway Occupancy Time for Boeing 737-Class Aircraft.

Figure 7.6: Runway Occupancy Time for Airbus 319-Class Aircraft.
Figure 7.7: Runway Occupancy Time for Canadair Regional Jet 200-Class Aircraft.

Table 7.6 presents values of wake separation proposed by the FAA in RECAT II, and Table 7.7 presents the percentage of time arrivals are restricted by ROT on RECAT II and RECAT III operations.

Table 7.6: RECAT II Wake Separation FAA Proposed Matrix for DEN 16R.

<table>
<thead>
<tr>
<th>Leader</th>
<th>B752</th>
<th>A320</th>
<th>A319</th>
<th>B738</th>
<th>B737</th>
<th>DH8D</th>
<th>E170</th>
<th>CRJ9</th>
<th>CRJ2</th>
<th>E145</th>
</tr>
</thead>
<tbody>
<tr>
<td>B752</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
</tr>
<tr>
<td>A320</td>
<td>D</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>A319</td>
<td>D</td>
<td>2</td>
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<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
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<td>2</td>
</tr>
<tr>
<td>B738</td>
<td>D</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
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<td>B737</td>
<td>D</td>
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<td>DH8D</td>
<td>D</td>
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<td>2</td>
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<td>E170</td>
<td>E</td>
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<td>2</td>
<td>2</td>
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<tr>
<td>CRJ9</td>
<td>E</td>
<td>2</td>
<td>2</td>
<td>2</td>
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<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>CRJ2</td>
<td>E</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
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<td>E</td>
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<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 7.7: Percentage of RECAT II and RECAT III Operations Limited by ROT for DEN 16R.

<table>
<thead>
<tr>
<th>RECAT II</th>
<th>RECAT III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of arrivals restricted by ROT</td>
<td>79</td>
</tr>
</tbody>
</table>

* Critical aircraft is B752
7.5.1.3 Runway End 17R

Table 7.9 presents values of wake separation proposed by the FAA in RECAT II, and Table 7.8 presents calculated values of ROT and approach speed for each aircraft studied on this runway.

Table 7.8: Runway and Aircraft Parameters for DEN 17R.

<table>
<thead>
<tr>
<th>Aircraft ID</th>
<th>A319</th>
<th>A320/ A321</th>
<th>B737</th>
<th>B738/ B739</th>
<th>B744</th>
<th>B752</th>
<th>B763</th>
<th>CRJ2</th>
<th>CRJ9/ CRJ7</th>
<th>DH8D</th>
<th>E120</th>
<th>E145</th>
<th>E170</th>
<th>MD83</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fleet Mix (%)</td>
<td>13</td>
<td>16</td>
<td>16</td>
<td>20</td>
<td>1</td>
<td>3</td>
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<td>9</td>
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<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Approach Ground Speed (knots)</td>
<td>159</td>
<td>164</td>
<td>160</td>
<td>171</td>
<td>168</td>
<td>163</td>
<td>158</td>
<td>159</td>
<td>150</td>
<td>158</td>
<td>158</td>
<td>159</td>
<td>165</td>
<td></td>
</tr>
<tr>
<td>ROT (s)</td>
<td>63</td>
<td>62</td>
<td>61</td>
<td>61</td>
<td>70</td>
<td>69</td>
<td>71</td>
<td>61</td>
<td>59</td>
<td>62</td>
<td>59</td>
<td>62</td>
<td>61</td>
<td>62</td>
</tr>
</tbody>
</table>

Table 7.9: RECAT II Wake Separation FAA Proposed Matrix for DEN 17R.

<table>
<thead>
<tr>
<th>Leader</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>D</th>
<th>D</th>
<th>D</th>
<th>D</th>
<th>D</th>
<th>D</th>
<th>E</th>
<th>E</th>
<th>E</th>
<th>E</th>
<th>E</th>
<th>F</th>
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<tbody>
<tr>
<td>B744</td>
<td>B</td>
<td>2</td>
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</tr>
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<td>MD83</td>
<td>D</td>
<td>*</td>
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<td>2</td>
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<td>2</td>
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<td>2</td>
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<td>2</td>
</tr>
<tr>
<td>DH8D</td>
<td>D</td>
<td>*</td>
<td>2</td>
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<td>2</td>
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</tr>
<tr>
<td>E170</td>
<td>E</td>
<td>*</td>
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<tr>
<td>CRJ9</td>
<td>E</td>
<td>*</td>
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<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
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<td>2</td>
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</tr>
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<td>CRJ2</td>
<td>E</td>
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<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>E145</td>
<td>E</td>
<td>*</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
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<td>2</td>
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</tr>
<tr>
<td>E120</td>
<td>F</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>2</td>
</tr>
</tbody>
</table>

Note: *No effect.

For runway end 17R, 4% of operations are for Boeing 747, and Boeing 767 aircraft in group B and C from RECAT 1.5 classifications, for which wake separations when following are from 3.5-nm to 0 nm. For this runway, 96% of operations belong to groups D and E in the FAA RECAT 1.5 wake matrix, with separations from 2-4.8 nm. For this reason, 7% of operations are not restricted by ROT, as shown in Table 7.10 when the Boeing 747-400-class aircraft is considered the critical aircraft.
Table 7.10: Percentage of RECAT II and RECAT III Operations Limited by ROT for DEN 17R.

<table>
<thead>
<tr>
<th>RECAT II</th>
<th>RECAT III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of arrivals restricted by ROT</td>
<td>3</td>
</tr>
<tr>
<td>*Critical aircraft is B744</td>
<td></td>
</tr>
</tbody>
</table>

7.5.1.4 Runway End 34R

Runway end 34R is predominantly operated by aircraft that belong to groups D and E in the FAA RECAT 1.5 wake matrix. These aircraft have similar weight carrying capabilities, MCC, and wake generation capabilities. For this reason, separations between leaders and followers in this runway fall in the 2-nm range, meaning that there is little to no wake influence between these aircraft pairs. Table 7.11 presents results for approach speed and ROT for each aircraft under study.

Table 7.11: Runway and Aircraft Parameters for DEN 34R.

<table>
<thead>
<tr>
<th>Aircraft ID</th>
<th>A319</th>
<th>A320/A321</th>
<th>B737</th>
<th>B738/B739</th>
<th>B752/B755</th>
<th>CRJ2</th>
<th>CRJ9/CRJ7</th>
<th>DH8D</th>
<th>E145</th>
<th>E170</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fleet Mix (%)</td>
<td>9</td>
<td>12</td>
<td>18</td>
<td>23</td>
<td>1</td>
<td>19</td>
<td>12</td>
<td>1</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Approach Ground Speed (knots)</td>
<td>158</td>
<td>162</td>
<td>161</td>
<td>171</td>
<td>160</td>
<td>158</td>
<td>161</td>
<td>147</td>
<td>155</td>
<td>158</td>
</tr>
<tr>
<td>ROT (s)</td>
<td>63</td>
<td>61</td>
<td>61</td>
<td>59</td>
<td>62</td>
<td>61</td>
<td>61</td>
<td>62</td>
<td>59</td>
<td>61</td>
</tr>
</tbody>
</table>

Table 7.12 presents values of wake separation proposed by the FAA in RECAT II, and Table 7.13 presents the percentage of operations restricted by ROT in RECAT II and RECAT III.

Table 7.12: RECAT II Wake Separation FAA Proposed Matrix for DEN 34R.

<table>
<thead>
<tr>
<th>Follower</th>
<th>B752</th>
<th>A320</th>
<th>A319</th>
<th>B738</th>
<th>B737</th>
<th>DH8D</th>
<th>E170</th>
<th>CRJ9</th>
<th>CRJ2</th>
<th>E145</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leader</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>E</td>
<td>E</td>
<td>E</td>
</tr>
<tr>
<td>B752</td>
<td>D</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
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<td>2</td>
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<td>2</td>
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<td>2</td>
</tr>
<tr>
<td>A319</td>
<td>D</td>
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<td>2</td>
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</tr>
<tr>
<td>B738</td>
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</tr>
<tr>
<td>B737</td>
<td>D</td>
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<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>DH8D</td>
<td>D</td>
<td>2</td>
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<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>E170</td>
<td>E</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>CRJ9</td>
<td>E</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>CRJ2</td>
<td>E</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
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<td>E</td>
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<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
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</tr>
</tbody>
</table>

132
Table 7.13: Percentage of RECAT II and RECAT III Operations Limited by ROT for DEN 34R.

<table>
<thead>
<tr>
<th></th>
<th>RECAT II</th>
<th>RECAT III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of arrivals restricted by ROT</td>
<td>1</td>
<td>*94</td>
</tr>
</tbody>
</table>

*Critical aircraft is B752*

7.5.1.5 Runway End 35L

Runway end 35L is predominantly operated by aircraft that belong to groups D and E in the FAA RECAT 1.5 wake matrix. These aircraft have similar weight carrying capabilities, MCC, and wake generation capabilities. For this reason, separations between leaders and followers in this runway fall in the 2-nm range, as shown in Table 7.15, meaning that there is little to no wake influence between aircraft pairs. Table 7.14 presents results for approach speed and ROT for each aircraft under study.

Table 7.14: Runway and Aircraft Parameters for DEN 35L.

<table>
<thead>
<tr>
<th>Aircraft ID</th>
<th>A319</th>
<th>A320/A321</th>
<th>B737</th>
<th>B738/B739</th>
<th>B752/B755</th>
<th>CRJ2</th>
<th>CRJ9/CRJ7</th>
<th>E145</th>
<th>E170</th>
<th>MD83</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fleet Mix (%)</td>
<td>12</td>
<td>17</td>
<td>17</td>
<td>18</td>
<td>2</td>
<td>15</td>
<td>12</td>
<td>2</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Approach Ground Speed (knots)</td>
<td>161</td>
<td>165</td>
<td>164</td>
<td>173</td>
<td>156</td>
<td>162</td>
<td>163</td>
<td>162</td>
<td>161</td>
<td>156</td>
</tr>
<tr>
<td>ROT (s)</td>
<td>62</td>
<td>62</td>
<td>61</td>
<td>61</td>
<td>67</td>
<td>60</td>
<td>60</td>
<td>58</td>
<td>61</td>
<td>67</td>
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</tbody>
</table>

Table 7.15 presents values of wake separation proposed by the FAA in RECAT II, and Table 7.16 presents calculated values for the percentage of operations restricted by ROT in RECAT II and RECAT III. As shown in Table 7.16 ROT would be the determining factor for at least 49 percent of all aircraft separations in RECAT III.
Table 7.15: RECAT II Wake Separation FAA Proposed Matrix for DEN 35L.

<table>
<thead>
<tr>
<th>Leader</th>
<th>B752</th>
<th>A320</th>
<th>A319</th>
<th>B738</th>
<th>B737</th>
<th>MD83</th>
<th>E170</th>
<th>CRJ9</th>
<th>CRJ2</th>
<th>E145</th>
</tr>
</thead>
<tbody>
<tr>
<td>B752</td>
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<td>2</td>
</tr>
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<td>2</td>
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<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
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<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>B738</td>
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<td>2</td>
<td>2</td>
</tr>
<tr>
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<td>D</td>
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<td>2</td>
<td>2</td>
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</tr>
<tr>
<td>E170</td>
<td>E</td>
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<td>2</td>
<td>2</td>
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</tr>
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<tr>
<td>E145</td>
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<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
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</tr>
</tbody>
</table>

Table 7.16: Percentage of RECAT II and RECAT III Operations Limited by ROT for DEN 35L.

<table>
<thead>
<tr>
<th></th>
<th>RECAT II</th>
<th>RECAT III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of arrivals restricted by ROT</td>
<td>1</td>
<td>49</td>
</tr>
</tbody>
</table>

*Critical aircraft is B738*

7.5.1.6 Runway End 35R

Runway end 35R is predominantly operated by aircraft that belong to groups D and E in the FAA RECAT 1.5 wake matrix. These aircraft have similar weight carrying capabilities, MCC, and wake generation capabilities. For this reason, separations between leaders and followers in this runway are between 0-2 nm, meaning that there is little to no wake influence between these aircraft pairs. Table 7.17 presents calculated values of ROT and approach speed for each aircraft studied on this runway.

Table 7.17: Runway and Aircraft Parameters for DEN 35R.

<table>
<thead>
<tr>
<th>Aircraft ID</th>
<th>A319</th>
<th>A320/ A321</th>
<th>B737</th>
<th>B738/ B739</th>
<th>B752/ B753</th>
<th>CRJ2</th>
<th>CRJ9/ CRJ7</th>
<th>E120</th>
<th>E145</th>
<th>E170</th>
<th>MD83</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fleet Mix (%)</td>
<td>11</td>
<td>17</td>
<td>16</td>
<td>22</td>
<td>2</td>
<td>15</td>
<td>9</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Approach Ground Speed (knots)</td>
<td>160</td>
<td>166</td>
<td>164</td>
<td>174</td>
<td>159</td>
<td>161</td>
<td>160</td>
<td>160</td>
<td>164</td>
<td>168</td>
<td></td>
</tr>
<tr>
<td>ROT (s)</td>
<td>62</td>
<td>60</td>
<td>61</td>
<td>59</td>
<td>64</td>
<td>60</td>
<td>61</td>
<td>61</td>
<td>60</td>
<td>59</td>
<td>59</td>
</tr>
</tbody>
</table>

Table 7.18 presents values of wake separation proposed by the FAA in RECAT II, and Table 7.19 presents the percentage of operations restricted by ROT in RECAT II and RECAT III.
Table 7.18: RECAT II Wake Separation FAA Proposed Matrix for DEN 35R.

<table>
<thead>
<tr>
<th>Leader</th>
<th>B752</th>
<th>A320</th>
<th>A319</th>
<th>B738</th>
<th>B737</th>
<th>MD83</th>
<th>E170</th>
<th>CRJ9</th>
<th>CRJ2</th>
<th>E145</th>
<th>E120</th>
</tr>
</thead>
<tbody>
<tr>
<td>Follower</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>F</td>
</tr>
<tr>
<td>B752</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
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<td>A320</td>
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<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
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<td>A319</td>
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<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>B738</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
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<td>2</td>
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<td>2</td>
<td>2</td>
</tr>
<tr>
<td>B737</td>
<td>2</td>
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<td>2</td>
<td>2</td>
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<td>2</td>
<td>2</td>
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<td>2</td>
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<td>2</td>
<td>2</td>
</tr>
<tr>
<td>E170</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>CRJ9</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>CRJ2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
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<tr>
<td>E145</td>
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<td>2</td>
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</tr>
<tr>
<td>E120</td>
<td>F</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
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<td>2</td>
</tr>
</tbody>
</table>

Note: *No effect.

Table 7.19: Percentage of RECAT II and RECAT III Operations Limited by ROT for DEN 35R.

<table>
<thead>
<tr>
<th>RECAT II</th>
<th>Percentage of arrivals restricted by ROT</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>RECAT III</td>
<td>*Percentage of arrivals restricted by ROT</td>
<td>88</td>
</tr>
</tbody>
</table>

* Critical aircraft is B752

7.5.2 Results for La Guardia Airport

7.5.2.1 Runway End 04

The aircraft operating on runway end 04 predominantly belong to groups D and E in the FAA RECAT 1.5 wake matrix, as shown in Table 7.21. These aircraft have similar weight carrying capabilities, MCC, and wake generation capabilities. For this reason, separations between leaders and followers for this runway fall in the 2-nm range, meaning that there is little to no wake influence between these aircraft pairs. Table 7.20 presents calculated values of ROT and approach speed for each aircraft studied on this runway.
Table 7.20: Runway and Aircraft Parameters for LGA 04.

<table>
<thead>
<tr>
<th>Aircraft ID</th>
<th>A319</th>
<th>A320/ A321</th>
<th>B737</th>
<th>B738/ B739</th>
<th>CRJ2</th>
<th>CRJ9/ CRJ7</th>
<th>E145</th>
<th>E170</th>
<th>E190</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fleet Mix (%)</td>
<td>4</td>
<td>14</td>
<td>9</td>
<td>11</td>
<td>8</td>
<td>22</td>
<td>7</td>
<td>15</td>
<td>8</td>
</tr>
<tr>
<td>Approach Ground Speed (knots)</td>
<td>147</td>
<td>150</td>
<td>149</td>
<td>152</td>
<td>150</td>
<td>149</td>
<td>146</td>
<td>149</td>
<td>145</td>
</tr>
<tr>
<td>ROT (s)</td>
<td>52</td>
<td>53</td>
<td>52</td>
<td>54</td>
<td>46</td>
<td>46</td>
<td>46</td>
<td>46</td>
<td>49</td>
</tr>
</tbody>
</table>

Table 7.21: RECAT II Wake Separation FAA Proposed Matrix for LGA 04.

<table>
<thead>
<tr>
<th>Leader</th>
<th>A319</th>
<th>A320/ A321</th>
<th>B737</th>
<th>B738/ B739</th>
<th>CRJ2</th>
<th>CRJ9/ CRJ7</th>
<th>E145</th>
<th>E170</th>
<th>E190</th>
</tr>
</thead>
<tbody>
<tr>
<td>A320 D</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
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</tr>
<tr>
<td>A319 D</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>B738 D</td>
<td>2</td>
<td>2</td>
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<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
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</tr>
<tr>
<td>B737 D</td>
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<td>2</td>
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<tr>
<td>E190 D</td>
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<tr>
<td>E170 D</td>
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<tr>
<td>CRJ9 E</td>
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<tr>
<td>CRJ2 E</td>
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<td>2</td>
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<td>2</td>
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<td>2</td>
<td>2</td>
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</tr>
<tr>
<td>E145 E</td>
<td>2</td>
<td>2</td>
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<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 7.22 presents the percentage of operations restricted by ROT in RECAT II and RECAT III. For RECAT III at least 73 percent of operations are restricted by ROT.

Table 7.22: Percentage of RECAT II and RECAT III Operations Limited by ROT for LGA 04.

<table>
<thead>
<tr>
<th></th>
<th>RECAT II</th>
<th>RECAT III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of arrivals restricted by ROT</td>
<td>1</td>
<td>73</td>
</tr>
</tbody>
</table>

* Critical aircraft is B738

7.5.2.2 Runway End 22

The aircraft operating on runway end 22 predominantly belong to groups D and E in the FAA RECAT 1.5 wake matrix. These aircraft have similar weight carrying capabilities, MCC, and wake generation capabilities. For this reason, separations between leaders and followers for this runway fall in the 2-nm range, meaning that there is little to no wake influence between these aircraft pairs. Table 7.24 presents wake separation values proposed by the FAA in RECAT II, and Table 7.23 presents calculated values of ROT and approach speed for each aircraft studied on this runway.
Table 7.23: Runway and Aircraft Parameters for LGA 22.

<table>
<thead>
<tr>
<th>Aircraft ID</th>
<th>A319</th>
<th>A320/A321</th>
<th>B737</th>
<th>B738/B739</th>
<th>CRJ2</th>
<th>CRJ9/CRJ7</th>
<th>E145</th>
<th>E170</th>
<th>E190</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fleet Mix (%)</td>
<td>4</td>
<td>14</td>
<td>8</td>
<td>10</td>
<td>7</td>
<td>22</td>
<td>7</td>
<td>18</td>
<td>8</td>
</tr>
<tr>
<td>Approach Ground Speed (knots)</td>
<td>149</td>
<td>152</td>
<td>153</td>
<td>155</td>
<td>155</td>
<td>152</td>
<td>152</td>
<td>150</td>
<td>148</td>
</tr>
<tr>
<td>ROT (s)</td>
<td>53</td>
<td>53</td>
<td>52</td>
<td>55</td>
<td>49</td>
<td>49</td>
<td>49</td>
<td>51</td>
<td>51</td>
</tr>
</tbody>
</table>

Table 7.24: RECAT II Wake Separation FAA Proposed Matrix for LGA 22.

<table>
<thead>
<tr>
<th>Leader</th>
<th>A320</th>
<th>A319</th>
<th>B738</th>
<th>B737</th>
<th>E190</th>
<th>E170</th>
<th>CRJ9</th>
<th>CRJ2</th>
<th>E145</th>
</tr>
</thead>
<tbody>
<tr>
<td>A320</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
</tr>
<tr>
<td>A319</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
</tr>
<tr>
<td>B738</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
</tr>
<tr>
<td>B737</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
</tr>
<tr>
<td>E190</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
</tr>
<tr>
<td>E170</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
</tr>
<tr>
<td>CRJ9</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
</tr>
<tr>
<td>CRJ2</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
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<td>E</td>
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<td>E</td>
<td>E</td>
<td>E</td>
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</table>

Table 7.25: Percentage of RECAT II and RECAT III Operations Limited by ROT for LGA 22.

<table>
<thead>
<tr>
<th>RECAT II</th>
<th>Percentage of arrivals restricted by ROT</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>RECAT III</td>
<td>*Percentage of arrivals restricted by ROT</td>
<td>71</td>
</tr>
</tbody>
</table>

* Critical aircraft is B738

7.5.2.3 Runway End 31

The aircraft operating on runway end 31 predominantly belong to groups D and E in the FAA RECAT 1.5 wake matrix, as shown in Table 7.27. These aircraft have similar weight carrying capabilities, MCC, and wake generation capabilities. For this reason, separations between leaders and followers for this runway fall in the 2-nm range, meaning that there is light to no wake influence between these aircraft pairs. Table 7.26 presents calculated values of ROT and approach speed for each aircraft studied on
this runway, and Table 7.28 presents the percentage of operations restricted by ROT in RECAT II and RECAT III.

Table 7.26: Runway and Aircraft Parameters for LGA 31.

<table>
<thead>
<tr>
<th>Aircraft ID</th>
<th>A319</th>
<th>A320/ A321</th>
<th>B737</th>
<th>B738/ B739</th>
<th>CRJ2</th>
<th>CRJ9/ CRJ7</th>
<th>E145</th>
<th>E170</th>
<th>E190</th>
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<tbody>
<tr>
<td>Fleet Mix (%)</td>
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<td>8</td>
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<td>7</td>
<td>23</td>
<td>8</td>
<td>18</td>
<td>8</td>
</tr>
<tr>
<td>Approach Ground Speed (knots)</td>
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<td>145</td>
<td>144</td>
<td>148</td>
<td>147</td>
<td>144</td>
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<td>142</td>
<td>139</td>
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<tr>
<td>ROT (s)</td>
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<td>52</td>
<td>48</td>
<td>48</td>
<td>49</td>
<td>49</td>
<td>50</td>
</tr>
</tbody>
</table>

Table 7.27: RECAT II Wake Separation FAA Proposed Matrix for LGA 31.

<table>
<thead>
<tr>
<th>Follower</th>
<th>A320</th>
<th>A319</th>
<th>B738</th>
<th>B737</th>
<th>E190</th>
<th>E170</th>
<th>CRJ9</th>
<th>CRJ2</th>
<th>E145</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leader</td>
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<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
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</tr>
<tr>
<td>E190</td>
<td>D</td>
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<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
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</tr>
<tr>
<td>E170</td>
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<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>CRJ9</td>
<td>E</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>CRJ2</td>
<td>E</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
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<tr>
<td>E145</td>
<td>E</td>
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<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 7.28: Percentage of RECAT II and RECAT III Operations Limited by ROT for LGA 31.

<table>
<thead>
<tr>
<th>RECAT II</th>
<th>Percentage of arrivals restricted by ROT</th>
<th>1</th>
</tr>
</thead>
</table>

*Critical aircraft is B738

| RECAT III | *Percentage of arrivals restricted by ROT | 74 |

7.6 Conclusions and Recommendations

Runways studied at DEN and LGA have a fleet mix with a majority of aircraft with similar characteristics; belonging to groups D and E in the wake categorizations. Proposed time separations between aircraft in groups D and E are equal to or below their values or ROT. This is not reflected in the percentage of operations restricted by ROT in RECAT II due to the operational error buffers added by controllers.
According to ROT limitations presented in the results chapter, no significant capacity gains would result from RECAT III implementation unless values of ROT for such aircraft are reduced.

Results for DEN show that current ROT limitations range from 1 percent to 79 percent of total operations if RECAT II were to be enforced and between 48 percent and 99 percent if RECAT III were to be implemented.

Results for LGA show that current ROT limitations are 1 percent of total operations if RECAT II were to be enforced and between 71 percent and 99 percent if RECAT III were to be implemented.

Reliable technologies for calculating and managing dynamic separations have to be developed, as well as cost-benefit analyses to contrast the potential savings from wake separation reductions with the cost of implementing and approving the selected concepts and needed technology.

Further studies on the implications of reduced wake separations need to be performed. Some of the factors that influence these implications are the effects of aircraft noise and gate availability at the destination airport.

A major limitation to wake vortex mitigation is the lack of data collection on environmental turbulence and other environmental parameters. A LIDAR data collection process would create databases for conditions and frequencies that could be used in future wake behavior research and reduce the uncertainty of some parameters, such as typical values of turbulence, especially at low altitudes and at busy airports (Perras, Dasey et al. 2000).

For effective management of wake separation implementation, current operational buffers need to be studied at airports under capacity constraints. Current challenges with buffers can be addressed by detailed and accurate recordings of airport operational rules that specify when runways are being operated under VMC or IMC conditions. It is also important to forecast how reduced wake separations between aircraft will affect operational buffers in the future. If buffer the will continue to increase, then there is no point in decreasing wake separation.

ASDE-X technology, which monitors real-time aircraft activity from a variety of sources such as radar, satellite-based surveillance, multilateration sensors, and aircraft transponders, is only available at 35 airports. All airports desiring to implement dynamic wake separation will need to upgrade to similar capabilities.

In the near future, if aircraft weight is integrated to air traffic control monitors, the controller could add operational time buffers when an approaching or departing aircraft is fully loaded. This will
avoid having to over-separate aircraft whose wake circulation strengths do not pose additional danger to follower aircraft.

To capitalize on dynamic wake separations gains in RECAT III, awareness-raising programs for collaboration between air traffic controllers and pilots are needed that convey the importance of decreasing occupancy of the runway, a scarce resource.

7.7 Acknowledgments

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7.8 Disclaimer

The contents of this material reflect the views of the author only. Neither the Federal Aviation Administration nor the United States Department of Transportation nor the National Aeronautics and Space Administration makes any warranty or guarantee, or promise, expressed or implied, concerning the content or accuracy of the views expressed herein.

Any opinion, findings, and conclusion or recommendations presented herein are those of the author and do not necessarily reflect the views of the FAA or NASA.

7.9 References


8. Conclusions and Recommendations

8.1 Summary Conclusion

This research identified 16 wake mitigation concepts and 3 sub-concepts and categorized them according to dependency on airport fleet, runway orientation, single runway operation, and aircraft or environmental condition.

Many of the wake separation concepts are quite recent, and some are still ideas with no implementations in an airport or aircraft. Research regarding their effectiveness is inconclusive, so the current research critically analyzed the drawbacks of these concepts based on the parameters that drive each model.

A research gap was found in the most important benchmark: capacity benefit. Only those concepts that were already in testing presented a preliminary measure of increased operations at airports under study. Because capacity improvement is one of the most attractive benefits of wake mitigation, ideally the potential airport capacity improvement under each of the proposed concepts should be studied.

Dynamic wake mitigation is one near-term effort that could provide capacity benefit prior to 2025 and could be initiated by air traffic control; these are some of the reasons why it was the concept chosen for further study in this research.

The dynamic wake mitigation concept proposes to increase runway capacity without modifying existing infrastructure. Its approach is to discretize current wake aircraft groups by analyzing characteristics of each pair of leader and follower aircraft as well as the environment where the aircraft travel. This approach requires a thorough understanding of wake vortex and the parameters that influence wake behavior.

According to the research findings, several concepts enable dynamic wake separation. Separations can be determined dynamically based on specific airport fleet operations only or by environmental conditions and aircraft factors. This research focuses on dynamic wake mitigation by environmental conditions and aircraft factors, while also considering airport-specific conditions such as ROT.

The research shows that knowing the environmental conditions of the location of wake generation increases the potential to improve airport capacity. A better understanding of how dynamic parameters such as wind, temperature, environmental turbulence, and aircraft weight affect wake behavior intensity, location, and decay can provide several benefits, including the reduction of wake encounters.
Chapter 4 discussed the research’s simulation of aircraft operations during arrival and departure as well as the environmental conditions in the aircraft flight path. This study helped to understand wake circulation strength, lateral and vertical behavior, and the interaction with environmental conditions, all to reduce wake vortex separations. Results from this simulation aid in the assessment of dynamic separations as a wake mitigation concept.

For aircraft in the final approach segment, wake circulation strength of the leading aircraft is critical to guarantee safe operation. Wake circulation strength decays with time, and its lifetime depends on the initial circulation strength, the ambient weather conditions such as the environmental turbulence, thermal stratification as measured by the Brunt-Vaisala frequency, and interaction with the ground and obstacles that cause three-dimensional instabilities (Proctor, Hamilton et al. 2004).

In Chapter 5, the research used measured values of environmental turbulence for the in-ground-effect, aircraft weight data recorded during aircraft operations, wind speed and air temperature for simulation of arrival and departures procedures at airports. Environmental turbulence ranges from weak ($4 \times 10^{-5} \text{ m}^2/\text{s}^3$) to intense ($1.5 \times 10^{-2} \text{ m}^2/\text{s}^3$) with 80% of the values between moderate ($1.35 \times 10^{-3} \text{ m}^2/\text{s}^3$) and intense ($1.5 \times 10^{-2} \text{ m}^2/\text{s}^3$). Aircraft weight on arrival accounts for 75% to 85% of the of MALW depending on the aircraft. Values of wind speed and air temperatures are according to typical values at the airports under study.

The simulation generated cumulative density function curves of wake behavior under real-world conditions to calculate values of wake circulation strength capacities that follower aircraft would endure during approach and departure. The simulation used the FAA RECAT II proposed matrix as a baseline to derive MCC values that meet FAA safety standards. A 95% confidence interval was used to calculate the MCC for each aircraft under study.

Runway throughput performance currently depends on wake turbulence separation, driven by the leading aircraft’s wake circulation and the following aircraft’s wake circulation strength capacity, or minimum radar separation, driven by communication, surveillance, and collision avoidance or by leading aircraft parameters such as ROT.

Chapter 6 discussed the research’s simulation of aircraft operations during arrival, as well as the environmental conditions in the aircraft flight path, to derive dynamic wake separations and evaluate their possible gains and feasibility of operation and implementation under RECAT III. The simulation used Chicago ORD unique aircraft fleet mix, ROT, approach speed, and operational buffer data for each runway end studied to calculate potential capacity benefits if wake RECAT III were implemented and the percentage of operations that would be restricted by ROT.
The analysis showed that, for aircraft pairs separated 2-nm or less, further reduction beyond RECAT II is not operationally feasible. Wake separations of 2-nm or less already imply little to no wake dependency between the aircraft pair. When this is the case, the challenges in wake separation are to meet ROT and to make sure aircraft separations allow sufficient time for human operational variations without causing aircraft turn-arounds or double-aircraft-occupancy runway violations.

Chapter 7 discussed this research’s simulation of arrival operations that allow inter-arrival departures for Denver International Airport and La Guardia Airport. The analysis showed that on runways that operate under capacity constraints, 85% or more of the total number of operations are conducted by aircraft with similar wake generation capabilities as well as aircraft with similar MCC. The implication is that FAA-proposed RECAT II separations produce time separations very close in magnitude to ROT. In many cases 85% or more of the total number of operations are restricted by ROT. This finding indicates that dynamic wake mitigation can increase runway capacity at the airports studied.

The next section discusses the challenges, implications, and recommendations of dynamic wake separations to help the reader evaluate the feasibility of the proposed concept.

8.2 Challenges and Recommendations

Air traffic controllers, pilots, and policymakers face new challenges as aircraft wake separations transition from a static matrix of size 6 by 6 to a static matrix of proposed size 123 by 123 and, later on, to a proposed dynamic wake separation with innumerable possible separations between each aircraft pair. Dynamic wake separation is not a recategorization of aircraft; it is a revolution of the current management of aircraft in the airspace. With dynamic separation, the roles of controllers, computers, and data collection devices would be transformed by giving computers decision-making power and making the system dependent on them.

8.2.1 Data Collection and Reporting

One of the major constraints of dynamic wake separation at airports is its dependence on real-time or near-real-time data collection and broadcasting technologies. These technologies would need to measure and report temperature, environmental turbulence, wind speed, air humidity, air density, and aircraft weight, altitude, and speed.

Data on environmental conditions near the airport and data on aircraft parameters need to be collected and shared among the users of the system. Airports currently collect wind, temperature, and
humidity data. However, environmental turbulence, identified as one of the environmental factors with the greatest influence on wake vortex behavior, is only being collected at airports that are part of the wake research program, and it is being used for research and validation purposes only. Aircraft weight is recorded but not shared. The implementation of dynamic wake mitigation will require live data to be collected and reported to the air traffic controller so that decisions about the separation between each aircraft can be made (see Figure 8.1).

Data collection also faces challenges such as the reliability of data collected under all weather conditions. It is important to identify and guarantee that current measuring devices, such as LIDAR, can accurately capture environmental turbulence data in heavy rain, thunderstorms, or frozen precipitation. Currently, accurate measurements cannot be recorded when the air is too clear or too dense, very dry, or under snow conditions. LIDAR development includes the addition of X-band frequencies and other technologies to improve system capabilities (Perras, Dasey et al. 2000).

The wake literature indicates that weather can dominate vortex spacing reductions. To safely adjust wake vortex separation, a greater understating of weather measurements, fluctuations, and frequency is needed. Weather events such as updraft winds can also impact wake propagation and displacement, so there is a need to understand these events and their frequency better.

Aircraft weight is one of the aircraft parameters with the greatest influence on wake vortex behavior. Due to airlines’ privacy policies, weight values are not in the public domain. The implementation of dynamic wake mitigation will require live aircraft weight data monitoring and
reporting. Ideally, aircraft weight could be a feature added to ASDE-X. This information could also be used for other purposes such as pavement condition assessment and monitoring, which is influenced by aircraft weight and traffic volume. Figure 8.2 shows an example of how a monitoring tool such as ASDE-X could display aircraft weight.

For RECAT III to be implemented, aircraft weight needs to be collected and reported. Shared aircraft weight could be used in combination with a wake behavior model to calculate more accurate aircraft circulation capacities, understand the bounds of wake disturbances that are comfortable for passengers and that do not pose an operational danger, and tailor dynamic separations.

![Figure 8.2: ASDE-X Aircraft Data Display With Added Aircraft Weight Feature.](image)

8.2.2 Airport and Air Traffic Control Parameters

Runway occupancy time is a limiting factor to dynamic wake separation because ROT already limits RECAT II separations for certain aircraft. Depending on the runway exit configuration of the destination airport, each aircraft will take a certain amount of time to clear the runway. To maximize
the benefits of dynamic wake mitigation, ROT should be less than dynamic wake mitigation. The existence of cases where ROT is greater than dynamic wake mitigation shows that the NEXTGEN plan to increase airport capacity requires additional work. One possible solution is to research higher speed runway exits, measure their performance, and include them in airport master plans as future improvements.

Raising and maintaining crew awareness of runways as a limited resource will help minimize ROT and eliminate excessive runway use due to exit proximity, convenience, or any other factor. This is a cultural issue that could be addressed by promoting collaboration between controllers and pilots to consider the capacity of the system.

Aircraft technologies such as Brake to Vacate (BTV) systems used by Airbus could help pilots minimize ROT by automatically calculating and displaying realistic braking profiles to reach their preferred exit while minimizing ROT. This approach accounts for passenger comfort, noise, fuel consumption, and CO₂ emissions.

ASDE-X technology currently deployed in 35 airports could help reduce ROT by monitoring real-time surface activity taken from a variety of sources, including radar, Automatic Dependent Surveillance-Broadcast (ADS-B), multilateration sensors, and aircraft transponders. ASDE-X fuses and displays this data, allowing controllers to know the precise location of aircraft and transponder-equipped vehicles on runways, taxiways, and approach corridors, as well as aircraft flying within five miles of the airport. Such monitoring technologies provide a level of accuracy of aircraft position that could allow controllers to reduce operational buffers, resulting in higher runway utilization.

Airport design considerations such airside design and terminal configurations could reduce ROT and taxiing times as well as emissions and fuel burn. These considerations could include designing rapid exits and turn-offs at the correct locations and angles.

Current operational buffers during IFR and VFR operations need to be measured and studied to understand how future safe separations could rely on buffers as well as the variations in buffers per airport and per aircraft pair. Decreased separations might cause operational buffers to increase, resulting in a capacity detriment compared to current separations.

As suggested by results at Chicago International Airport, it might be useful to study the effects of assigning aircraft with similar wake MCC and weight carrying capabilities to the same runway, with the goal of further lowering wake separation and increasing runway capacity. However, maximizing runway capacity should be paired with further studies on gate availability and airport flow during peak hours to maintain or improve the efficiency of the system.
Increasing arrival throughput will decrease inter-arrival departures, which will have an impact on overall runway capacity. Research on allowing double occupancy on runways for arriving and departing aircraft under favorable environmental conditions and aircraft parameters could be performed to assess the risks and benefits of changes in current regulations.

Aircraft wake separations might also be reduced at higher altitudes. It can be inferred that lower values of EDR in the upper atmosphere would increase the duration of wake behavior. Interestingly, recent research using static separations has found that values of circulation strength at cruising altitude and during approach procedures to an airport are similar. This phenomenon is due to the inverse variation of the aircraft flight velocity and air density, as they roughly compensate for each other (Holzapfel and Gerz 2012).

8.2.3 Human Factors and Capital Cost

The complexity of implementing dynamic wake separation could represent an additional human factor load for controllers and pilots, who currently memorize and double check the validity of the separation required for each aircraft pair. The simplicity of current separations helps the air traffic controller to control and validate aircraft separations at all times.

The capital costs of dynamic wake separation should also be considered before implementation. Based on the set of analyses proposed above, a benefit-cost study is recommended that accounts for the cost of maintenance, cost of operation, cost of federal approvals, the time required for such approvals, the impact of emission and noise due to increased operations during peak hours, and increased runway throughput. This would enable a holistic picture of airport operations that could be used for decision making if dynamic wake separations were to be implemented. It would be naïve to recommend the implementation of dynamic wake mitigation before taking the steps above and weighing benefits and costs.

8.2.4 Risk Tolerance for Wake Disturbance

A defined methodology to select a critical aircraft to derive MCCs should be openly discussed. There are several possibilities, such as:

- Selecting the heaviest aircraft in the national airspace system or in the RECAT II matrix.
- Selecting the aircraft from the RECAT II matrix that results in the lowest circulation for the follower.
Selecting the critical aircraft based on aircraft fleet operating at each runway, taking into consideration either point A or point B explained above.

Open discussions are also needed on values of wake circulation capacities for each aircraft in the national airspace system and the FAA’s risk tolerance in balancing wake separations with airport capacity.

To increase current runway throughput, MALW and MTOW cannot be used in all wake separation scenarios, but rather those runway specific critical aircraft scenarios. Current research on recategorization efforts considers 85% of the aircraft MALW to derive the wake separations. This is according to aircraft operations database (Tittsworth, Cheng et al. 2016).

The use of aircraft monitoring technologies such as ASDE-X could motivate a change in aircraft procedures and airport operational rules, such as allowing safe runway-double-occupancy between aircraft arriving and aircraft in the process of exiting the runway.

8.3 The Future of Dynamic Wake Mitigation

In the future, aircraft self-separation could be accomplished by each leading aircraft measuring and reporting the wake vortex circulation strength it generates. The leading aircraft could measure environmental turbulence and validate it with the aircraft’s vertical movements, using data from onboard vertical accelerometers and accounting for wind, temperature, and humidity measurements and aircraft parameters such as weight and configuration (see Figure 8.3). This would result in a wake turbulence report (Cornman 2016). Aircraft in the vicinity could compare the wake turbulence report to their previously assigned MCC, based on speed, current weight, procedure, and aircraft configuration, to calculate the required separation distance behind nearby generators.
Accomplishing self-separation will require that aircraft be equipped to collect data such as weight, speed, altitude, flap angle configuration, and surrounding conditions such as wind, temperature, environmental turbulence, and humidity. The equipment must be able to use these data to calculate and report generated wake. In the near term, wake turbulence information could be sent to the air traffic controller, who would decide and enforce the separation of follower aircraft.

Currently, the ATPA tool warns controllers if aircraft are too close together. The final approach controller is in control of air traffic when the aircraft is about 15-nm away from the runway threshold and would be responsible for enforcing dynamic wake separation. In the long term, the aircraft would be able to determine and enforce separation distances automatically. In this case, computer tools will be needed to calculate, report, and enforce complex dynamic separations that depend on aircraft parameters and environmental conditions, and the air traffic control would coordinate and manage flight operations.

In the future, improved fast-time wake transport and decay models could be used operationally, not only within the terminal airspace but also as onboard aircraft tools to support maneuver procedures, such as dynamic wake separation (Ahmad, VanValkenburg et al. 2016).

Self-separation will require improvements to physical models of vortex behavior, wake vortex sensor technology, and measurements of relevant meteorological variables. Such improvements would apply to both departure and arrival operations (Perras, Dasey et al. 2000).
Finally, anecdotal evidence suggests that environmental turbulence is becoming more prevalent as a byproduct of climate change. Environmental turbulence is a result of weather, and intensifying global warming influences weather patterns, which in turn would influence dynamic wake separations (Smith 2016).

8.4 References


Appendix A. MATLAB Codes

1.1 Wake Vortex Behavior Prediction

This code is a Monte Carlo approach simulation to determine wake vortex behavior under different environmental conditions and aircraft dependent conditions.

The environmental conditions taken into consideration for Monte Carlo simulation are: Altitudes, Mass (Vinitial), Environmental Turbulence, Wind and Temperature. Brunt Vaisala is also considered as according to NASA it is influenced by temperature.

I would recommend that before modifying name, ranges of values and format for any of these files you would read papers by NASA and emails to from Dr. Fred Proctor (NASA) to Julio Roa on Wake Vortex Binder. Going through the literature first will give you a better idea of the range of values that should be considered for each parameter.

File names and formats should not be changed because otherwise the NASA model will not be able to recognize them.

The some of the calculations from the APA model will be displayed in the command window. This is normal.

% AMONG THE FILES NEEDD TO RUN THIS CODE ARE:
% APA suite executable
% BADA_IGE
% ISA density table
% Environmental_turbulence, Qdata and q.csv
% Cross_flow, Udata and u.csv
% Temperature, Tdata and t.csv
% ACDATA
% TRAJEC.DAT
% APA.OUT
% apa_output_parser (function)
% With the use of APA algorithm and this code we calculate:
% Circulation strength over time
% Circulation lateral displacement over time
% Circulation

vertical displacement over time

%
% NOTE:
% All units required for calculation in APA are metric. Example:
% Velocity m/s
% altitude: m
% weight: kg
% Time: seconds
% Wake Circulation strength: m^2/s
% Environmental Turbulence: m^2/s^3
% etc.
%* I would recommend that before modifying name, ranges of values and
% format for any of these files you would read papers by NASA and emails
% to from Dr.Fred Proctor (NASA) to Julio Roa on Wake Vortex Binder.
% Going through the literature first will give you a better idea of
% the range of values that should be considered for each parameter.
%*File names and formats should not be changed because otherwise the NASA
% model will not be able to recognize them.
%
% The some of the calculations from the APA model will be displayed in the
% command window. This is normal.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%LOAD NECESSARY DATA - DEFINE PARAMETERS - DEFINE UPPER AND LOWER BOUNDS
% profile off
% profile on
clear all
clc
load BADA_IGE % this is aircraft performance characteristics for each altitude.
ISADensitytable = csvread('ISADensityTable.csv'); % Table with air density
% condition for each altitude.
% First column is geopotential altitude in meters.
% Second column is air density in kg/m^3
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
fid = fopen('Aircraft_Info_Common_metric_units.csv','r');
% Aircraft information this file contains: Key Field, Aircraft Name,
% Manufacturer, ShortName,BADAName, WakeClass, OperatingEmptyWeight(kg),
% MaximumLandingWeight(kg), MaximumTakeoffWeight(kg),
% Wingspan(m),WingArea(m-m),RECATGroup,RECATGroupinNumber
% creates a cell array that contains data from file
% Aircraft_Info_Common_metric_units.csv
masswingspanlookup = textscan(fid, '%s%s%s%s%s%s%f%f%f%f%f%s%f',...
'delimiter', ',','headerlines',1);
acid

= masswingspanlookup{1}; % Aircraft ID

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oew_list_kg = masswingspanlookup[7];
malw_list_kg = masswingspanlookup[8];
mtow_list_kg = masswingspanlookup[9];
ws_m = masswingspanlookup[10];

% Define parameters that are needed in Monte Carlo simulation.
% Defines the number of variations of mass for this aircraft that will be
% executed in Monte Carlo simulation.
no_masses=12;

% This factor will be used later on, to calculate initial vortex spacing
% called (b0); which is the 4th input in ACDATA file.
initial_vortex_separation_factor = pi/4;
gravity = 9.81; % Gravity (m/s^2)
ft_to_m = 0.3048; % Defines variable with unit conversion from ft to meter
m_to_ft = 3.2808;
knots_to_m_per_second = 0.514;

% According to literature the maximum or upper bound for IGE BEHAVIOR on
% wake is for an altitude of generator wingspan * 3.
wingspan_multiplier = 3;
longitude = 0; % APA input parameter

% THIS INDEX SHOULD BE CHANGED ACCORDING TO THE AIRCRAFT YOU ARE TRYING TO
% ANALYZE.
aircraft_indice=98; % Indice of Aircraft that will be analyzed.

aircraft_name = BADA_IGE(aircraft_indice).Aircraft_Name;
BADA_IGE_Altitude_ft = BADA_IGE(aircraft_indice).Altitude;
round_altitude_to_nearest_number_ft = 50;
altitude_initial_indice = 2; % Defines the indice for the initial altitude
% that will be analyzed.
% Takes into account that engines are not at altitude zero and that resolution
% of BADA data is low (FL).

% To decrease computation effort altitude is calculated every 100 ft from
% 50 ft to 3 wingspans.
altitude_increment_step = 2;

% Defines how many variation of aircraft mass will be taken into consideration
% for simulation
aircraft_mass_initial_indice = 1;
aircraft_mass_final_indice = no_masses;
aircraft_mass_lower_bound_departure_factor = 0.65; % According to TranStats load factor.
aircraft_mass_lower_bound_arrival_factor = 0.65; % According to TranStats load factor.

% Defines how many variation of environmental turbulence will be taken into
% consideration for simulation

% According to Ed Johnson in wake meeting the intense atmosphere (0.015 indice 1)
% is not very common. Indice 1-5 corresponds to intense atmosphere.
% Example: [intense 0.015, strong 0.00717, moderate_to_strong 0.00302, moderate 0.00135, weak 0.00004, very_weak 0.0000001] units (m^2/s^3)

% The first column of this file is the environmental turbulence intensity
% (1 intense - 6 very weak) and second column is the value in (m^2/s^3)
% as required by APA.
edr_values_table_from_intense_to_veryweak = csvread('environmental_turbulence.csv');
% edr_values_from_intense_to_veryweak_m2_per_s3 = edr_values_table_from_intense_to_veryweak(:,2);
edr_values_from_intense_to_veryweak_m2_per_s3 = generateEDR(20);

% Defines how many variation of cross-flow values (m/s) will be taken into consideration for simulation
wind_value_initial_indice = 1;

% Indice 1 is zero wind and indice 11 is so meter per second wind.
winds = wind_value_initial_indice;
wind_value_final_indice = 6;

% The first column of this file is cross-flow in knots and second column in m/s as required by APA.
winds_table_from_intense_to_veryweak = csvread('cross_flow.csv');
winds_from_intense_to_veryweak_m_per_s = winds_table_from_intense_to_veryweak(:,2);

% Defines how many variation of temperature (kelvin) values will be taken into consideration for simulation
temperature_value_initial_indice = 1;
temperature_value_final_indice = 6;

% The first column of this file is temperature in celsius and second column in kelvin as required by APA.
temperature_values_table_from_high_to_low = csvread('temperature.csv');
temperature_values_from_high_to_low_kelvin = temperature_values_table_from_high_to_low(:,2);

VInitial_counter = 0; % this is a counter to save VInitial_all(VInitial_counter,1)
loop_counter = 0;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Get the general flight information from BADA data for Circulation Calculation
% Monte Carlo simulation starts below this line.
for aircraft = aircraft_indice %i = 1:116 %For all Aircraft Type in the BADA data
    % Define aircraft parameters
    actype = acid(aircraft);
}
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\[ \text{wingspan}_m = \text{wspan}_m(\text{aircraft}); \quad \text{m} \]
\[ \text{initial\_vortex\_separation}_m = \text{initial\_vortex\_separation\_factor}*\text{wingspan}_m; \quad \text{m} \]
\[ \text{wake}(\text{aircraft\_indice}).\text{aircraft\_name}=\text{BADA\_IGE}(\text{aircraft\_indice}).\text{Aircraft\_Name}; \]
\[ \text{wake}(\text{aircraft\_indice}).\text{initial\_vortex\_separation}_m=\text{initial\_vortex\_separation}_m; \]
\[ \text{oeo}_k\_g = \text{oeo\_list\_kg}(\text{aircraft}); \quad \text{kg} \]
\[ \text{mtow}_k\_g = \text{mtow\_list\_kg}(\text{aircraft}); \quad \text{kg} \]
\[ \text{malw}_k\_g = \text{malw\_list\_kg}(\text{aircraft}); \quad \text{kg} \]

\[ \text{aircraft\_mass\_lower\_bound\_departure}_k\_g=... \]
\[ \text{aircraft\_mass\_lower\_bound\_departure\_factor}*\text{mtow}_k\_g; \quad \text{oeo}_k\_g; \]
\[ \text{aircraft\_mass\_upper\_bound\_departure}_k\_g=\text{mtow}_k\_g; \]
\[ \text{aircraft\_mass\_lower\_bound\_arrival}_k\_g=... \]
\[ \text{aircraft\_mass\_lower\_bound\_arrival\_factor}*\text{malw}_k\_g; \quad \text{oeo}_k\_g; \]
\[ \text{aircraft\_mass\_upper\_bound\_arrival}_k\_g=\text{malw}_k\_g; \]

\% Define aircraft mass
\% MOTW and MALW are already in kg
\% IMPORTANT: Use the next line for DEPARTING profiles
\% \text{acmass}_k\_g = \text{linspace}(\text{aircraft\_mass\_lower\_bound\_departure}_k\_g,...
\% \text{aircraft\_mass\_upper\_bound\_departure}_k\_g,\text{no\_masses});\]

\% Define aircraft mass
\% IMPORTANT: Use the next line for ARRIVAL profiles
\% \text{acmass}_k\_g = \text{linspace}(\text{aircraft\_mass\_lower\_bound\_arrival}_k\_g,...
\% \text{aircraft\_mass\_upper\_bound\_arrival}_k\_g,\text{no\_masses});\]

\% Define final altitude for aircraft simulation (trackpoints means
\% max altitude for this aircraft).
\% \text{number\_of\_trackpoints} = \text{length}(\text{BADA\_IGE}(\text{aircraft}).\text{Altitude});\%feet

\%Find indice for Altitud in ft that corresponds to 3*wingspan. This the
\%upper boundary for the IGE behavior.
\% \text{upper\_bound\_for\_wake\_IGE\_behavior\_ft} = ...
\% \text{wspan}_m(\text{aircraft})*\text{wingspan\_multiplier}^\text{m\_to\_ft};

\%round up to the next 50 ft (variable Altitud step is 50 ft) and find indice
\% \text{rounded\_upper\_bound\_for\_wake\_IGE\_behavior\_ft} = ...
\% \text{round\_altitude\_to\_nearest\_number\_ft}*(\text{ceil} ... 
\% (\text{upper\_bound\_for\_wake\_IGE\_behavior\_ft}/\text{round\_altitude\_to\_nearest\_number\_ft}));

\% find indice for variable above
\% \text{rounded\_indice\_upper\_bound\_for\_wake\_IGE\_behavior} = ...
\% \text{find}(\text{BADA\_IGE\_Altitude}_ft=\text{rounded\_upper\_bound\_for\_wake\_IGE\_behavior\_ft});

\% Indice corresponding to 3*wingspan to feet \% for IGE chose
\% indice 13 wich is about 180 meters \%\text{number\_of\_trackpoints}-1;
\% \text{altitude\_final\_indice} = \text{rounded\_indice\_upper\_bound\_for\_wake\_IGE\_behavior};

\%j = 2:\text{number\_of\_trackpoints}-1 \%for all flight level
\%for \text{altitudes\_indices} = ...
\% \text{altitude\_initial\_indice} = \text{altitude\_increment\_step}\%\text{altitude\_final\_indice} 

altitude_m = BADA_IGE_Altitud_ft(altitudes_indices) * ft_to_m;
rho_kg_per_m3 = densitylookup(ISADensitytable,altitude_m);

% Define aircraft speed %knots to m/s
%groundspeed_m_per_s = ...
BADA_IGE(aircraft).climb_tas(altitudes_indices)*knots_to_m_per_second;

% Use DESCENT_TAS for landing profiles %knots to m/s
groundspeed_m_per_s = ...
BADA_IGE(aircraft).descent_tas(altitudes_indices)*knots_to_m_per_second;

% Aircraft mass variations
% n=1:no_masses
for aircraft_mass_variations=
    aircraft_mass_initial_indice:aircraft_mass_final_indice
        aircraft_mass_kg=acmass_kg(aircraft_mass_variations);
        % Calculate VInitial this is an Input for APA which represents
        % Wake Vortex Initial Descent Velocity and its units are meters
        % per second. According to NASA George Greene (Algorithm for
        % Prediction of Trailing Vortex Evolution). Included in Wake vortex Binder.
        % m/s % According to formula in journal papers.
        VInitial_m_per_s = ...
            (aircraft_mass_kg*gravity)/(2*pi*rho_kg_per_m3*groundspeed_m_per_s*...
            (initial_vortex_separation_m)^2);

    VInitial_counter=VInitial_counter+1;
    VInitial_all(VInitial_counter,1)=VInitial_m_per_s; %m/s

% In this for loop Environmental Turbulence values get inserted
% into the simulation
% edr_value_initial_indice:edr_value_final_indice;
% this is an input parameter that affects how turbulence decays.
for edr_values_variations=
    1:size(edr_values_from_intense_to_veryweak_m2_per_s3,1)
        % We are changing values of edr (non-normalized) in APA file
        % called QDATA
        edr_value_m2_per_s3=...
            edr_values_from_intense_to_veryweak_m2_per_s3(edr_values_variations);

    %The file q.csv contains environmental turbulence values
    % recommended by NASA.
    % Note: This file is not in a format needed for APA nor does
    % it contain the number of values for column altitude which
    % is needed in file that will be executed.
edr_list = csvread('q.csv');
edr_list(:,2) = edr_value_m2_per_s3;

% The values of edr for all altitudes is modified according
% to values assigned in Monte Carlo simulation.

% THE CODE BELOW MODIFIES THE FILE QDATA WHICH CONTAINS
% ENVIRONMENTAL TURBULENCE FOR EACH ALTITUDE. This file
% cannot have any extension otherwise executable will not run.

fid7 = fopen ('QDATA','w');

% the file format for QDATA includes a first value which
% specifies the number of rows which is always 120 for this
% input file.
fprintf(fid7, '%f 
',120);
fprintf(fid7, '%f %f 
',edr_list');
fclose(fid7);

% In this for loop Cross-Flow Velocity (WIND) values for
% each altitud get inserted into the simulation.
% this is an input parameter that affects how turbulence decays.
for wind_values_variations =...
wind_value_initial_indice:wind_value_final_indice;

% We are changing values of edr (non-normalized) in APA
% file called QDATA
wind_value_m_per_s =...
wind_values_from_intense_to_veryweak_m_per_s...
(wind_values_variations);

%The file u.csv contains cross-flow values given by NASA.
%Note: This file is not in format needed for APA nor does
%it contain the number of values for column altitude which
%is needed in file that will be executed.

% u corresponds to udata file provided by NASA
wind_list = csvread('u.csv');

% the values of cross-flow for all altitudes is modified
% according to values assigned in Monte Carlo simulation.
wind_list(:,2) = wind_value_m_per_s;

% THE CODE BELOW MODIFIES THE FILE QDATA WHICH CONTAINS
% ENVIRONMENTAL TURBULENCE FOR EACH ALTITUDE. This file
% cannot have any extension otherwise executable will
% not run.

fid7 = fopen ('UDATA','w');

% the file format for UDATA includes a first value which
fprintf(fid7, '%f
', 120);
fprintf(fid7, '%f %f
', wind_list);
fclose(fid7);

% In this for loop Temperature values in (Kelvin) for each altitud get inserted into the simulation.
% this is an input parameter that affects how turbulence decays.
for temperature_values_variations = ...
    temperature_value_initial_indice:temperature_value_final_indice;
    
    % We are changing values of temperature in APA file called TDATA
    temperature_value_kelvin = ...
    temperature_values_from_high_to_low_kelvin ...
    (temperature_values_variations);
    
    %The file t.csv contains temperature values given by NASA.
    %Note: This file is not in format needed for APA nor does it contain the number of values for column altitude which is needed in the file that will be executed.
    
    % t corresponds to tdata file provided by NASA
    temperature_list = csvread('t.csv');
    % the values of temperature for all altitudes is modified according to values assigned in Monte Carlo simulation.
    temperature_list(:,2) = temperature_value_kelvin;

    % THE CODE BELOW MODIFIES THE FILE TDATA WHICH CONTAINS TEMPERATURE IN KELVIN FOR EACH ALTITUDE. This file cannot have any extension otherwise executable will not run.
    fid7 = fopen ('TDATA', 'w');
    
    % the file format for TDATA includes a first value which specifies the number of rows which is always 30 for this input file.
    fprintf(fid7, '%f\n', 30);
    fprintf(fid7, '%f %f\n', temperature_list);
    fclose(fid7);

    %INPUT file for each APA run, this line intends to save APA inputs for each run for further analysis.
    delete ACDATA TRAJEC.DAT APA.OUT
% INPUTS for APA
fid5 = fopen('ACDATA','a');
fprintf(fid5, '%f,%f,%f,%f \n', longitude, altitude_m, VInitial_m_per_s, initial_vortex_separation_m);
fclose(fid5);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Saves the inputs above in an easy to study format
%
input(aircraft).input(altitudes_indices).input(aircraft_mass_variations).longitude = longitude;
%
input(aircraft).input(altitudes_indices).input(aircraft_mass_variations).altitude_m = altitude_m;
%
input(aircraft).input(altitudes_indices).input(aircraft_mass_variations).VInitial_m_per_s = VInitial_m_per_s;
%
input(aircraft).input(altitudes_indices).input(aircraft_mass_variations).initial_vortex_separation_m = initial_vortex_separation_m;

%% Run APA Suite Model:
% All units on APA are metric.
% This means meters, kg, seconds.

system('APA_Suite_4_53.exe');

%% Import the output file and parse the result of
% APA from output file and Parse data from TRAJECT.DAT

% Function declaration:
% function [out_arg1, out_arg2, ...] = function_name(in_arg1, in_arg2, ...)

[time_s, circulation_strength_left_m2_per_s,...
 lateral_position_left_m, vertical_position_left_m,...
 circulation_strength_right_m2_per_s, lateral_position_right_m,...
 vertical_position_right_m] = apa_output_parser();

loop_counter=loop_counter+1;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Saves the inputs and output in an easy to study format
% If wind is not going to be included in simulation
% then comment wind for loop and comment wake input-output
% section below and uncomment this wake input-output section.
%
% wake(aircraft_indice).aircraft_name=aircraft_name;
% wake(aircraft_indice).wingspan=wingspan;
% wake(aircraft_indice).MTOW_kg=mtow;
% wake(aircraft_indice).MALW_kg=malw;

% wake(aircraft_indice).wake_behavior(edr_values_variations + (VInitial_counter-1)*edr_value_final_indice).altitude_m=altitude_m;
\% wake(aircraft_indice).wake_behavior(edr_values_variations + (VInitial_counter-1)*edr_value_final_indice).groundspeed_m_per_s=groundspeed_m_per_s;
\% wake(aircraft_indice).wake_behavior(edr_values_variations + (VInitial_counter-1)*edr_value_final_indice).aircraft_mass=aircraft_mass;
\% wake(aircraft_indice).wake_behavior(edr_values_variations + (VInitial_counter-1)*edr_value_final_indice).edr_value=edr_value;
\% wake(aircraft_indice).wake_behavior(edr_values_variations + (VInitial_counter-1)*edr_value_final_indice).VInitial=VInitial;
\% wake(aircraft_indice).wake_behavior(edr_values_variations + (VInitial_counter-1)*edr_value_final_indice).time=time;
\%
\% saves the inputs and output of simulation in a
\% variable called wake
\% wake(aircraft_indice).aircraft_name=aircraft_name;
\% This output structure could be unorthodox but it
\% gives us the ability to save the several aircrafts
\% at the same time and analyze results with previously
\% created codes.

wake(aircraft_indice).wingspan_m=wingspan_m;
wake(aircraft_indice).MTOW_kg=mtow_kg;
wake(aircraft_indice).MALW_kg=malw_kg;

wake(aircraft_indice).wake_behavior(loop_counter).altitude_m=altitude_m;
wake(aircraft_indice).wake_behavior(loop_counter).aircraft_mass_kg=aircraft_mass_kg;
wake(aircraft_indice).wake_behavior(loop_counter).edr_value_m2_per_s3=edr_value_m2_per_s3;
wake(aircraft_indice).wake_behavior(loop_counter).wind_value_m_per_s=wind_value_m_per_s;
wake(aircraft_indice).wake_behavior(loop_counter).temperature_value_kelvin=temperature_value_kelvin;
wake(aircraft_indice).wake_behavior(loop_counter).VInitial_m_per_s=VInitial_m_per_s;
wake(aircraft_indice).wake_behavior(loop_counter).rho_kg_per_m3=rho_kg_per_m3;
wake(aircraft_indice).wake_behavior(loop_counter).groundspeed_m_per_s=groundspeed_m_per_s;

wake(aircraft_indice).wake_behavior(loop_counter).time_s=time_s;

wake(aircraft_indice).wake_behavior(loop_counter).circulation_strength_left_m2_per_s=circulation_strength_left_m2_per_s;
wake(aircraft_indice).wake_behavior(loop_counter).lateral_position_left_m=lateral_position_left_m;
wake(aircraft_indice).wake_behavior(loop_counter).vertical_position_left_m=vertical_position_left_m;

wake(aircraft_indice).wake_behavior(loop_counter).circulation_strength_right_m2_per_s=circulation_strength_right_m2_per_s;
wake(aircraft_indice).wake_behavior(loop_counter).lateral_position_right_m=lateral_position_right_m;
wake(aircraft_indice).wake_behavior(loop_counter).vertical_position_right_m=vertical_position_right_m;

\%
\% saves output by itself in output structure file.
\% In case that is needed just uncomment lines
\% below.
% output(aircraft).output(altitudes_indices).output(aircraft_mass_variations).time = time;
% output(aircraft).output(altitudes_indices).output(aircraft_mass_variations).circulation_strength_left =
circulation_strength_left;
% output(aircraft).output(altitudes_indices).output(aircraft_mass_variations).lateral_position_left =
lateral_position_left;
% output(aircraft).output(altitudes_indices).output(aircraft_mass_variations).vertical_position_left =
vertical_position_left;
% output(aircraft).output(altitudes_indices).output(aircraft_mass_variations).circulation_strength_right =
circulation_strength_right;
% output(aircraft).output(altitudes_indices).output(aircraft_mass_variations).lateral_position_right =
lateral_position_right;
% output(aircraft).output(altitudesIndices).output(aircraft_mass_variations).vertical_position_right =
vertical_position_right;
end
%for temperature_values_variations =
% temperature_value_initial_indice:temperature_value_final_indice
end
%for wind_values_variations =
% wind_value_initial_indice:wind_value_final_indice
end % for edr_values_variations=
% edr_value_initial_indice:edr_value_final_indice
end % for aircraft_mass_variations=
% aircraft_mass_initial_indice:aircraft_mass_final_indice
end % for altitudes=altitude_initial_indice:altitude_final_indice
end % for aircraft=aircraft_indice

%save('Wake_Vortex_Prediction_Variables','-v7.3')
save('wake_behavior_simulation_output','wake','-v7.3')

%save('Wake_Vortex_Prediction_Variables','-v7.3')
save('wake_behavior_simulation_output','wake','-v7.3')

% Set appropiate delimiter; for when you try to specify the directory from
% where data should be loaded and where data should be saved.

% if (ismac==1)
%   SLASH = '/';
% elseif (ismac == 0)
%   SLASH = '\';
% end

% CHECKING UNIQUE VALUES FOR CERTAIN AIRCRAFT
1.2 Wake Behavior at Standard Times Matrix

This code creates a matrix called (all_circulation_data) that contains all values of independent variables and dependent variables. This matrix can be used for ANNOVA and also to export matrix to SPSS for further analysis.

```
wake_behavior_at_standard_times_matrix = zeros(size(wake_behavior_at_standard_times,2)*241,9);
current_big_matrix_index = 1;

for environment_index = 1:size(wake_behavior_at_standard_times,2)
    for time_series = 1:241
        wake_behavior_at_standard_times_matrix(current_big_matrix_index,1) = ...
            wake_behavior_at_standard_times(environment_index).altitude_m;
        current_big_matrix_index = current_big_matrix_index + 1;
    end
end
```

wake_behavior_at_standard_times_matrix(current_big_matrix_index,6) = ...
    wake_behavior_at_standard_times(environment_index).time_s(time_series);

wake_behavior_at_standard_times_matrix(current_big_matrix_index,7) = ...
    wake_behavior_at_standard_times(environment_index).circulation_strength_right_m2_per_s(time_series);

wake_behavior_at_standard_times_matrix(current_big_matrix_index,8) = ...
    wake_behavior_at_standard_times(environment_index).lateral_position_right_m(time_series);

wake_behavior_at_standard_times_matrix(current_big_matrix_index,9) = ...
    wake_behavior_at_standard_times(environment_index).vertical_position_right_m(time_series);

current_big_matrix_index = current_big_matrix_index + 1;
end
eend

% WRITE THE CSV FILE
csvwrite('wake_behavior_at_standard_time_matrix_Departure_A388_12M_12E_6W_6T.csv',wake_behavior_at_standard_times_matrix);

1.3 Prepares NASA Model Output for Artificial Neural Network

This code prepares output from APA which is variable wake_behavior_simulation_output.mat for neural network.

This code resumes input and output file called wake_behavior_simulation_output from APA. From APA data is collected every 0.2 seconds and a resolution higher than one second is not needed for the analysis.

%%%%%%%%%%%%%%%%%%%%%%
% PREPARES NASA MODEL OUTPUT FOR ARTIFICIAL NEURAL NETWORK %
% CODED BY: JULIO ROA %
% PREDICT CIRCULATION FOR A WAKE VORTEX TIME SEPARATION %
% PREDICT WAKE VORTEX TIME SEPARATION FOR A MAXIMUM CIRCULATION CAPACITY %
%%%%%%%%%%%%%%%%%%%%%%
%% NEURAL NETWORK AT STANDARD TIME
%% This code prepares the dependent and independent variables for the
%% Artificial Neural Network. It groups all independent variables into one
%% matrix and then normalizes them and the same is done for the dependent
%% variables.

%% This code:
%% preallocation for neural network matrix of dependent and independent variables
%% normalizes dependent and independent variables
%% Runs neural network (shows indices for training, testing and validation
%% Calculates MSE to identify neural network performance

%INPUT: ALTITUD, EDR, WIND, TEMPERATURE, MASS, CIRCULATION
%OUTPUT: TIME IN SECONDS (DYNAMIC TIME SEPARATION)

%% PREPARE DATA FOR NEURAL NETWORK TRAINING.
%% Optimization step to initiate the matrix
total_size_row = 0;
for row_index = 1:number_of_sets_of_data
    total_size_row = ...
    total_size_row + size(wake_behavior_at_standard_times(row_index).time_s,2);
end
x_value_for_regression = zeros(total_size_row,6);
y_value_for_regression = zeros(total_size_row,1);

%% CONSTRUCT DATA INTO MATRIX
%% PERFORM DATA ESCALAMIENTO:
%% VALOR ESCALADO = (VALOR - VALOR MINIMO) / (VALOR MAXIMO - VALOR MINIMO)
current_row_index = 1;
altitude_at_standard_time_normalized =...  
    ([wake_behavior_at_standard_times(:,:,).altitude_m] - ...
    min([wake_behavior_at_standard_times(:,:,).altitude_m]))...  
    / (max([wake_behavior_at_standard_times(:,:,).altitude_m])- ...
    min([wake_behavior_at_standard_times(:,:,).altitude_m]));
edr_at_standard_time_normalized = ...
    ([wake_behavior_at_standard_times(:,:,).edr_value_m2_per_s3] - ...
    min([wake_behavior_at_standard_times(:,:,).edr_value_m2_per_s3])...  
    / (max([wake_behavior_at_standard_times(:,:,).edr_value_m2_per_s3])-
    min([wake_behavior_at_standard_times(:,:,).edr_value_m2_per_s3]));
wind_at_standard_time_normalized = ...
    ([wake_behavior_at_standard_times(:,:,).wind_value_m_per_s] - ...
    min([wake_behavior_at_standard_times(:,:,).wind_value_m_per_s])...  

% END NEURAL NETWORK AT STANDARD TIME
/ (max([wake_behavior_at_standard_times(:).wind_value_m_per_s]) -... 
im([wake_behavior_at_standard_times(:).wind_value_m_per_s]));

temperature_at_standard_time_normalized = ...
    ([wake_behavior_at_standard_times(:).temperature_value_kelvin] - ... 
im([wake_behavior_at_standard_times(:).temperature_value_kelvin])... 
    / (max([wake_behavior_at_standard_times(:).temperature_value_kelvin]) -...
    min([wake_behavior_at_standard_times(:).temperature_value_kelvin]));

aircraft_mass_at_standard_time_normalized = ...
    ([wake_behavior_at_standard_times(:).aircraft_mass_kg] - ... 
im([wake_behavior_at_standard_times(:).aircraft_mass_kg])... 
    / (max([wake_behavior_at_standard_times(:).aircraft_mass_kg]) -...
    min([wake_behavior_at_standard_times(:).aircraft_mass_kg]));

% Escalamiento inside time series for each time series of time and circulation. 
% looking inside each time series for min and max values of time and 
% circulation and then is normalizing.
min_time_s = min((wake_behavior_at_standard_times(1).time_s(:))); 
for row_index = 2:number_of_sets_of_data
    min_time_row = min((wake_behavior_at_standard_times(row_index).time_s(:))); 
    if (min_time_s > min_time_row)
        min_time_s = min_time_row;
    end
end

max_time_s = max((wake_behavior_at_standard_times(1).time_s(:))); 
for row_index = 2:number_of_sets_of_data
    max_time_row = max((wake_behavior_at_standard_times(row_index).time_s(:))); 
    if (max_time_s < max_time_row)
        max_time_s = max_time_row;
    end
end

min_circulation_strength_right_m2_per_s = ... 
im((wake_behavior_at_standard_times(1).circulation_strength_right_m2_per_s(:))); 
for row_index = 2:number_of_sets_of_data
    min_time_row = ...
        min((wake_behavior_at_standard_times... 
          (row_index).circulation_strength_right_m2_per_s(:))); 
    if (min_circulation_strength_right_m2_per_s > min_time_row)
        min_circulation_strength_right_m2_per_s = min_time_row;
    end
end

max_circulation_strength_right_m2_per_s = ... 
max((wake_behavior_at_standard_times(1).circulation_strength_right_m2_per_s(:))); 
for row_index = 2:number_of_sets_of_data
max_time_row = ...
    max((wake_behavior_at_standard_times(row_index).circulation_strength_right_m2_per_s(:)));
    if (max_circulation_strength_right_m2_per_s < max_time_row)
        max_circulation_strength_right_m2_per_s = max_time_row;
    end
end

% CONSTRUCT DATA INTO MATRIX FOR DEPENDENT AND INDEPENDENT VARIABLES.
% This data is normalized.
for row_index = 1:number_of_sets_of_data

circulation_at_standard_time_normalized = ...
    ((wake_behavior_at_standard_times(row_index).circulation_strength_right_m2_per_s(:)) ...  
        - min_circulation_strength_right_m2_per_s) ...  
    / (max_circulation_strength_right_m2_per_s ...  
        - min_circulation_strength_right_m2_per_s);

time_at_standard_time_normalized = ...
    ((wake_behavior_at_standard_times(row_index).time_s(:)) ...  
        - min_time_s) ...  
    / (max_time_s ...  
        - min_time_s);

  % circulation_at_standard_time_normalized = ...
  % (wake_behavior_at_standard_times(row_index).circulation_strength_right_m2_per_s(:)) ...  
  % - min(wake_behavior_at_standard_times(row_index).circulation_strength_right_m2_per_s(:)) ...  
  % / (max(wake_behavior_at_standard_times(row_index).circulation_strength_right_m2_per_s(:)) ...  
  % - min(wake_behavior_at_standard_times(row_index).circulation_strength_right_m2_per_s(:)));  
  %
  %
  %    time_at_standard_time_normalized = 
  %    (wake_behavior_at_standard_times(row_index).time_s(:)) ...  
  %    - min(wake_behavior_at_standard_times(row_index).time_s(:))) ...  
  %    / (max(wake_behavior_at_standard_times(row_index).time_s(:)) ...  
  %    - min(wake_behavior_at_standard_times(row_index).time_s(:)));  
  %
for time_series = 1:size(wake_behavior_at_standard_times(row_index).time_s,2)
    if(wake_behavior(row_index).circulation_strength_right_m2_per_s(time_series) ==0)
        continue; % for a certain value of time circulation
    end
    x_value_for_regression(current_row_index,1) = ...
        altitude_at_standard_time_normalized(row_index);
    x_value_for_regression(current_row_index,2) = ...
        edr_at_standard_time_normalized(row_index);
    x_value_for_regression(current_row_index,3) = ...
        wind_at_standard_time_normalized (row_index);
    x_value_for_regression(current_row_index,4) = ...
        temperature_at_standard_time_normalized(row_index);
    x_value_for_regression(current_row_index,5) = ...
        aircraft_mass_at_standard_time_normalized(row_index);
\texttt{x\_value\_for\_regression(current\_row\_index,6) = ...}
\texttt{circulation\_at\_standard\_time\_normalized(time\_series);}

\texttt{\% y value \{independent variable\} will give us the output.}
\texttt{y\_value\_for\_regression(current\_row\_index) = ...}
\texttt{time\_at\_standard\_time\_normalized(time\_series);}

\texttt{current\_row\_index = current\_row\_index + 1;}
\texttt{end}
\texttt{end}

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
\% AT THIS STEP; CREATE NEURAL NETWORK USING CODE BELOW. \%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
\% DEFINE DEPENDENT AND INDEPENDENT VARIABLES

\texttt{independent\_variables = x\_value\_for\_regression';}
\texttt{dependent\_variable = y\_value\_for\_regression';}

\% Choose a Training Function
\% For a list of all training functions type: help nntrain
\% 'trainlm' is usually fastest.
\% 'trainbr' takes longer but may be better for challenging problems.
\% 'trainscg' uses less memory. Suitable in low memory situations.
\texttt{training\_function = 'trainbr'; \% Levenberg-Marquardt backpropagation.}

\% Create a Fitting Network
\texttt{hidden\_layer\_size = [3, 3];}
\texttt{neural\_network = fitnet(hidden\_layer\_size,training\_function);}
\texttt{\% fitnet returns a function fitting neural network with a hidden layer size}
\texttt{\% of hiddenSizes and training function, specified by the training function.}

\% Choose Input and Output Pre/Post-Processing Functions
\% For a list of all processing functions type: help nnprocess
\texttt{neural\_network.input.processFcns = {'removeconstantrows','mapminmax'};}
\texttt{neural\_network.output.processFcns = {'removeconstantrows','mapminmax'};}

\% Setup Division of Data for Training, Validation, Testing
\% For a list of all data division functions type: help nndivide
\texttt{neural\_network.divideFcn = 'dividerand'; \% Divide data randomly}
\texttt{neural\_network.divideMode = 'sample'; \% Divide up every sample}
\texttt{neural\_network.divideParam.trainRatio = 70/100;}
\texttt{neural\_network.divideParam.valRatio = 15/100;}
\texttt{neural\_network.divideParam.testRatio = 15/100;}

\% Choose a Performance Function
\% For a list of all performance functions type: help nnperformance
\texttt{neural\_network.performFcn = 'mse'; \% Mean Squared Error}
% Choose Plot Functions
% For a list of all plot functions type: help nnplot
neural_network.plotFcns = {'plotperform','plottrainstate','ploterrhist', ...
    'plotregression', 'plotfit'};

% Train the Network
[neural_network,tr] = train(neural_network,independent_variables,dependent_variable);

% Test the Network
y = neural_network(independent_variables);
e = gsubtract(dependent_variable,y);
performance = perform(neural_network,dependent_variable,y);

% Recalculate Training, Validation and Test Performance
trainTargets = dependent_variable .* tr.trainMask{1};
valTargets = dependent_variable .* tr.valMask{1};
testTargets = dependent_variable .* tr.testMask{1};

% This variable will contain performance (MSE) of training.
trainPerformance = perform(neural_network,trainTargets,y);

% This variable will contain performance (MSE) of validation.
valPerformance = perform(neural_network,valTargets,y);

% This variable will contain performance (MSE) of testing.
testPerformance = perform(neural_network,testTargets,y);

% View the Network
view(neural_network)

% Plots
% Uncomment these lines to enable various plots.
figure, plotperform(tr)
figure, plottrainstate(tr)
figure, ploterrhist(e)
figure, plotregression(t,y)
figure, plotfit(net,x,t)

% Deployment
% Change the (false) values to (true) to enable the following code blocks.
% See the help for each generation function for more information.
% if (true)
%   % Generate MATLAB function for neural network for application
%   % deployment in MATLAB scripts or with MATLAB Compiler and Builder
%   % tools, or simply to examine the calculations your trained neural
%   % network performs.
%   genFunction(net,'myNeuralNetworkFunction');
%   y = myNeuralNetworkFunction(x);
% end
% if (false)
%   % Generate a matrix-only MATLAB function for neural network code
%   % generation with MATLAB Coder tools.
% genFunction(net,'myNeuralNetworkFunction','MatrixOnly','yes');
% y = myNeuralNetworkFunction(x);
% end
% if (true)
% % Generate a Simulink diagram for simulation or deployment with.
% % Simulink Coder tools.
% gensim(net);
% end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% SAVE INDICES FOR VALUES USED IN TRAINING, VALIDATION, AND TEST.
% This structure contains all of the information concerning the training
% of the network. For example, tr.trainInd, tr.valInd and tr.testInd
% contain the indices of the data points that were used in the training,
% validation and test sets, respectively.
% training_indices = tr.trainInd;
% validation_indices = tr.valInd;
% testing_indices = tr.testInd;

save('all_variables_that_resulted_from_nn_A388_Arrival')

% *** TESTING NEURAL NETWORK ***
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% WAKE BEHAVIOR NEURAL NETWORK EXECUTION AND TESTING
% CODE OR FUNCTION TO TRANSLATE THE INPUT FROM USER INTO NORMALIZED INPUT
% THAT NN CAN WORK WITH.

% DEFINE CURRENT CONDITIONS
altitude_m = 45.72; % 15.24;
edr_value_m2_per_s3 = 0.000027;
wind_value_m_per_s = 2; % 1.7882;
temperature_value_kelvin = 320; %298;
aircraft_mass_kg = 200000; %141970;

%This category classifies aircraft from super heavy(A or 1) to light (F or 6)
aircraft_group = 3;
% DEFINE MAXIMUM WAKE CIRCULATION CAPACITY
circulation_strength_m2_per_s = 200;

% FUNCTION TO TRANSFORM THE INPUTS TO NORMALIZED INPUTS FOR THE NEURAL
% NETWORK: [output]=function_name(input)
[altitude_m,edr_value_m2_per_s3,wind_value_m_per_s,temperature_value_kelvin, ...
aircraft_mass_kg,circulation_strength_m2_per_s]= ...
wake_behavior_nn_transformation_input...
[altitude_m,edr_value_m2_per_s3,wind_value_m_per_s, ...
temperature_value_kelvin,aircraft_mass_kg,...
circulation_strength_m2_per_s,aircraft_group);
% EXAMPLE:
% altitude_m = 0.6
% edr_value_m2_per_s3 = 0.4
% wind_value_m_per_s = 0.3
% temperature_value_kelvin = 0.8
% aircraft_mass_kg = 0.9
% circulation_strength_m2_per_s = 0.7
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% REDEFINE PARAMETERS AND INJECT INTO NEURAL NETWORK.
inputs_to_find_time = ... 
[altitude_m edr_value_m2_per_s3 wind_value_m_per_s temperature_value_kelvin...
 aircraft_mass_kg circulation_strength_m2_per_s];

% PREDICT RESULTS
% net variable depends on the variable we are saving.
wake_dynamic_time_separation_normalized = sim(neural_network,inputs_to_find_time');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% CALL THE FUNCTION TO TRANSLATE THE OUTPUT FROM THE NN (wake dynamic separation)
% WHICH IS NORMALIZED INTO NON NORMALIZED TIME SEPARATION

wake_dynamic_time_separation = ...
    wake_behavior_nn_transformation_output(wake_dynamic_time_separation_normalized);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% NEURAL NETWORK STATISTICAL TEST
% Statistical test for neural network MSE for all the data.

total_square = 0;
for i = 1:size(traning_indices,2)
    y_from_nn = sim(neural_network,{x_value_for_regression(traning_indices(i),:)}');
    total_square = ...
        total_square + (y_from_nn - y_value_for_regression(traning_indices(i)))^2;
end

MSE = total_square/size(x_value_for_regression,1);
disp(MSE);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% DO MY OWN COMPARISON BETWEEN NEURAL NETWORK AND DATA

% Plot data vs nn for indices that were not used during the nn training.

% NEURAL NETWORK:
% For normalized value of: altitude= 0.2 wind= 0.4 temp = 0.6 mass= 0.81 edr = 0.0467
% Plot circulation vs time
% DATA:
% For normalized value of: altitude= 0.2 wind= 0.4 temp = 0.6 mass= 0.81 edr = 0.0467
% Plot circulation vs time

% INPUT NORMALIZED VALUES IN ORDER TO RUN NEURAL NETWORK
altitude_at_standard_time_normalized_validation = 0.2;
wind_at_standard_time_normalized_validation = 0.4;
temperature_at_standard_time_normalized_validation=0.6;
aircraft_mass_at_standard_time_normalized_validation = 0.81;

% This value of edr has been fixed. for plotting illustration purposes.
edr_at_standard_time_normalized_validation = 0.0467;

% unique(x_value_for_regression(:,1)); % if you need to know the unique 
% values inside the matrix that contains the independent variables.

% CALCULATE TIME SEPARATION ON NN AND COMPARE WITH REAL DATA
performance_figure_index = 1;
total_square = 0;
circ_to_plot_performance = zeros(1,2);
real_time_to_plot_performance= zeros(1,2);
time_from_nn_to_plot_performance = zeros(1,2);
for regression_matrix_index = 1:size(x_value_for_regression,1)
    if(abs(x_value_for_regression(regression_matrix_index,1) - altitude_at_standard_time_normalized_validation) > 1e-2)
        continue;
    end
    if(abs(x_value_for_regression(regression_matrix_index,2) - edr_at_standard_time_normalized_validation) > 1e-2)
        continue;
    end
    if(abs(x_value_for_regression(regression_matrix_index,3) - wind_at_standard_time_normalized_validation) > 1e-2)
        continue;
    end
    if(abs(x_value_for_regression(regression_matrix_index,4) - temperature_at_standard_time_normalized_validation) > 1e-2)
        continue;
    end
    if(abs(x_value_for_regression(regression_matrix_index,5) - aircraft_mass_at_standard_time_normalized_validation) > 1e-2)
        continue;
    end
    circ_to_plot_performance(performance_figure_index) = x_value_for_regression(regression_matrix_index,6);
    real_time_to_plot_performance(performance_figure_index) = y_value_for_regression(regression_matrix_index);
    time_from_nn_to_plot_performance(performance_figure_index) = sim(neural_network,(x_value_for_regression(regression_matrix_index,:))');
end

circ_to_plot_performance(performance_figure_index) = ...
x_value_for_regression(regression_matrix_index,6);
real_time_to_plot_performance(performance_figure_index) = ...
y_value_for_regression(regression_matrix_index);

% use neural to predict time value based on given inputs.
time_from_nn_to_plot_performance(performance_figure_index) = ...
sim(neural_network,(x_value_for_regression(regression_matrix_index,:))');

%Calculate the MSE between nn predicted and real data
total_square = total_square + (time_from_nn_to_plot_performance...
( performance_figure_index) - ...
real_time_to_plot_performance(performance_figure_index))^2;
performance_figure_index = performance_figure_index + 1;
end
MSE = total_square/(performance_figure_index-1);

% PLOT time separation vs circulation strength for edr : 0.1, 0.2, 0.3,
figure
ylabel('Circulation normalized');
xlabel('Time normalized');
plot(circ_to_plot_performance,real_time_to_plot_performance,'*', ...
    circ_to_plot_performance,time_from_nn_to_plot_performance, '-');
%text(['MSE =',num2str(MSE)]);
text('MSE');

1.4 Wake Behavior Compressed

This script will shorten wake behavior at standard times file by excluding Vinitial, density, among others.

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                                                                        
%                        WAKE BEHAVIOR COMPRESSED                          
%                          CODED BY: JULIO ROA                           
%                                                                        
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% wake_behavior_arrival_compress = wake(13).wake_behavior;
wake_behavior_arrival_shorten = wake_behavior_at_standard_times;

wake_behavior_arrival_shorten = ...
    rmfield(wake_behavior_arrival_shorten, 'VInitial_m_per_s');

wake_behavior_arrival_shorten = ...
    rmfield(wake_behavior_arrival_shorten, 'rho_kg_per_m3');

wake_behavior_arrival_shorten = ...
    rmfield(wake_behavior_arrival_shorten, 'groundspeed_m_per_s');

wake_behavior_arrival_shorten = ...
    rmfield(wake_behavior_arrival_shorten, 'circulation_strength_left_m2_per_s');

wake_behavior_arrival_shorten = ...
    rmfield(wake_behavior_arrival_shorten, 'lateral_position_left_m');

wake_behavior_arrival_shorten = ...
    rmfield(wake_behavior_arrival_shorten, 'vertical_position_left_m');
save('wake_behavior_arrival_shorten_A388_12M_12E_6W_6T', 'wake_behavior_arrival_shorten', '-v7.3')
save('wake_behavior_arrival_shorten_A388_16M_12E_6W_6T', 'wake_behavior_arrival_shorten', '-v7.3')
save('wake_behavior_arrival_shorten_A388_18M_12E_6W_6T', 'wake_behavior_arrival_shorten', '-v7.3')

save('wake_behavior_departure_shorten_A388_12M_12E_6W_6T', 'wake_behavior_arrival_shorten', '-v7.3')

% SHORTEN WAKE BEHAVIOR AT STANDARD TIMES FILES BY EXCLUDING VINITIAL, DENSITY, AMONG OTHERS
wake_behavior_departure_shorten = wake_behavior_at_standard_times;

wake_behavior_departure_shorten = ...
rmfield(wake_behavior_departure_shorten, 'VInitial_m_per_s');

wake_behavior_departure_shorten = ...
rmfield(wake_behavior_departure_shorten, 'rho_kg_per_m3');

wake_behavior_departure_shorten = ...
rmfield(wake_behavior_departure_shorten, 'groundspeed_m_per_s');

wake_behavior_departure_shorten = ...
rmfield(wake_behavior_departure_shorten, 'circulation_strength_left_m2_per_s');

wake_behavior_departure_shorten = ...
rmfield(wake_behavior_departure_shorten, 'lateral_position_left_m');

wake_behavior_departure_shorten = ...
rmfield(wake_behavior_departure_shorten, 'vertical_position_left_m');

save('wake_behavior_departure_shorten', 'wake_behavior_departure_shorten', '-v7.3')
1.5 Function: Airport Schedule

This function simulates an airport schedule / single runway utilization and it will be used by to inject aircraft into a runway in other codes.

```
function y = w_03_airline_schedule_function()
    % Letter A, B, C represent aircraft groups.
    y = ['A' 'B' 'C'; 'A' 'B' 'C'; 'B' 'D' 'F'; 'D' 'C'];
end
```

1.6 Wake Behavior Statistics and Plots

This code intends to study wake_simulation_output which includes APA results to understand how environmental factor and aircraft dependent factors affect circulation strength over time (circulation decay).

```
% CLEAR ALL VARIABLES IN THE WORKSPACE
clear all
clc

% LOAD DATA FROM THE SIMULATION CALLED WAKE_VORTEX_PREDICTION
%(NASA APA MONTE CARLO SIMULATION).
load wake_behavior_simulation_output.mat
```
% load BADA_IGE % this is aircraft performance characteristics for each
% altitude.

% DEFINE KEY PARAMETERS TO INTERPRET DATA:
%(aircraft, time_initial and time_final)
% aircraft_indice=13;

% If you would like to find aircraft indice automatically.
aircraft_indice=size(wake,2);

% store wake behavior results for each aircraft from APA in variable
% called wake_behavior.
wake_behavior = wake(aircraft_indice).wake_behavior;
% wake_behavior = wake_behavior_at_standard_times

% IDENTIFY THE NUMBER OF DATA SETS INSIDE WAKE BEHAVIOR; this is the number
% of operations (example: arrivals) that were simulated.
% count how many set of data we have 43200
number_of_sets_of_data = numel(wake_behavior);
% number_of_sets_of_data = 20; %used to do short data verification
% where working with all data sets are not needed.

% PREPARE DATA FOR ANALYSIS AND FOR CREATION OF MODEL

% COUNT HOW MANY EMPTY ROWS (WITH ZERO) THAT CAME FROM APA OUTPUT WITH
% TIME SERIES EQUAL TO ZERO.
cnt = 0; % Count
for time_series = 1 : number_of_sets_of_data
    if(wake_behavior(time_series).time_s == 0)
        cnt = cnt + 1;
    end
end

% DELETE ANY ROW THAT ONLY CONTAINS ZERO IN TIME SERIES.
index_for_non_zero = 1;
wake_behavior_without_zero_rows=zeros(1,number_of_sets_of_data);
for time_series = 1 : number_of_sets_of_data
    if (wake_behavior(time_series).time_s == 0)
        continue;
    end
    wake_behavior_without_zero_rows(index_for_non_zero) =...
    wake_behavior(time_series);
    index_for_non_zero = index_for_non_zero + 1;
end

% UNDERSTAND THE UNIQUE VALUES THAT WERE TAKEN INTO CONSIDERATION FOR THE
% MONTE CARLO SIMULATION AND APA WAKE NASA MODEL
unique_altitude_m = unique([wake_behavior.altitude_m])
size_unique_altitude_m = size(unique_altitude_m);
min_altitude_m = min([wake_behavior.altitude_m]);
max_altitude_m = max([wake_behavior.altitude_m]);

unique_aircraft_mass_kg = unique([wake_behavior.aircraft_mass_kg])
size_unique_aircraft_mass_kg = size(unique_aircraft_mass_kg);
min_aircraft_mass_kg = min([wake_behavior.aircraft_mass_kg]);
max_aircraft_mass_kg = max([wake_behavior.aircraft_mass_kg]);

unique_edr_value_m2_per_s3 = unique([wake_behavior.edr_value_m2_per_s3])
size_unique_edr_value_m2_per_s3 = size(unique_edr_value_m2_per_s3);
min_edr_value_m2_per_s3 = min([wake_behavior.edr_value_m2_per_s3]);
max_edr_value_m2_per_s3 = max([wake_behavior.edr_value_m2_per_s3]);

unique_wind_value_m_per_s = unique([wake_behavior.wind_value_m_per_s])
size_unique_wind_value_m_per_s = size(unique_wind_value_m_per_s);
min_wind_value_m_per_s = min([wake_behavior.wind_value_m_per_s]);
max_wind_value_m_per_s = max([wake_behavior.wind_value_m_per_s]);

unique_temperature_value_kelvin =...
    unique([wake_behavior.temperature_value_kelvin])
size_unique_temperature_value_kelvin = size(unique_temperature_value_kelvin);
min_temperature_value_kelvin = min([wake_behavior.temperature_value_kelvin]);
max_temperature_value_kelvin = max([wake_behavior.temperature_value_kelvin]);

unique_VInitial_m_per_s = unique([wake_behavior.VInitial_m_per_s])
size_unique_VInitial_m_per_s = size(unique_VInitial_m_per_s);
min_VInitial_m_per_s = min([wake_behavior.VInitial_m_per_s]);
max_VInitial_m_per_s = max([wake_behavior.VInitial_m_per_s]);

% FIND MINIMUM AND MAX TIME IN EACH TIME SERIES
min_time_s = min((wake_behavior_at_standard_times(1).time_s(1)));
for row_index = 2:number_of_sets_of_data
    min_time_row = min((wake_behavior_at_standard_times...
        (row_index).time_s(1)));
    if (min_time_s > min_time_row)
        min_time_s = min_time_row;
    end
end

max_time_s = max((wake_behavior_at_standard_times(1).time_s(1)));
for row_index = 2:number_of_sets_of_data
    max_time_row = max((wake_behavior_at_standard_times...
        (row_index).time_s(1)));
    if (max_time_s < max_time_row)
        max_time_s = max_time_row;
    end
end
min_circulation_strength_right_m2_per_s = min((wake_behavior_at_standard_times(1).circulation_strength_right_m2_per_s(:)));  
for row_index = 2:number_of_sets_of_data  
    min_time_row = min((wake_behavior_at_standard_times(row_index).circulation_strength_right_m2_per_s(:)));  
    if (min_circulation_strength_right_m2_per_s > min_time_row)  
        min_circulation_strength_right_m2_per_s = min_time_row;  
    end  
end  
max_circulation_strength_right_m2_per_s = max((wake_behavior_at_standard_times(1).circulation_strength_right_m2_per_s(:)));  
for row_index = 2:number_of_sets_of_data  
    max_time_row = max((wake_behavior_at_standard_times(row_index).circulation_strength_right_m2_per_s(:)));  
    if (max_circulation_strength_right_m2_per_s < max_time_row)  
        max_circulation_strength_right_m2_per_s = max_time_row;  
    end  
end  

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% DEFINE INITIAL TIME SECONDS AND FINAL TIME SECONDS TO BE ANALYZED AND
% FIND THEIR INDICES

%Find indice for time_initial; Example: what is the indice at time 0 seconds.
time_initial_seconds=0;  
time_initial_indice=zeros(1,number_of_sets_of_data);  

%Find indice for time_initial (This is the lower time limit to be analyzed);  
% Example: what is the indice at time 0 seconds.  
% plot time 1 and circulation lenght  
for time_series = 1 : number_of_sets_of_data  
    % If row has value of zero in time struc due to APA calculation then  
    % ignore this row.  
    if (wake_behavior(time_series).time_s == 0)  
        continue;  
    end  
    % lowest value of time that starts with time_final indice.  
    % Ex: 120.1, 120.3, 120.4 pick indice for 120.1  
    checked_data = wake_behavior(time_series).time_s = time_initial_seconds;  
    list_of_indice_bigger_than_time_initial_seconds = find(checked_data>=0);  
    time_initial_indice(time_series) = ...  
        list_of_indice_bigger_than_time_initial_seconds(1);  
end
%Find indice for time_final (This is the upper time limit to be analyzed);
% Example: what is the indice at time 120 seconds.
time_final_seconds=240;
time_final_indice = zeros(1,number_of_sets_of_data);

% This loop looks for time_final_indice for each set of data. In other words for each set of data what is the index for the value of time (time_final_seconds).
% plot time 1 and circulation lenght
for time_series = 1 : number_of_sets_of_data

% If row has value of zero in time struc due to APA calculation then ignore this row.
if (wake_behavior(time_series).time_s == 0)
    continue;
end

% lowest value of time that starts with time_final_indice.
% Ex: 120.1,120.3, 120.4 pick indice for 120.1
checked_data = wake_behavior(time_series).time_s - time_final_seconds;
list_of_indice_bigger_than_time_final_seconds = find(checked_data>0);
time_final_indice(time_series) =...
    list_of_indice_bigger_than_time_final_seconds(1);
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% ANALYZE WAKE FROM TIME_INITIAL TO TIME_FINAL SECONDS AT STANDADRD TIMES.
%PLOT WAKE VORTEX CIRCULATION STRENGTH, WAKE LATERAL DISPLACEMENT AND WAKE VERTICAL DISPLACEMENT FROM TIME_INITIAL TO TIME_FINAL SECONDS.
%                                 Example from 0 sec to 120 secconds.
%Plot CIRCULATION STRENGHT  from  TIME_INITIAL to TIME_FINAL.
%Plot LATERAL POSITION      from  TIME_INITIAL to TIME_FINAL
%Plot VERTICAL POSITION     from  TIME_INITIAL to TIME_FINAL

aircraft_indice=size(wake,2);
% store wake behavior results for each aircraft from APA in variable % called wake_behavior.
wake_behavior_aircraft_name = wake(aircraft_indice).aircraft_name;

close all;
figure(1);
ylabel('Wake Vortex Circulation (m^2/s)','Fontsize',18);
xlabel('Time (s)','Fontsize',18);
% text(240,600,['Group A - Arrival',num2str(wake_behavior_aircraft_name)]);
hold on;

figure(2);
% ylabel('Wake Lateral displacement (m)','Fontsize',18);
% xlabel('Time (s)','Fontsize',18);
% % text(250,250,['Aircraft Name = ',num2str(wake_behavior_aircraft_name)]);
%% % text(200,170,['Group A - Arrival']);
%% hold on;

%% figure(3);
%% ylabel('Wake Vertical Displacement (m)','Fontsize',18);
%% xlabel('Time (s)','Fontsize',18);
%% xlim([0,220]);
%% % % % text(200,220,['Group A - Arrival',num2str(wake_behavior_aircraft_name))));
%% hold on;

%% plot time 1 and circulation lenght
for time_series = 1 : number_of_sets_of_data

    % If row has value of zero in time struc due to APA calculation then
    % ignore this row. This should be a time series for each row but not
    % zero
    if (wake_behavior(time_series).time_s == 0)
        continue;
    end

figure(1); %Circulation strength from time_initial to time_final
plot(wake_behavior(time_series).time_s(time_initial_indice:... 
    time_final_indice(time_series)),...
    wake_behavior(time_series).circulation_strength_right_m2_per_s... 
    (time_initial_indice(time_series):... 
    time_final_indice(time_series)) ); %,'*b'

figure(2); % Lateral position from time_initial to time_final
plot(wake_behavior(time_series).time_s(time_initial_indice:... 
    time_final_indice(time_series)), ... 
    wake_behavior(time_series).lateral_position_right_m...
    (time_initial_indice(time_series):... 
    time_final_indice(time_series)));

figure(3); % Vertical position from time_initial to time_final
plot(wake_behavior(time_series).time_s...
    (time_initial_indice:time_final_indice(time_series)),...
    wake_behavior(time_series).vertical_position_right_m...
    (time_initial_indice(time_series):... 
    time_final_indice(time_series)));
end

%% ADDING TO TXT TO PLOT CREATED ABOVE.
%% aircraft_indice=size(wake,2);
%% Store wake behavior results for each aircraft from APA in variable called
%% wake_behavior.
%% wake_behavior_aircraft_name = wake(aircraft_indice).aircraft_name;
%% text(200,170,['Aircaft Name = ',num2str(wake_behavior_aircraft_name)));
%% text(200,160,['altitude, edr, wind, temp, mass'])
%% text(200,150,[num2str(altitude_m), num2str(edr_value_m2_per_s3),... 
%% num2str(wind_value_m_per_s), num2str(temperature_value_kelvin),... 
%% num2str(aircraft_mass_kg))

180
% xlim([0,max(array_circulation_strength)])

saveas(figure(1),'A388_arr_circulation_vs_time_ARR_A388_36M_1000pdfE_1W_1T_1A','epsc');
saveas(figure(1),'A388_arr_circulation_vs_time_12M_16E_6W_6T_1A','epsc');
% saveas(gcf,'GA_arr_wake_lateral_displacement_vs_time','epsc');
saveas(gcf,'GA_arr_wake_vertical_displacement_vs_time','epsc');
saveas(gcf,'GA_arr_wake_circulation_vs_time','epsc');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% PLOT WAKE LATERAL DISPLACEMENT FOR WIND ZERO
% Plot LATERAL POSITION from TIME_INITIAL to TIME_FINAL
figure(2);
ylabel('Wake Lateral Displacement (m)', 'Fontsize',18);
xlabel('Time (s)', 'Fontsize',18);
%text(250,250,['Aircraft Name = ',num2str(wake_behavior_aircraft_name)]);
%text(200,170,['Group A - Arrival']);
hold on;

number_of_plotted_lines = 0; % count the number of plot lines
% plot time 1 and circulation lenght
for time_series = 1 : number_of_sets_of_data
    if (wake_behavior(time_series).wind_value_m_per_s == 0)
        continue;
    end
    hold on
    figure(2); % Lateral position from time_initial to time_final
    plot(wake_behavior(time_series).time_s(time_initial_index:...
    time_final_index(time_series)), wake_behavior...
    (time_series).lateral_position_right_m(time_initial_index...
    time_final_index(time_series)));
    number_of_plotted_lines = number_of_plotted_lines + 1;
end
saveas(gcf,'GA_arr_wake_lateral_displacement_vs_time_no_wind','epsc');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Plot all time vs all circulation
figure
% plot time 1 and circulation lenght
for time_series = 1 : number_of_sets_of_data
    plot(wake_behavior(time_series).time_s(time_series), wake_behavior...
    (time_series).circulation_strength_right_m2_per_s(time_series));
    hold on;
end
grid on

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
time_to_find_hist_60 = 60;
time_value_array = wake_behavior_at_standard_times.time_s;
index_of_time_hist = time_value_array==time_to_find_hist_60;
circulation_value_to_plot_hist_60 = ...
    zeros(1,size(wake_behavior_at_standard_times,2));
for time_series = 1:size(wake_behavior_at_standard_times,2)
    circulation_value_to_plot_hist_60(time_series)= ...
        wake_behavior_at_standard_times...
            (time_series).circulation_strength_right_m2_per_s(index_of_time_hist);
end

time_to_find_hist_120 = 120;
time_value_array = wake_behavior_at_standard_times.time_s;
index_of_time_hist = time_value_array==time_to_find_hist_120;
circulation_value_to_plot_hist_120 = ...
    zeros(1,size(wake_behavior_at_standard_times,2));
for time_series = 1:size(wake_behavior_at_standard_times,2)
    circulation_value_to_plot_hist_120(time_series)= ...
        wake_behavior_at_standard_times...
            (time_series).circulation_strength_right_m2_per_s(index_of_time_hist);
end

time_to_find_hist_180 = 180;
time_value_array = wake_behavior_at_standard_times.time_s;
index_of_time_hist = time_value_array==time_to_find_hist_180;
circulation_value_to_plot_hist_180 = ...
    zeros(1,size(wake_behavior_at_standard_times,2));
for time_series = 1:size(wake_behavior_at_standard_times,2)
    circulation_value_to_plot_hist_180(time_series)= ...
        wake_behavior_at_standard_times...
            (time_series).circulation_strength_right_m2_per_s(index_of_time_hist);
end

time_to_find_hist_240 = 240;
time_value_array = wake_behavior_at_standard_times.time_s;
index_of_time_hist = time_value_array==time_to_find_hist_240;
circulation_value_to_plot_hist_240 = zeros(1,size...
    (wake_behavior_at_standard_times,2));
for time_series = 1:size(wake_behavior_at_standard_times,2)
    circulation_value_to_plot_hist_240(time_series)= ...
        wake_behavior_at_standard_times...
            (time_series).circulation_strength_right_m2_per_s(index_of_time_hist);
end
subplot (2,2,1);
hist(circulation_value_to_plot_hist_60);
xlabel('Circulation (m^2/s)');
ylabel('Frequency');
legend('60 sec ', 'location','northeast');

subplot (2,2,2);
hist(circulation_value_to_plot_hist_120)
xlabel('Circulation (m^2/s)');
ylabel('Frequency');
legend('120 sec ', 'location','northeast');

subplot (2,2,3);
hist(circulation_value_to_plot_hist_180)
xlabel('Circulation (m^2/s)');
ylabel('Frequency');
legend('180 sec ', 'location','northeast');

subplot (2,2,4);
hist(circulation_value_to_plot_hist_240)
xlabel('Circulation (m^2/s)');
ylabel('Frequency');
legend('240 sec ', 'location','northeast');

saveas(gcf,'GA_arr_histogram_60_120_180_240','epsc');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% CREATE 3D CDF PLOT FOR CIRCULACTION AND TIME
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% DEFINE INITIAL CONDITIONS

% Define initial conditions

time_interval_s = 60:1:240;
% circulation_strenght_interval_m2_per_s = 0:1:650;
circulation_interval_A = 0:0.0125:99.9;
circulation_interval_B = 100:25:399.99;
circulation_interval_C = 400:0.125:650;
circulation_strenght_interval_m2_per_s = [circulation_interval_A circulation_interval_B circulation_interval_C];

[time_matrix,circulation_matrix] = ...
    meshgrid(time_interval_s,circulation_strenght_interval_m2_per_s);

pdf_by_time_cir = zeros(size(circulation_strenght_interval_m2_per_s,2),...
    size(time_interval_s,2));
cdf_by_time_cir = zeros(size(circulation_strenght_interval_m2_per_s,2),...
    size(time_interval_s,2));

for time_index = 1:size(time_interval_s,2)
    %%% Construct data to find pdf by time_index
    data = zeros(1,number_of_sets_of_data);
    for condition_index = 1:number_of_sets_of_data
        data(condition_index) = ...
            wake_behavior_at_standard_times...
                (condition_index).circulation_strength_right_m2_per_s(time_index);
    end

...
% CREATE CDF PLOT FOR CIRCULATION FOR TIMES: TIME_VALUE= 0, 60, 120, 180, 240

% DEFINE INITIAL CONDITIONS

time_interval_s = 0:1:240;
circulation_strenght_interval_m2_per_s = 0:1:650;

% CREATE CDF FOR CIRCULATION AT TIMES 0, 60, 120, 180 AND 240 SECONDS.
time_value = [0 60 120 180 240];
% [time_matrix,circulation_matrix]=meshgrid...
% (time_interval,circulation_interval);

pdf_by_time_cir = zeros(size(circulation_strenght_interval_m2_per_s,2)...
    ,size(time_value,2));
cdf_by_time_cir = zeros(size(circulation_strenght_interval_m2_per_s,2)...
    ,size(time_value,2));

for index_to_retrieve = 1:size(time_value,2)

    %time_value(index_to_retrieve) returns the time to find pdf.
    %However, it starts from 0. Hence, we must add 1 to find the
    %index in the data
    time_index = time_value(index_to_retrieve) + 1;
    %%%%%Construct data to find pdf by time_index
    data=zeros(1,number_of_sets_of_data);
    for condition_index = 1:number_of_sets_of_data
        data(condition_index)= ...
        wake_behavior_at_standard_times...
        condition_index).circulation_strength_right_m2_per_s...
        (time_index);
    end

    [pdf,bins]= hist(data,circulation_strenght_interval_m2_per_s);
    pdf_by_time_cir(:,index_to_retrieve) = pdf/number_of_sets_of_data;
    cdf_by_time_cir(:,index_to_retrieve) =...
        cumsum(pdf_by_time_cir(:,index_to_retrieve));
end

figure
% surf(time_matrix,circulation_matrix,pdf_by_time_cir);
% colormap([1 1 0;0 1 1]);
for index_to_retrieve = 1:size(time_value,2)
    plot(cdf_by_time_cir(:,index_to_retrieve),'DisplayName',...
         num2str(time_value(index_to_retrieve)));
    hold on
end
legend('show');
%legend('show ','location','northeast');
ylabel('CDF','Fontsize',18);
xlabel('Circulation (m^2/s)','Fontsize',18);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% PDF
% Plot Pdf combined with 90%, 95% 99%
% PLOT ALL THREE confidence levels of CIRCULATIONS Strengh t IN ONE PLOT.
all_circulation_strength_data = zeros(number_of_sets_of_data, ... 
                                 size(wake_behavior_at_standard_times(1).time_s,2));
for time_series = 1:number_of_sets_of_data
    all_circulation_strength_data(time_series,:) = ...
        wake_behavior_at_standard_times(time_series).circulation_strength_right_m2_per_s;
end
pdf_circulation_strength_99 = prctile(all_circulation_strength_data,99);
pdf_circulation_strength_95 = prctile(all_circulation_strength_data,95);
pdf_circulation_strength_90 = prctile(all_circulation_strength_data,90);
figure
plot(standard_time_value,pdf_circulation_strength_99,'.k',...
     standard_time_value, pdf_circulation_strength_95,'*b',...
     standard_time_value,pdf_circulation_strength_90,'+r');
ylabel('Wake Vortex Circulation (m^2/s)','Fontsize',18);
xlabel('Time (s)','Fontsize',18);
set(gca,'XTick',0:60:240);
grid on;
%title('Circulation Strength behind A380 with 99 95 90 Confidence',...
% 'Fontsize',12);
legend('A380 99 percentile ','A380 95 percentile','A380 90 percentile',...
       'location','northeast');
saveas(gcf,'A380_arr_percentile_99_95_90','epsc');

% Plot Pdf with 99% confidence
standard_time_value =1:1:246;
figure
plot(standard_time_value,pdf_circulation_strength_95,'+b');
ylabel('Wake Vortex Circulation (m^2/s)','Fontsize',18);
xlabel('Time (s)','Fontsize',18);
set(gca,'XTick',0:60:240);
% xlim([0,180])
grid on;
% title('Circulation Strength behind generator 99 Confidence', ...
% 'FontSize',12);
legend('E170 95 percentile ', 'location','northeast');
saveas(gcf,'E170_arr_percentile_95','epsc');


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% THIS CODE GOES INTO PDF CREATED ABOVE AND CALCULATES CIRCULATION FOR A
% GIVEN TIME SEPARATION.

% This static time based separation is calculated for arrivals based on
% aproach speed by ASDX and current regulation in distance.
% For departure is based on time separation according to current
% regulations.
static_time_based_wake_separation_s_per_group= [64 121 154 173 165 223];

maximum_circulation_capacity_99confidence_m2_per_s_per_group= ... 
    spline(7,pdf_circulation_strength_99,... 
    static_time_based_wake_separation_s_per_group);

maximum_circulation_capacity_95confidence_m2_per_s_per_group= ... 
    spline(standard_time_value,pdf_circulation_strength_95,... 
    static_time_based_wake_separation_s_per_group);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%PLOT CIRCULATION STRENGHT vs TIME and 95 CONFIDENCE CURVE; on same plot
ylabel('Circulation (m^2/s)','FontSize',18);
xlabel('Time (s)','FontSize',18);
% text(240,600,['Group A - Arrival',num2str(wake_behavior_aircraft_name)]);
hold on;
figure(1); %Circulation strength from time_initial to time_final
% plot time 1 and circulation lenght
for time_series = 1 : number_of_sets_of_data
    % If row has value of zero in time struc due to APA calculation then
    %ignore this row. This should be a time series for each row but not
    %zero
    if (wake_behavior(time_series).time_s == 0)
        continue;
    end
    hold on
    plot(wake_behavior(time_series).time_s(time_initial_indice: ..., 
    time_final_indice(time_series)), wake_behavior... 
    (time_series).circulation_strength_right_m2_per_s... 
    (time_initial_indice(time_series):time_final_indice(time_series)));
end

% CALCULATE AND PLOT 95 % CONFIDENCE CURVE
all_circulation_strength_data = zeros(number_of_sets_of_data, ...
size(wake_behavior_at_standard_times(1).time_s,2));

for time_series = 1:number_of_sets_of_data

    all_circulation_strength_data(time_series,:) = ...
    wake_behavior_at_standard_times...
    (time_series).circulation_strength_right_m2_per_s;
end

pdf_circulation_strength_95 = prctile(all_circulation_strength_data,95);

%figure
hold on
plot(standard_time_value,pdf_circulation_strength_95,'*b');
% ylabel('Circulation (m^2/s)','Fontsize',18);
% xlabel('Time (s)','Fontsize',18);
set(gca,'XTick',0:60:240);
grid on;
% title('Circulation Strength behind generator 95 Confidence',...
% 'Fontsize',12);
legend('95 percentile ','location','northeast');
%saveas(gcf,'All_circulation_and_95_percentile','epsc');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% PLOT CIRCULATION STRENGTH FROM TIME_INITIAL_SECONDS to TIME_FINAL_SECONDS
% vs. ENVIRONMETAL & AIRCRAFT DEPENDENT FACTORS.
% In order to plot environmetal factors vs Circulation strength
% time_initial to time_final for each data set.The mean value of
% circulation from time_initial_seconds to time_final_seconds needs to
% be calculated.
% Altitude    vs Circulation for each data set.
% EDR         vs Circulation for each data set.
% Wind        vs Circulation for each data set.
% Temperature vs Circulation for each data set.
% VInitial    vs Circulation for each data set.

%INDENTIFY AND PLOT AVERAGE OF CIRCULATION (for all times) FOR EACH TIME
%SERIES.
% This line initiates the array to find average of each value.
mean_values_circulation = zeros(1, number_of_sets_of_data);

% for time from 1 second to 120 seconds
for time_series = 1 : number_of_sets_of_data

    % If row has value of zero in time struc due to APA calculation
    %then ignore this row.
    if (wake_behavior(time_series).time_s == 0)
        continue;
    end

end
% Calculate the mean values of circulation strength for each series.
mean_values_circulation(time_series) = mean(wake_behavior...
(time_series).circulation_strength_right_m2_per_s...
(time_initial_indice(time_series):time_final_indice(time_series)))
end

figure;
plot([wake_behavior.altitude_m], mean_values_circulation, '*');
xlabel('Altitude (m)');
ylabel('Mean circulation (m^2/s)');

figure;
plot([wake_behavior.edr_value_m2_per_s3], mean_values_circulation, '+');
xlabel('Environmental Turbulence (m^2/s^3)');
ylabel('Mean Circulation (m^2/s)');

figure;
plot([wake_behavior.wind_value_m_per_s], mean_values_circulation, '.');
xlabel('Wind velocity (m/s)');
ylabel('Mean Circulation (m^2/s)');
set(gca, 'XTickLabel', unique([wake_behavior.wind_value_m_per_s]));

figure;
plot([wake_behavior.temperature_value_kelvin], mean_values_circulation, '*');
xlabel('Temperature (K)');
ylabel('Mean Circulation (m^2/s)');

figure;
plot([wake_behavior.VInitial_m_per_s], mean_values_circulation, '+');
xlabel('Wake Initial Descent Velocity (m/s)');
ylabel('Mean Circulation (m^2/s)');

figure
plot([wake_behavior.aircraft_mass_kg], mean_values_circulation, '*');
xlabel('Aircraft Mass (kg)');
ylabel('Mean Circulation (m^2/s)');

figure
plot([wake_behavior.groundspeed_m_per_s], mean_values_circulation, '-');
xlabel('Groundspeed (m/s)');
ylabel('Mean Circulation (m^2/s)');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% ANALYZE WAKE CIRCULATION AT TIME_FINAL SECONDS. Example: 120 or
% 240 SECONDS.
% CREATE VARIABLES THAT CONTAIN WAKE_BEHAVIOR DATA AT TIME_FINAL SECONDS;
% ONLY.
time_final_indice = zeros(1,number_of_sets_of_data);
current_value_time = zeros(1,number_of_sets_of_data);
current_value_circulation = zeros(1,number_of_sets_of_data); %
current_value_lateral_pos_right = zeros(1,number_of_sets_of_data);
current_value_vertical_pos_right = zeros(1,number_of_sets_of_data);

% plot time 1 and circulation length
for time_series = 1 : number_of_sets_of_data
    % If row has value of zero in time struc due to APA calculation then
    % ignore this row.
    if (wake_behavior(time_series).time_s == 0)
        continue;
    end

    checked_data = wake_behavior(time_series).time_s - time_final_seconds;
    list_of_indices_of_time_bigger_than_time_final = find(checked_data>0);
    time_final_indice(time_series) = ...
        list_of_indices_of_time_bigger_than_time_final(1);

    current_value_circulation(time_series) = wake_behavior...
        {time_series}.circulation_strength_right_m2_per_s ...
        {list_of_indices_of_time_bigger_than_time_final(1)};

    current_value_time(time_series) = wake_behavior(time_series).time_s...
        {list_of_indices_of_time_bigger_than_time_final(1)};

    current_value_lateral_pos_right(time_series) = wake_behavior...
        {time_series}.lateral_position_right_m ...
        {list_of_indices_of_time_bigger_than_time_final(1)};

    current_value_vertical_pos_right(time_series) = wake_behavior...
        {time_series}.vertical_position_right_m ...
        {list_of_indices_of_time_bigger_than_time_final(1)};

end   % number of sets of data

% DEFINE PLOTS
%Create figure for wake circulation strenght, lateral displacement
%and vertical displacement at time_final_seconds.
close all;
figure(4);
ylabel('Circulation (m^2/s)');
xlabel('Time (s)');
hold on;

figure(5);
ylabel('Lateral displacement (m)');
xlabel('Time (s)');
hold on;

figure(6);
ylabel('Vertical displacement (m)');
xlabel('Time (s)');
hold on;
% PLOT CIRCULATION       AT TIME_FINAL_SECONDS
% PLOT LATERAL POSITION  AT TIME_FINAL_SECONDS
% PLOT VERTICAL POSITION AT TIME_FINAL_SECONDS

for time_series = 1 : number_of_sets_of_data
    if (wake_behavior(time_series).time_s == 0)
        continue;
    end

figure(4); %Circulation strength
plot(wake_behavior(time_series).time_s(time_final_indice(time_series)),
    wake_behavior(time_series).circulation_strength_right_m2_per_s(time_final_indice(time_series)),'*');

figure(5); % Lateral position
plot(wake_behavior(time_series).time_s(time_final_indice(time_series)),
    wake_behavior(time_series).lateral_position_right_m(time_final_indice(time_series)),'.');

figure(6); % Vertical position
plot(wake_behavior(time_series).time_s(time_final_indice(time_series)),
    wake_behavior(time_series).vertical_position_right_m(time_final_indice(time_series)),'+');
end

% MORE PLOTS
% PLOT CIRCULATION STRENGTH AT TIME_FINAL_SECONDS (Example: 120 sec) VS.
% ENVIRONMENTAL & AIRCRAFT DEPENDENT FACTORS.
% The idea is to get an idea of how environmental factors influence
% circulation strength at final time.

figure;
title(['Circulation vs Altitud at time: ' int2str(time_final_seconds)...
    ' (s)']);
ylabel('Circulation (m^2/s)');
xlabel('Altitude (m)');
hold on
% plot all values of Altitude vs. Circulation
plot([wake_behavior(:).altitude_m],current_value_circulation,'+');

figure;
title(['Circulation vs Env. Turbulence at time ' int2str...
    (time_final_seconds) ' (s)']);
ylabel('Circulation (m^2/s)');
xlabel('EDR (m)');
hold on
% plot all values of EDR vs. Circulation
plot([wake_behavior(:).edr_value_m2_per_s3],current_value_circulation,'*');
figure;
title(['Circulation vs Wind at time ' int2str(time_final_seconds) ' (s)'])
ylabel('Circulation (m^2/s)');
xlabel('Wind (m/s)');
hold on
% plot all values of Wind vs. Circulation
plot([wake_behavior(:).wind_value_m_per_s],current_value_circulation,',');

figure;
title(['Circulation vs Temperature at time ' int2str(time_final_seconds) ' (s)'])
ylabel('Circulation (m^2/s)');
xlabel('Temperature (k)');
hold on
% plot all values of Temperature vs. Circulation
plot([wake_behavior(:).temperature_value_kelvin],current_value_circulation,+);

figure;
title(['Circulation vs VInitial at time ' int2str(time_final_seconds) ' (s)'])
ylabel('Circulation (m^2/s)');
xlabel('Wake Initial descent V (m)');
hold on
% plot all values of Vinitial vs. Circulation
plot([wake_behavior(:).VInitial_m_per_s],current_value_circulation,*);

figure;
title(['Circulation vs Aircraft Mass at time ' int2str(time_final_seconds) ' (s)'])
ylabel('Circulation (m^2/s)');
xlabel('Aircraft Mass (Kg)');
hold on
% plot all values of Vinitial vs. Circulation
plot([wake_behavior(:).aircraft_mass_kg],current_value_circulation,*);

% PLOT HISTOGRAM OF CIRCULATION AT TIME_FINAL_SECONDS
figure;
title(['Circulation Histogram at time ' int2str(time_final_seconds) ' (s)'])
ylabel('Frequency');
xlabel('Circulation (m^2/s)');
hold on
hist(current_value_circulation); % check normality, is it bell shape

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% CREATE MODELS AT TIME FINAL IN THIS CASE
% 120 SECODDD. Since all current_value_circulations
% are for time final and time final in this
% case is 120 seconds.
% CREATING A MODEL WILL HELP UNDERSTAND HOW WAKE CIRCULATION IS
% INDIVIDUALLY INFLUENCED BY EACH PARAMETER.
% If categorical variable is being considered one at a time.
%Then look below:

%Explains how is Circulation Strength affected by Altitude
aoctool([wake_behavior(:,).VInitial_m_per_s],current_value_circulation,...
    [wake_behavior(:,).altitude_m])

%Explains how is Circulation Strength affected by Environmental Turbulence
aoctool([wake_behavior(:,).VInitial_m_per_s],current_value_circulation,...
    [wake_behavior(:,).edr_value_m2_per_s3])

%Explains how is Circulation Strength affected by Wind Value
aoctool([wake_behavior(:,).VInitial_m_per_s],current_value_circulation,...
    [wake_behavior(:,).wind_value_m_per_s])

%Explains how is Circulation Strength affected by Temperature
aoctool([wake_behavior(:,).VInitial_m_per_s],current_value_circulation,...
    [wake_behavior(:,).temperature_value_kelvin])

%Explains how is Circulation Strength affected by Wake Initial Descent
% Velocity
aoctool([wake_behavior(:,).VInitial_m_per_s],current_value_circulation,...
    [wake_behavior(:,).aircraft_mass_kg])

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% CREATE MODEL TO UNDERSTAND HOW CIRCULATION IS INFLUENCED BY ALL PARAMETER
% AND HOW PARAMETERS AFFECT EACH OTHER. REGRESSION WITH CATEGORICAL
% VARIABLES

%CREATE A TABLE WITH DEPENDENT AND INDEPENDENT VARIABLES.
%This table is needed in order to use main effects model and/or
% the full model.
wake_behavior_data = table([wake_behavior(:,).altitude_m]',...
    [wake_behavior(:,).edr_value_m2_per_s3]',...
    [wake_behavior(:,).wind_value_m_per_s]', ...
    [wake_behavior(:,).temperature_value_kelvin]',...
    [wake_behavior(:,).VInitial_m_per_s]',current_value_circulation', ...
    'VariableNames',{'altitude','edr','wind','temperature','Vini',...
    'circulation'});

%CREATE A MAIN EFFECTS MODEL TO UNDERSTAND HOW CONDITIONS AFFECT
% CIRCULATION
fit_main_effect_model = fitlm(wake_behavior_data,...
    'circulation~altitude+edr+wind+temperature+Vini');

% CREATE A FULL MODEL TO UNDERSTAND HOW CONDITIONS AFFECT CIRCULATION AND
% HOW THEY AFFECT EACH OTHER.
fit_full_model = fitlm(wake_behavior_data,...
    'circulation~altitude*edr*wind*temperature*Vini');
% STATISTICAL ANALYSIS

% Calculate the average value and standard dev for all values at
% time = 0 to time 120 seconds

% gather all values of the wind x-axis
key_wind = [wake_behavior.wind_value_m_per_s];

% gather all values of the turbulence x-axis
key_edr = [wake_behavior.edr_value];

% gather all values of the Vo x-axis
key_VInitial = [wake_behavior.VInitial];

% gather all the values in y-axis which are circulation
val = mean_values_circulation;

% Find the unique value of the array key_wind, or key_edr, key_VInitial
ukey_wind = unique(key_wind);
ukey_edr = unique(key_edr);
ukey_VInitial = unique(key_VInitial);
mean_value_wind = zeros(1, numel(ukey_wind));
mean_value_edr = zeros(1, numel(ukey_edr));
mean_value_VInitial = zeros(1, numel(ukey_VInitial));

for time_series_index = 1:numel(ukey_wind) %
    % Calculate the mean value of the unique key that we want
    mean_value_wind(time_series_index) = mean(val(key_wind == ukey_wind ...
        {time_series_index}));
end

for time_series_index = 1:numel(ukey_edr) %
    % Calculate the mean value of the unique key that we want
    mean_value_edr(time_series_index) = mean(val(key_edr == ukey_edr ...
        {time_series_index}));
end

for time_series_index = 1:numel(ukey_VInitial) %
    % Calculate the mean value of the unique key that we want
    mean_value_VInitial(time_series_index) = mean(val(key_VInitial == ...
        ukey_VInitial(time_series_index)));
end

% CALCULATE STANDARD DEVIATIONS

% Calculate the Standard Deviation for how values of circulation change bc
% of wind edr and VInitial. If standard deviation is below 10% it does not
% affect too much.
std_wind = zeros(1, size(ukey_wind, 2));
for time_series_index = 1:numel(ukey_wind) %
% Calculate the mean value of the unique key that we want
std_wind(time_series_index)=std2(val(key_wind==ukey_wind... 
(time_series_index))); 
end

std_edr = zeros(1,size(ukey_edr,2));
for time_series_index=1:numel(ukey_edr) %
  % Calculate the mean value of the unique key that we want
  std_edr(time_series_index)=std2(val(key_edr==ukey_edr... 
  (time_series_index))); 
end

std_VInitial = zeros(1,size(ukey_VInitial,2));
for time_series_index=1:numel(ukey_VInitial) %
  % Calculate the mean value of the unique key that we want
  std_VInitial(time_series_index)=std2(val(key_VInitial==... 
  ukey_VInitial(time_series_index))); 
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%SENSITIVITY ANALYSIS
% Calculate the range of the value for each condition like wind, turbulence
% and VInitial.

min_wind = zeros(1,size(ukey_wind,2));
max_wind = zeros(1,size(ukey_wind,2));
for time_series_index=1:numel(ukey_wind) %
  min_wind(time_series_index)=mean_value_wind(time_series_index) -... 
  std_wind(time_series_index); %lower bound
  max_wind(time_series_index)=mean_value_wind(time_series_index) +... 
  std_wind(time_series_index); % upper bound
end

%%If we have a set X, all data will range from [mean(x) - std(x) ; mean(x) + std(x)]
plot(ukey_wind,min_wind,ukey_wind,max_wind);

min_edr = zeros(1,size(ukey_edr,2));
max_edr = zeros(1,size(ukey_edr,2));
for time_series_index=1:numel(ukey_edr) %
  min_edr(time_series_index)=mean_value_edr(time_series_index) -... 
  std_edr(time_series_index); %lower bound
  max_edr(time_series_index)=mean_value_edr(time_series_index) +... 
  std_edr(time_series_index); % upper bound
end
plot(ukey_edr,min_edr,ukey_edr,max_edr);

min_VInitial = zeros(1,size(ukey_VInitial,2));
max_VInitial = zeros(1,size(ukey_VInitial,2));
for time_series_index=1:numel(ukey_VInitial) %
  min_VInitial(time_series_index)=mean_value_VInitial(time_series_index) -... 
  std_VInitial(time_series_index); %lower bound
  max_VInitial(time_series_index)=mean_value_VInitial(time_series_index) +... 
  std_VInitial(time_series_index); % upper bound
end
plot(ukey_VInitial,min_VInitial,ukey_VInitial,max_VInitial...
(time_series_index) + std_VInitial(time_series_index);

end

plot(ukey_VInitial,min_VInitial,ukey_VInitial,max_VInitial);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% CREATE CUMMULATIVE DENSITY FUNCTIONS FOR CIRCULATION STRENGTHS BASED ON
% WAKE BEHAVIOR OUTPUT FROM THE SIMULATION WITH NASA MODEL.

% Calculate the range of the value for each condition like wind, turbulence
% and VInitial.

figure
cdfplot(histresults_60_FL13)
hold on
cdfplot(histresults_80_FL13);
cdfplot(histresults_100_FL13);
cdfplot(histresults_120_FL13);
grid on
%    grid minor
%    formats and bolds titles on plot
%    set(gca,'fontsize',16,'fontweight','bold');
%    xlim([ , ])
ylim([0,1.05]);
% start at, spacing 200, x axis limit
set(gca,'XTick',[0:150:3000]); %,'XTickLabel',{'A388','IGE'});
ylabel('Cumulative Distribution Function','Fontsize',18);
xlabel('Circulation (m^2/s)','Fontsize',18);
title('Circulation CDF t=60,80,100,120 seconds','Fontsize',18);
%    text(1100,0.35,'A388 IGE FL13', 'Fontsize', 12, 'Color','black')
legend('60 sec ','80 sec','100 sec','120 sec', 'location','southeast');
%    savefig('Circulation CDF t_60_80_100_120')
saveas(gcf,'Circulation CDF t_60_80_100_120','epsc');

close all;
figure(1);
ylabel('Wake Vortex Circulation (m^2/s)','Fontsize',18);
xlabel('Time (s)','Fontsize',18);
%    text(240,600,['Group A - Arrival',num2str(wake_behavior_aircraft_name)]);
hold on;

%    figure(2);
%    ylabel('Wake Lateral displacement (m)','Fontsize',18);
%    xlabel('Time (s)','Fontsize',18);
%    %text(250,250,['Aircraft Name = ',num2str(wake_behavior_aircraft_name)]);
%    %text(200,170,['Group A - Arrival'])
%    hold on;
% figure(3);
% ylabel('Wake Vertical Displacement (m)', 'FontSize', 18);
% xlabel('Time (s)', 'FontSize', 18);
% xlim([0, 220]);
% % % text(200, 220, ['Group A - Arrival', num2str(wake_behavior_aircraft_name)]);
% hold on;

% plot time 1 and circulation length
for time_series = 1 : number_of_sets_of_data
  % If row has value of zero in time struc due to APA calculation then
  % ignore this row. This should be a time series for each row but not
  % zero
  if (wake_behavior(time_series).time_s == 0)
    continue;
  end
  figure(1); % Circulation strength from time_initial to time_final
  cdfplot(wake_behavior(time_series).circulation_strength_right_m2_per_s...
    {time_initial_index(time_series):...
    time_final_index(time_series)});

  figure(2); % Lateral position from time_initial to time_final
  plot(wake_behavior(time_series).time_s(time_initial_index:...
    time_final_index(time_series)), ...
    wake_behavior(time_series).lateral_position_right_m...
    {time_initial_index(time_series):...
    time_final_index(time_series)});

  figure(3); % Vertical position from time_initial to time_final
  plot(wake_behavior(time_series).time_s...
    {time_initial_index:time_final_index(time_series)}),...
    wake_behavior(time_series).vertical_position_right_m...
    {time_initial_index(time_series):...
    time_final_index(time_series)});
end
1.7 Function to Create Wisker Plot for Wake Behavior

function y = w_04_constructdata_wiskerplot_function(circulation_strenght, wake_behavior_data)
    y=zeros(1,size(wake_behavior_data,2));

    for row_index_for_constructuring = 1:size(wake_behavior_data,2)
        time_series = wake_behavior_data(row_index_for_constructuring).time_s;
        circulation_series =
            wake_behavior_data(row_index_for_constructuring).circulation_strength_right_m2_per_s;

        first_zeros_index = find(~circulation_series, 1);
        if size(first_zeros_index,2) > 0
            time_series_to_interpolate = time_series(1:first_zeros_index);
            circulation_series_to_interpolate =
                circulation_series(1:first_zeros_index);
        else
            time_series_to_interpolate = time_series;
            circulation_series_to_interpolate = circulation_series;
        end
        if size(time_series_to_interpolate ,2) < 2
            continue
        end
        unique_cir_series= unique(circulation_series_to_interpolate);
        if size(circulation_series_to_interpolate,2) ~= size(unique_cir_series,2)
            continue
        end

        y(row_index_for_constructuring) = pchip(circulation_series_to_interpolate,...
            time_series_to_interpolate,circulation_strenght);
    end
end
1.8 Wake Behavior Dynamic Conditions Interpolation

The objective of this code is to use a previously created function called: w_03_airline_schedule_function; and use the logic explained in each step below in order to interpolate between each dynamic environmental condition and use wake behavior at standard time (data from simulation and NASA MODEL APA) in order to derive dynamic separations.
Group_D_Arrival_wake_behavior_at_standard_times= wake_behavior_at_standard_times;
clear wake_behavior_at_standard_times

load('Group_E_Arrival_wake_behavior_at_standard_times.mat')
Group_E_Arrival_wake_behavior_at_standard_times= wake_behavior_at_standard_times;
clear wake_behavior_at_standard_times

load('Group_F_Arrival_wake_behavior_at_standard_times.mat')
Group_F_Arrival_wake_behavior_at_standard_times= wake_behavior_at_standard_times;
clear wake_behavior_at_standard_times

% LOAD WAKE BEHAVIOR AT STANDARD TIME DEPARTURES
% Either the analysis is being done for arrival or departure.
% If arrival is being done then there no need to load varibles below.
load('Group_A_Departure_wake_behavior_at_standard_times.mat');
Group_A_Departure_wake_behavior_at_standard_times= wake_behavior_at_standard_times;
clear wake_behavior_at_standard_times

load('Group_B_Departure_wake_behavior_at_standard_times.mat');
Group_B_Departure_wake_behavior_at_standard_times= wake_behavior_at_standard_times;
clear wake_behavior_at_standard_times

load('Group_C_Departure_wake_behavior_at_standard_times.mat');
Group_C_Departure_wake_behavior_at_standard_times= wake_behavior_at_standard_times;
clear wake_behavior_at_standard_times

load('Group_D_Departure_wake_behavior_at_standard_times.mat');
Group_D_Departure_wake_behavior_at_standard_times= wake_behavior_at_standard_times;
clear wake_behavior_at_standard_times

load('Group_E_Departure_wake_behavior_at_standard_times.mat');
Group_E_Departure_wake_behavior_at_standard_times= wake_behavior_at_standard_times;
clear wake_behavior_at_standard_times

load('Group_F_Departure_wake_behavior_at_standard_times.mat');
Group_F_Departure_wake_behavior_at_standard_times= wake_behavior_at_standard_times;
clear wake_behavior_at_standard_times

% STEP 2
% IMPORTOR READ MAXIMUM CIRCULATION CAPACITY
% Import Maximum Circulation Capacity (MCC) matrix or values: for all
% aircraft groups (critical aircrafts). MMC is applied based on follower.
Group_A_circulation_strength_right_m2_per_s=488;
Group_B_circulation_strength_right_m2_per_s=323;
Group_C_circulation_strength_right_m2_per_s=252;
Group_D_circulation_strength_right_m2_per_s=220;
Group_E_circulation_strength_right_m2_per_s=233;
Group_F_circulation_strength_right_m2_per_s=140;

% STEP 3
% IDENTIFY MIN AND MAX AIRPORT CONDITIONS
% Limits on Altitude will be different for each aircraft group on the % In_Ground effect analysis.
% FOR THE REASON THAT CIRCULATION STRENGTH IS WHAT IS DETERMINING THE % LONGITUDINAL SEPARATION THEN ASSUME ALL AIRCRAFT ARE FLYING AT SAME % ALTITUDE. (still under discussion)....
min_altitude_m = min([Group_F_Arrival_wake_behavior_at_standard_times.altitude_m]);
max_altitude_m = max([Group_F_Arrival_wake_behavior_at_standard_times.altitude_m]);

% ALL CONDITIONS BELOW WILL BE THE SAME FOR ALL AIRCRAFT GROUP
min_wind_value_m_per_s =
min([Group_A_Arrival_wake_behavior_at_standard_times.wind_value_m_per_s]);
max_wind_value_m_per_s =
max([Group_A_Arrival_wake_behavior_at_standard_times.wind_value_m_per_s]);

min_temperature_value_kelvin =
min([Group_A_Arrival_wake_behavior_at_standard_times.temperature_value_kelvin]);
max_temperature_value_kelvin =
max([Group_A_Arrival_wake_behavior_at_standard_times.temperature_value_kelvin]);

min_edr_value_m2_per_s3 =
min([Group_A_Arrival_wake_behavior_at_standard_times.edr_value_m2_per_s3]);
max_edr_value_m2_per_s3 =
max([Group_A_Arrival_wake_behavior_at_standard_times.edr_value_m2_per_s3]);

% STEP 3
% IDENTIFY MIN AND MAX AIRCRAFT MASS FOR EACH AIRCRAFT GROUP
Group_A_min_aircraft_mass_kg =
min([Group_A_Arrival_wake_behavior_at_standard_times.aircraft_mass_kg]);
Group_A_max_aircraft_mass_kg =
max([Group_A_Arrival_wake_behavior_at_standard_times.aircraft_mass_kg]);

Group_B_min_aircraft_mass_kg =
\[
\text{min([Group_B\_Arrival\_wake\_behavior\_at\_standard\_times.\aircraft\_mass\_kg]);}
\]
\[
\text{Group\_B\_max\_aircraft\_mass\_kg = max([Group_B\_Arrival\_wake\_behavior\_at\_standard\_times.\aircraft\_mass\_kg]);}
\]
\[
\text{Group\_C\_min\_aircraft\_mass\_kg = min([Group_C\_Arrival\_wake\_behavior\_at\_standard\_times.\aircraft\_mass\_kg]);}
\]
\[
\text{Group\_C\_max\_aircraft\_mass\_kg = max([Group_C\_Arrival\_wake\_behavior\_at\_standard\_times.\aircraft\_mass\_kg]);}
\]
\[
\text{Group\_D\_min\_aircraft\_mass\_kg = min([Group_D\_Arrival\_wake\_behavior\_at\_standard\_times.\aircraft\_mass\_kg]);}
\]
\[
\text{Group\_D\_max\_aircraft\_mass\_kg = max([Group_D\_Arrival\_wake\_behavior\_at\_standard\_times.\aircraft\_mass\_kg]);}
\]
\[
\text{Group\_E\_min\_aircraft\_mass\_kg = min([Group_E\_Arrival\_wake\_behavior\_at\_standard\_times.\aircraft\_mass\_kg]);}
\]
\[
\text{Group\_E\_max\_aircraft\_mass\_kg = max([Group_E\_Arrival\_wake\_behavior\_at\_standard\_times.\aircraft\_mass\_kg]);}
\]
\[
\text{Group\_F\_min\_aircraft\_mass\_kg = min([Group_F\_Arrival\_wake\_behavior\_at\_standard\_times.\aircraft\_mass\_kg]);}
\]
\[
\text{Group\_F\_max\_aircraft\_mass\_kg = max([Group_F\_Arrival\_wake\_behavior\_at\_standard\_times.\aircraft\_mass\_kg]);}
\]
\[
\% \text{ IMPORT AIRLINE RUNWAY SCHEDULE IN THE FORM OF LEADER AND FOLLOWER}
\]
\[
\text{array\_aircraft = w\_03\_airline\_schedule\_function();}
\]
\[
\% \text{ START CLOCK FOR ENVIRONMENTAL CONDITIONS}
\]
\[
\% \text{ Environmental conditions}
\]
\[
\text{altitude\_array = []};
\]
\[
\text{edr\_value\_array = []};
\]
\[
\text{temperature\_value\_array = []};
\]
\[
\text{wind\_value\_array = []};
\]
\[
\% \text{ This clock changes environmental conditions every 15 mins}
\]
\[
\text{current\_clock = 0;}
\]
\[
\text{next\_pivot\_time = 0;}
\]
\[
\text{difference\_between\_env\_change = 900 ;% 15\text{ minutes} = 900\text{ seconds}}
\]
\[
\text{array\_final\_time = zeros(size(array\_aircraft,1),1);}\)
\[
\text{counter = 0;}
\]
\[
\text{for aircraft\_index = 1:size(array\_aircraft,1)-1}
\]
leader_aircraft = array_aircraft(aicraft_index);
follower_aircraft = array_aircraft(aicraft_index+1);

if current_clock >= next_pivot_time

    % READ MAX AND MIN FOR CURRENT AIRPORT CONDITIONS AND CREATE A
    % RANDOM FUNCTION GENERATOR THAT SIMULATES LIVE ENVIRONMENTAL
    % CONDITIONS AT AIRPORT.
    altitude_m=min_altitude_m + (max_altitude_m-min_altitude_m)*rand(1,1);

    edr_value_m2_per_s3= min_edr_value_m2_per_s3 + (max_edr_value_m2_per_s3-
    min_edr_value_m2_per_s3)*rand(1,1);

    temperature_value_kelvin=min_temperature_value_kelvin +
    (max_temperature_value_kelvin-min_temperature_value_kelvin)*rand(1,1);

    wind_value_m_per_s=min_wind_value_m_per_s + (max_wind_value_m_per_s-
    min_wind_value_m_per_s)*rand(1,1);

    next_pivot_time = next_pivot_time + difference_between_env_change;

    counter = counter + 1;
end
altitude_array  = [altitude_array altitude_m];
edr_value_array = [edr_value_array edr_value_m2_per_s3];
temperature_value_array = [temperature_value_array temperature_value_kelvin];
wind_value_array = [wind_value_array wind_value_m_per_s];

if follower_aircraft == 'A'
    circulation_strength_right_m2_per_s=
    Group_A_circulation_strength_right_m2_per_s;
elseif follower_aircraft == 'B'
    circulation_strength_right_m2_per_s=
    Group_B_circulation_strength_right_m2_per_s;
elseif follower_aircraft == 'C'
    circulation_strength_right_m2_per_s=
    Group_C_circulation_strength_right_m2_per_s;
end
else if follower_aircraft == 'D'
    circulation_strength_right_m2_per_s = Group_D_circulation_strength_right_m2_per_s;
elseif follower_aircraft == 'E'
    circulation_strength_right_m2_per_s = Group_E_circulation_strength_right_m2_per_s;
else
    circulation_strength_right_m2_per_s = Group_F_circulation_strength_right_m2_per_s;
end

% AIRCRAFT MASS IS IMPORTANT FOR THE LEADER (GENERATOR)
% THE CIRCULATION STRENGTH IS FOR THE FOLLOWER AIRCRAFT.
if leader_aircraft == 'A'
    aircraft_mass_kg = Group_A_min_aircraft_mass_kg + (Group_A_max_aircraft_mass_kg - Group_A_min_aircraft_mass_kg) * rand(1,1);
    time_s = w_04_wake_behavior_standard_time_interpolation_function(aircraft_mass_kg, edr_value_m2_per_s3, wind_value_m_per_s, ...
        temperature_value_kelvin, circulation_strength_right_m2_per_s, Group_A_Arrival_wake_behavior_at_standard_times);
elseif leader_aircraft == 'B'
    aircraft_mass_kg = Group_B_min_aircraft_mass_kg + (Group_B_max_aircraft_mass_kg - Group_B_min_aircraft_mass_kg) * rand(1,1);
    time_s = w_04_wake_behavior_standard_time_interpolation_function(aircraft_mass_kg, edr_value_m2_per_s3, wind_value_m_per_s, ...
        temperature_value_kelvin, circulation_strength_right_m2_per_s, Group_B_Arrival_wake_behavior_at_standard_times);
elseif leader_aircraft == 'C'
    aircraft_mass_kg = Group_C_min_aircraft_mass_kg + (Group_C_max_aircraft_mass_kg - Group_C_min_aircraft_mass_kg) * rand(1,1);
    time_s = w_04_wake_behavior_standard_time_interpolation_function(aircraft_mass_kg, edr_value_m2_per_s3, wind_value_m_per_s, ...
        temperature_value_kelvin, circulation_strength_right_m2_per_s, Group_C_Arrival_wake_behavior_at_standard_times);
elseif leader_aircraft == 'D'
    aircraft_mass_kg = Group_D_min_aircraft_mass_kg + (Group_D_max_aircraft_mass_kg - Group_D_min_aircraft_mass_kg) * rand(1,1);
    time_s = w_04_wake_behavior_standard_time_interpolation_function(aircraft_mass_kg, edr_value_m2_per_s3, wind_value_m_per_s, ...
        temperature_value_kelvin, circulation_strength_right_m2_per_s, Group_D_Arrival_wake_behavior_at_standard_times);
Group_D_min_aircraft_mass_kg)*rand(1,1);

time_s=w_04_wake_behavior_standard_time_interpolation_function(aircraft_mass_kg,edr_value_m2_per_s3, wind_value_m_per_s, ...
   temperature_value_kelvin,circulation_strength_right_m2_per_s,
Group_D_Arrival_wake_behavior_at_standard_times);

    elseif leader_aircraft == 'E'
        aircraft_mass_kg=Group_E_min_aircraft_mass_kg + (Group_E_max_aircraft_mass_kg-
Group_E_min_aircraft_mass_kg)*rand(1,1);

time_s=w_04_wake_behavior_standard_time_interpolation_function(aircraft_mass_kg,edr_value_m2_per_s3, wind_value_m_per_s, ...
   temperature_value_kelvin,circulation_strength_right_m2_per_s,
Group_E_Arrival_wake_behavior_at_standard_times);

    else
        aircraft_mass_kg=Group_F_min_aircraft_mass_kg + (Group_F_max_aircraft_mass_kg-
Group_F_min_aircraft_mass_kg)*rand(1,1);

time_s=w_04_wake_behavior_standard_time_interpolation_function(aircraft_mass_kg,edr_value_m2_per_s3, wind_value_m_per_s, ...
   temperature_value_kelvin,circulation_strength_right_m2_per_s,
Group_F_Arrival_wake_behavior_at_standard_times);
    end

% RESULTS
% DYNAMIC TIME SEPARATION (seconds) BETWEEN THE LEADER AND THE FOLLOWER ACCORDING
% TO THE SCHEDULE :
array_final_time(aicraft_index)=time_s;
current_clock = current_clock + 240;
end

chosen_environmental_cond = struct('altitude',altitude_array,'edr',edr_value_array,...
   'wind',wind_value_array,'temperature',temperature_value_array);
1.9  Create an Artificial Neural Network at Standard Time

Neural network at standard time
This code prepares the dependent and independent variables for the Artificial Neural Network. It groups all independent variables into one matrix and then normalizes them and the same is done for the dependent variables.

This code: preallocation for neural network matrix of dependent and independent variables normalizes dependent and independent variables. Runs neural network (shows indices for training, testing and validation calculates MSE to identify neural network performance) normalized

% % NORMALIZED THE INPUTS BEFORE NEURAL NETWORK

% INPUT: ALTITUD, EDR, WIND, TEMPERATURE, MASS, CIRCULATION
% OUTPUT: TIME IN SECONDS (DYNAMIC TIME SEPARATION)

% PREPARE DATA FOR NEURAL NETWORK TRAINING.
% Optimization step to initiate the matrix
total_size_row = 0;
for row_index = 1:number_of_sets_of_data
    total_size_row = total_size_row + size(wake_behavior_at_standard_times(row_index).time_s,2);
end
x_value_for_regression = zeros(total_size_row,6);
y_value_for_regression = zeros(total_size_row,1);

% CONSTRUCT DATA INTO MATRIX
% PERFORM DATA ESCALAMIENTO; VALOR ESCALADO = (VALOR - VALOR MINIMO)/ (VALOR MAXIMO - VALOR MINIMO)
current_row_index = 1;

altitude_at_standard_time_normalized =
([wake_behavior_at_standard_times(:,).altitude_m] -
min([wake_behavior_at_standard_times(:,).altitude_m]))... / (max([wake_behavior_at_standard_times(:,).altitude_m])-
min([wake_behavior_at_standard_times(:,).altitude_m]));

edr_at_standard_time_normalized =
([wake_behavior_at_standard_times(:,).edr_value_m2_per_s3] -
min([wake_behavior_at_standard_times(:,).edr_value_m2_per_s3]))... / (max([wake_behavior_at_standard_times(:,).edr_value_m2_per_s3])-
min([wake_behavior_at_standard_times(:,).edr_value_m2_per_s3]));

wind_at_standard_time_normalized =
([wake_behavior_at_standard_times(:,).wind_value_m_per_s] -
min([wake_behavior_at_standard_times(:,).wind_value_m_per_s]))... / (max([wake_behavior_at_standard_times(:,).wind_value_m_per_s])-
min([wake_behavior_at_standard_times(:,).wind_value_m_per_s]));

temperature_at_standard_time_normalized =
([wake_behavior_at_standard_times(:,).temperature_value_kelvin] -
min([wake_behavior_at_standard_times(:,).temperature_value_kelvin]))... / (max([wake_behavior_at_standard_times(:,).temperature_value_kelvin])-
min([wake_behavior_at_standard_times(:,).temperature_value_kelvin]));

aircraft_mass_at_standard_time_normalized =
([wake_behavior_at_standard_times(:,).aircraft_mass_kg] -
min([wake_behavior_at_standard_times(:,).aircraft_mass_kg]))... / (max([wake_behavior_at_standard_times(:,).aircraft_mass_kg])-
min([wake_behavior_at_standard_times(:,).aircraft_mass_kg]));

% Escalamiento inside time series for each time series of time and circulation.
% looking inside each time series for min and max values of time and
% circulation and then is normalizing.
min_time_s = min((wake_behavior_at_standard_times(1).time_s(:)));
for row_index = 2:number_of_sets_of_data
    min_time_row = min((wake_behavior_at_standard_times(row_index).time_s(:)));
if (min_time_s > min_time_row)
    min_time_s = min_time_row;
end
end

max_time_s = max((wake_behavior_at_standard_times(1).time_s(:)));  
for row_index = 2:number_of_sets_of_data
    max_time_row =  max((wake_behavior_at_standard_times(row_index).time_s(:)));  
    if (max_time_s < max_time_row)
        max_time_s = max_time_row;
    end
end

min_circulation_strength_right_m2_per_s =  
min((wake_behavior_at_standard_times(1).circulation_strength_right_m2_per_s(:)));  
for row_index = 2:number_of_sets_of_data
    min_time_row =  
    min((wake_behavior_at_standard_times(row_index).circulation_strength_right_m2_per_s(:)));  
    if (min_circulation_strength_right_m2_per_s > min_time_row)
        min_circulation_strength_right_m2_per_s = min_time_row;
    end
end

max_circulation_strength_right_m2_per_s =  
max((wake_behavior_at_standard_times(1).circulation_strength_right_m2_per_s(:)));  
for row_index = 2:number_of_sets_of_data
    max_time_row =  
    max((wake_behavior_at_standard_times(row_index).circulation_strength_right_m2_per_s(:)));  
    if (max_circulation_strength_right_m2_per_s < max_time_row)
        max_circulation_strength_right_m2_per_s = max_time_row;
    end
end

% CONSTRUCT DATA INTO MATRIX FOR DEPENDENT AND INDEPENDENT VARIABLES.  
% This data is normalized.  
for row_index = 1:number_of_sets_of_data

circulation_at_standard_time_normalized =
(wake_behavior_at_standard_times(row_index).circulation_strength_right_m2_per_s(:))

- min_circulation_strength_right_m2_per_s
/ (max_circulation_strength_right_m2_per_s ...
- min_circulation_strength_right_m2_per_s);

time_at_standard_time_normalized =
(wake_behavior_at_standard_times(row_index).time_s(:)) ...
- min_time_s ...
/ (max_time_s ...
- min_time_s);

circulation_at_standard_time_normalized =
[wake_behavior_at_standard_times(row_index).circulation_strength_right_m2_per_s(:)] ...

- min([wake_behavior_at_standard_times(row_index).circulation_strength_right_m2_per_s(:) ]))...
/ (max([wake_behavior_at_standard_times(row_index).circulation_strength_right_m2_per_s(:)]) ...
- min([wake_behavior_at_standard_times(row_index).circulation_strength_right_m2_per_s(:) ]));

time_at_standard_time_normalized =
[wake_behavior_at_standard_times(row_index).time_s(:)] ...
- min([wake_behavior_at_standard_times(row_index).time_s(:)]) ...
/ (max([wake_behavior_at_standard_times(row_index).time_s(:)]) ...
- min([wake_behavior_at_standard_times(row_index).time_s(:)]));

for time_series = 1:size(wake_behavior_at_standard_times(row_index).time_s,2)

if(wake_behavior(row_index).circulation_strength_right_m2_per_s(time_series) ==0)
    continue; % for a certain value of time circulation
end
    x_value_for_regression(current_row_index,1) = ...
    altitude_at_standard_time_normalized(row_index);
\[ x_{\text{value for regression}}(\text{current_row_index},2) = \ldots \]
\[ \text{edr at standard time normalized(row_index)}; \]
\[ x_{\text{value for regression}}(\text{current_row_index},3) = \ldots \]
\[ \text{wind at standard time normalized(row_index)}; \]
\[ x_{\text{value for regression}}(\text{current_row_index},4) = \ldots \]
\[ \text{temperature at standard time normalized(row_index)}; \]
\[ x_{\text{value for regression}}(\text{current_row_index},5) = \ldots \]
\[ \text{aircraft mass at standard time normalized(row_index)}; \]
\[ x_{\text{value for regression}}(\text{current_row_index},6) = \ldots \]
\[ \text{circulation at standard time normalized(time_series)}; \]
\[ y_{\text{value for regression}}(\text{current_row_index}) = \ldots \]
\[ \text{time at standard time normalized(time_series)}; \]
% y value (independent variable) will give us the output.
\[ \text{current_row_index} = \text{current_row_index} + 1; \]
end
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% AT THIS STEP; CREATE NEURAL NETWORK USING CODE BELOW. %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% DEFINE DEPENDENT AND INDEPENDENT VARIABLES
independent_variables = x_value_for_regression';
dependent_variable = y_value_for_regression';

% Choose a Training Function
% For a list of all training functions type: help nntrain
% 'trainlm' is usually fastest.
% 'trainbr' takes longer but may be better for challenging problems.
% 'trainscg' uses less memory. Suitable in low memory situations.
training_function = 'trainbr'; % Levenberg-Marquardt backpropagation.

% Create a Fitting Network
hidden_layer_size = [3, 3];
neural_network = fitnet(hidden_layer_size,training_function);
% fitnet returns a function fitting neural network with a hidden layer size
% of hiddenSizes and training function, specified by the training function.

% Choose Input and Output Pre/Post-Processing Functions
% For a list of all processing functions type: help nnprocess
neural_network.input.processFcns = {'removeconstantrows','mapminmax'};
neural_network.output.processFcns = {'removeconstantrows','mapminmax'};

% Setup Division of Data for Training, Validation, Testing
% For a list of all data division functions type: help nndivide
neural_network.divideFcn = 'dividerand';  % Divide data randomly
neural_network.divideMode = 'sample';  % Divide up every sample
neural_network.divideParam.trainRatio = 70/100;
neural_network.divideParam.valRatio = 15/100;
neural_network.divideParam.testRatio = 15/100;

% Choose a Performance Function
% For a list of all performance functions type: help nnperformance
neural_network.performFcn = 'mse';  % Mean Squared Error

% Choose Plot Functions
% For a list of all plot functions type: help nnplot
neural_network.plotFcns = {'plotperform','plottrainstate','ploterrhist', ...
    'plotregression', 'plotfit'};

% Train the Network
[neural_network,tr] = train(neural_network,independent_variables,dependent_variable);

% Test the Network
y = neural_network(independent_variables);
e = gsubtract(dependent_variable,y);
performance = perform(neural_network,dependent_variable,y);

% Recalculate Training, Validation and Test Performance
trainTargets = dependent_variable .* tr.trainMask{1};
valTargets = dependent_variable .* tr.valMask{1};
testTargets = dependent_variable .* tr.testMask{1};
trainPerformance = perform(neural_network,trainTargets,y);  % This variable will contain performance (MSE) of training.
valPerformance = perform(neural_network,valTargets,y);  % This variable will contain performance (MSE) of validation.
testPerformance = perform(neural_network,testTargets,y); % This variable will contain performance (MSE) of testing.

% View the Network
view(neural_network)

% Plots
% Uncomment these lines to enable various plots.
figure, plotperform(tr)
figure, plottrainstate(tr)
figure, ploterrhist(e)
figure, plotregression(t,y)
figure, plotfit(net,x,t)

% Deployment
% Change the (false) values to (true) to enable the following code blocks.
% See the help for each generation function for more information.
if (true)
    % Generate MATLAB function for neural network for application
    % deployment in MATLAB scripts or with MATLAB Compiler and Builder
    % tools, or simply to examine the calculations your trained neural
    % network performs.
    genFunction(net,'myNeuralNetworkFunction');
    y = myNeuralNetworkFunction(x);
end
if (false)
    % Generate a matrix-only MATLAB function for neural network code
    % generation with MATLAB Coder tools.
    genFunction(net,'myNeuralNetworkFunction','MatrixOnly','yes');
    y = myNeuralNetworkFunction(x);
end
if (true)
    % Generate a Simulink diagram for simulation or deployment with.
    % Simulink Coder tools.
    gensim(net);
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% SAVE INDICES FOR VALUES USED IN TRAINING, VALIDATION, AND TEST.
% This structure contains all of the information concerning the training
% of the network. For example, tr.trainInd, tr.valInd and tr.testInd
% contain the indices of the data points that were used in the training, % validation and test sets, respectively.
training_indices = tr.trainInd;
validation_indices = tr.valInd;
testing_indices = tr.testInd;

save('all_variables_that_resulted_from_nn_A388_Arrival')

% *** TESTING NEURAL NETWORK ***
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% WAKE BEHAVIOR NEURAL NETWORK EXECUTION AND TESTING
% CODE OR FUNCTION TO TRANSLATE THE INPUT FROM USER INTO NORMALIZED INPUT
% THAT NN CAN WORK WITH.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% DEFINE CURRENT CONDITIONS
altitude_m = 45.72; % 15.24;
edr_value_m2_per_s3 = 0.000027;
wind_value_m_per_s = 2; % 1.7882;
temperature_value_kelvin = 320; %298;
aircraft_mass_kg= 200000; %141970;
aircraft_group=3; % this category classifies aircraft from super heavy(A or 1) to light (F or 6)
% DEFINE MAXIMUM WAKE CIRCULATION CAPACITY
circulation_strength_m2_per_s = 200;

% FUNCTION TO TRANSFORM THE INPUTS TO NORMALIZED INPUTS FOR THE NEURAL
% NETWORK: [output]=function_name(input)

wake_behavior_nn_transformation_input(altitude_m, edr_value_m2_per_s3, wind_value_m_per_s, temperature_value_kelvin, ...
    aircraft_mass_kg, circulation_strength_m2_per_s)= ...

% EXAMPLE:
% altitude_m = 0.6
% edr_value_m2_per_s3 = 0.4
% wind_value_m_per_s = 0.3
% temperature_value_kelvin = 0.8
% aircraft_mass_kg = 0.9
% circulation_strength_m2_per_s = 0.7
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% REDEFINE PARAMETERS AND INJECT INTO NEURAL NETWORK.
inputs_to_find_time = [altitude_m edr_value_m2_per_s3 wind_value_m_per_s
  temperature_value_kelvin aircraft_mass_kg circulation_strength_m2_per_s];

% PREDICT RESULTS
wake_dynamic_time_separation_normalized = sim(neural_network, inputs_to_find_time');
net variable depends on the variable we are saving.

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% CALL THE FUNCTION TO TRANSLATE THE OUTPUT FROM THE NN (wake dynamic separation)
% WHICH IS NORMALIZED INTO NON NORMALIZED TIME SEPARATION

wake_dynamic_time_separation = ... 
  wake_behavior_nn_transformation_output (wake_dynamic_time_separation_normalized);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% NEURAL NETWORK STATISTICAL TEST
% Statistical test for neural network MSE for all the data.

  total_square = 0;
  for i = 1:size(traning_indices,2)
    y_from_nn = sim(neural_network, (x_value_for_regression (traning_indices(i),:))');
    total_square = total_square + (y_from_nn - y_value_for_regression (traning_indices(i)))^2;
  end

  MSE = total_square / size(x_value_for_regression,1);
disp(MSE);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% DO MY OWN COMPARISON BETWEEN NEURAL NETWORK AND DATA

% Plot data vs nn for indices that were not used during the nn training.

% NEURAL NETWORK:
% For normalized value of : altitude = 0.2 wind = 0.4 temp = 0.6 mass = 0.81 edr = 0.0467
% Plot circulation vs time
% DATA:
% For normalized value of : altitude= 0.2 wind=0.4 temp = 0.6 mass= 0.81 edr = 0.0467
% Plot circulation vs time

% INPUT NORMALIZED VALUES IN ORDER TO RUN NEURAL NETWORK
altitude_at_standard_time_normalized_validation = 0.2;
wind_at_standard_time_normalized_validation = 0.4;
temperature_at_standard_time_normalized_validation=0.6;
aircraft_mass_at_standard_time_normalized_validation = 0.81;
edr_at_standard_time_normalized_validation = 0.0467; % This value of edr has been fixed. for plotting illustration purposes.

% unique(x_value_for_regression(:,1)); % if you need to know the unique
% values inside the matrix that contains the independent variables.

% CALCULATE TIME SEPARATION ON NN AND COMPARE WITH REAL DATA
performance_figure_index = 1;
total_square = 0;
circ_to_plot_performance = zeros(1,2);
real_time_to_plot_performance= zeros(1,2);
time_from_nn_to_plot_performance = zeros(1,2);
for regression_matrix_index = 1:size(x_value_for_regression,1)
    if(abs(x_value_for_regression(regression_matrix_index,1) - ...
          altitude_at_standard_time_normalized_validation) > 1e-2)
        continue;
    end
    if(abs(x_value_for_regression(regression_matrix_index,2) - ... 
          edr_at_standard_time_normalized_validation) > 1e-2)
        continue;
    end
    if(abs(x_value_for_regression(regression_matrix_index,3) - ... 
          wind_at_standard_time_normalized_validation) > 1e-2)
        continue;
    end
    if(abs(x_value_for_regression(regression_matrix_index,4) - ... 
          temperature_at_standard_time_normalized_validation) > 1e-2)
        continue;
    end
    if(abs(x_value_for_regression(regression_matrix_index,5) - ... 
          aircraft_mass_at_standard_time_normalized_validation ) > 1e-2)
        continue;
    end
circ_to_plot_performance(performance_figure_index) = ... 
x_value_for_regression(regression_matrix_index,6);
real_time_to_plot_performance(performance_figure_index) = ... 
y_value_for_regression(regression_matrix_index);

time_from_nn_to_plot_performance(performance_figure_index) = ... 
sim(neural_network,(x_value_for_regression(regression_matrix_index,:))'); 
% use neural to predict time value based on given inputs.

%Calculate the MSE between nn predicted and real data
    total_square = total_square +
        (time_from_nn_to_plot_performance(performance_figure_index) - ... 
            real_time_to_plot_performance(performance_figure_index))^2;
    performance_figure_index = performance_figure_index + 1;
end
MSE = total_square/((performance_figure_index-1));

% PLOT  time separation vs ciculation strenght for edr : 0.1, 0.2, 0.3,
figure
ylabel('Circulation nomalized');
xlabel('Time normalized');
plot(circ_to_plot_performance,real_time_to_plot_performance,'*', ...
    circ_to_plot_performance,time_from_nn_to_plot_performance, '-');
    text(['MSE =',num2str(MSE)]);
    text('MSE');

1.10 Wake Behavior Dynamic Conditions Interpolation Function

This function can be used in order to interpolate for a given value of mass, edr, wind, temperature and circulation in order to identify the time separation. example given values of mass=, edr=.... identify closest value in data (table) for each input and read the time for this combination of values.

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% WAKE BEHAVIOR DYNAMIC CONDITIONS INTERPOLATION FUNCTION
% CODED BY: JULIO ROA
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function y = w_04_wake_behavior_standard_time_interpolation_function(aircraft_mass_kg, edr_value_m2_per_s3, wind_value_m_per_s, temperature_value_kelvin, circulation_strength_right, wake_behavior_data)

% FIND EXACT ENVIRONMENTAL VALUES
diff_mass = abs([wake_behavior_data(:).aircraft_mass_kg] - aircraft_mass_kg);
 [~,min_index] = min(diff_mass);
exact_mass = wake_behavior_data(min_index).aircraft_mass_kg;

diff_edr = abs([wake_behavior_data(:).edr_value_m2_per_s3] - edr_value_m2_per_s3);
 [~,min_index] = min(diff_edr);
exact_edr = wake_behavior_data(min_index).edr_value_m2_per_s3;

diff_wind_value = abs([wake_behavior_data(:).wind_value_m_per_s] - wind_value_m_per_s);
 [~,min_index] = min(diff_wind_value);
exact_wind_value = wake_behavior_data(min_index).wind_value_m_per_s;

diff_temperature_value = abs([wake_behavior_data(:).temperature_value_kelvin] - temperature_value_kelvin);
 [~,min_index] = min(diff_temperature_value);
exact_temperature_value = wake_behavior_data(min_index).temperature_value_kelvin;

% FIND INDICES IN DATA
for row_index_for_interpolate = 1:size(wake_behavior_data,2)
    if(abs(wake_behavior_data(row_index_for_interpolate).aircraft_mass_kg - ...
        exact_mass)>1e-3)
        continue;
    end
    if(abs(wake_behavior_data(row_index_for_interpolate).edr_value_m2_per_s3 - ...
        exact_edr)>1e-3)
        continue;
    end
if(abs(wake_behavior_data(row_index_for_interpolate).wind_value_m_per_s -
... 
    exact_wind_value)>1e-3)
    continue;
end

if(abs(wake_behavior_data(row_index_for_interpolate).temperature_value_kelvin
    exact_temperature_value)>1e-3)
    continue;
end
break;
end

%INTERPOLATE SERIES

time_series = wake_behavior_data(row_index_for_interpolate).time_s;
circulation_series =
wake_behavior_data(row_index_for_interpolate).circulation_strength_right_m2_p
    er_s;

first_zeros_index = find(~circulation_series, 1 );

time_series_to_interpolate = time_series(1:first_zeros_index);
circulation_series_to_interpolate = circulation_series(1:first_zeros_index);

y =
pchip(circulation_series_to_interpolate,time_series_to_interpolate,circulatio
    n_strenght_right);
end
1.11 Wake Behavior Dynamic Conditions Interpolation Function

This code uses function constructdata_wiskerplot in order to plot wisker plot for time vs circulation.

```matlab
index_to_cir_value = 1;
cir_to_plot = [ 150 200 250 300 350 400 450 500]; % Group A
cir_to_plot = [ 100 150 200 250 300 350 400 450]; % Group B
cir_to_plot = [ 50 100 150 200 225 250 275 300 ]; % Group C
cir_to_plot = [ 50 100 150 175 200 225 250 275]; % Group D
cir_to_plot = [ 50 75 100 125]; % Group E
cir_to_plot = [ 25 50 75]; % Group F

cir_to_plot = [ 100 275 300 325 350 400 425 450];
cir_to_plot = [ 100 200 300 400 450 500 525 550];
first_case_data = w_04_constructdata_wiskerplot_function ...
    (cir_to_plot(index_to_cir_value), wake_behavior_at_standard_times);
data_to_plot = zeros(size(first_case_data,2),size(cir_to_plot,2));
data_to_plot(:,1)=first_case_data;
for index_to_cir_value = 2:size(cir_to_plot,2)
data_to_plot(:,index_to_cir_value)=w_04_constructdata_wiskerplot_function ...
    (cir_to_plot(index_to_cir_value), wake_behavior_at_standard_times);
end

boxplot(data_to_plot,'Labels',{'150','200','250', '300', '350', '400', '450', '500'});

xlabel('Wake Vortex Circulation (m^2/s)','FontSize',18);
ylabel('Time (s)','FontSize',18);
legend([ 'Wake A380' ], 'location','northeast');
%grid on;
saveas(gcf,'GA_arr_wisker_plot_wake_circulation_vs_time','epsc');

% ALSO A HISTOGRAM SHOWING THE FREQUENCY OF CIRCULATION IS CREATED.
% DRAW HISTOGRAM FOR EACH CIRCULATION STRENGTH WHAT IS THE FREQUENCY OF TIMES.
% index from variable cir_to_plot
```
% this histogram is useful because if you have a maximum circulation
% capacity example of 250 m^2/s you will be able to tell the frequency of
% time separations for this circulation strength.

index_to_draw_hist = [1 2 3 4 5 6];

figure

for ind_hist = 1:size(index_to_draw_hist,2)
    subplot(3,2,ind_hist);
    histogram(data_to_plot(:,index_to_draw_hist(ind_hist)),10);
    % the number after the histogram represents the number of bins.
    xlabel('Time (s)');
    ylabel('Frequency');
    legend(['Wake ' num2str(cir_to_plot(index_to_draw_hist(ind_hist)))],
           'location','northeast');

end

saveas(gcf,'GA_arr_histogram_time_separation_for_wake_capacity','epsc');

1.12 Maximum Circulation Capacity

Current wake separations between leading and following aircraft can be used to determine the
maximum circulation a follower is approved to handle. For this wake circulation strength for leading
aircraft should be determined; this was done in code wake vortex prediction.

Steps description:

1. Define leading aircraft
2. Define follower aircraft
3. Generate circulation vs time curves for all possible conditions (leader dependent)
4. Define level of confidence
5. Generate circulation vs time pdf
6. Insert current static time separation between leader and follower (faa approved)
7. Determine maximum wake circulation capacity for follower aircraft

*If maximum wake circulation capacity has been previously determined, and the desire is to determine dynamic wake separation based on environmental conditions and aircraft dependent parameters:

8. Go to wake_behavior_neural_network or wake_behavior_regression_analysis

9. Define environmental conditions

10. Define aircraft dependent conditions

11. Insert maximum wake circulation capacity for follower aircraft on curve above

12. The required time separation between leader and follower will be determined

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                                                                        %
%                  MAXIMUM CIRCULATION CAPACITY                          %
%                      CODED BY: JULIO ROA                              %
%                                                                        %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

all_circulation_strength_data = zeros(number_of_sets_of_data, ...
                        size(wake_behavior_at_standard_times(1).time_s,2));

for time_series = 1:number_of_sets_of_data
all_circulation_strength_data(time_series,:) = ...

wake_behavior_at_standard_times(time_series).circulation_strength_right_m2_per_s;
end

% STEPS 4 & 5
% PLOT ALL THREE confidence levels of CIRCULATIONS Strenght IN ONE PLOT.
pdf_circulation_strength_99 = prctile(all_circulation_strength_data,99);
pdf_circulation_strength_95 = prctile(all_circulation_strength_data,95);
pdf_circulation_strength_90 = prctile(all_circulation_strength_data,90);

figure
plot(standard_time_value,pdf_circulation_strength_95,'*b')
ylabel('Circulation (m^2/s)','Fontsize',18);
xlabel('Time (s)','Fontsize',18);
legend('95 percentile ','location','northeast');
set(gca,'XTick',0:60:240);
grid on;
saveas(gcf,'Probability Density Function - Confidence 95','epsc');

figure
plot(standard_time_value,pdf_circulation_strength_99,'*b',standard_time_value,
pdf_circulation_strength_95,'.k',standard_time_value,
pdf_circulation_strength_90,'+r');
ylabel('Circulation (m^2/s)','Fontsize',18);
xlabel('Time (s)','Fontsize',18);
set(gca,'XTick',0:60:240);
grid on;
legend('99 percentile ','95 percentile','90 percentile', 'location','northeast');
%title('Circulation Strength behind generator 99 95 90 Confidence','Fontsize',12);
saveas(gcf,'Probability Density Function - Confidence 90, 95, 99','epsc');
% CALCULATE THE MAXIMUM WAKE CIRCULATION CAPACITY (MCC) FOR AIRCRAFTS BEHIND THIS GENERATOR.

% What is the maximum wake circulation strength capacity for an aircraft that is approved for static_time_based_wake_separation_s = #

% GOAL:

maximum_circulation_capacity_99confidence_m2_per_s_per_group=...
  spline(standard_time_value,pdf_circulation_strength_99,...
  static_time_based_wake_separation_s_per_group);

maximum_circulation_capacity_95confidence_m2_per_s_per_group=...
  spline(standard_time_value,pdf_circulation_strength_95,...
  static_time_based_wake_separation_s_per_group);

maximum_circulation_capacity_90confidence_m2_per_s_per_group=...
  spline(standard_time_value,pdf_circulation_strength_90,...
  static_time_based_wake_separation_s_per_group);

floor(maximum_circulation_capacity_95confidence_m2_per_s_per_group)

1.13 Dynamic Time Separation Behind Generator Aircraft

This code uses previously created neural network to calculate dynamic time separation that should be implemented behind a critical aircraft. Current airport conditions, leading aircraft conditions and the maximum circulation capacity (MCC) for follower should be defined

% DYNAMIC TIME SEPARATION BEHIND GENERATOR AIRCRAFT
  CODED BY: JULIO ROA
This code uses previously created neural network to calculate dynamic time separation that should be implemented behind a critical aircraft. Current airport conditions, leading aircraft conditions and the maximum circulation capacity (MCC) for follower should be defined.

```
clc
clear

% LOAD NEURAL NETWORK FOR EACH CRITICAL GENERATOR AIRCRAFT. 
% There is one critical aircraft per group
load net_IGE_ARR_A388_Vini.mat
load net_IGE_ARR_744_Vini.mat
load net_IGE_ARR_MD11_Vini.mat
load net_IGE_ARR_757_Vini.mat
load net_IGE_ARR_E175_Vini.mat
load net_IGE_ARR_SAAB2000_Vini.mat

% USE NEURAL NETWORK TO PREDICT; WAKE VORTEX DYNAMIC TIME SEPARATION FOR MAXIMUM WAKE CIRCULATION CAPACITY AND UNDER DEFINED CONDITIONS:

% DEFINE CURRENT CONDITIONS AT OR NEAR AIRPORT EVERY 15 MINUTES
altitude_m = 15.24; % from 50ft to 3 wingspan
edr_value_m2_per_s3 = 0.000072; % from zero (calm atmosphere) to an intense atmosphere
wind_value_m_per_s = 1.7882; % from zero wind condition to 15 meters per second.
temperature_value_kelvin = 298; % from 253.15 kelvin to 353.15 kelvin.

% DEFINE LEADING AIRCRAFT CONDITIONS
% In the near future this parameter will be changed by aircraft weight.
VInitial_m_per_s = 1.48; %For leading aircraft from 1.0527 meter per second to 1.6380 meters per second.

% DEFINE MAXIMUM WAKE CIRCULATION CAPACITY FOR FOLLOWER
circulation_strength_m2_per_s = 200; % This circulation capacity can be read from MCC matrix.

% REDEFINE PARAMETERS AND INJECT INTO NEURAL NETWORK.
inputs_to_find_time=[altitude_m edr_value_m2_per_s3 wind_value_m_per_s temperature_value_kelvin VInitial_m_per_s circulation_strength_m2_per_s];
```
%CALCULATE DYNAMIC TIME SEPARATION
wake_dynamic_time_separation_with_VInitial = sim(net,inputs_to_find_time'); % net corresponds to neural network of the critical generator

1.14 Function to Calculate the Minimum and Maximum Times at Specific MCC

This function is created to find the minimum and maximum time based on circulation strength for 95 confidence.

```
function [time_at_maximum_circulation_strenght,time_at_minimum_circulation_strenght,time_at_95_confidence]=
   w_07_Function_Calculate_Min_Max_Time_at_MCC(maximum_circulation_strength,number_of_sets_of_data,
   wake_behavior_at_standard_times)
   time_based_on_en_cond = zeros(1,number_of_sets_of_data);
   for environment_index = 1:number_of_sets_of_data
      time_data = wake_behavior_at_standard_times(environment_index).time_s;
      circulation_data=wake_behavior_at_standard_times(environment_index).circulation_strength_right_m2_per_s;
      circulation_data = abs(circulation_data-maximum_circulation_strength);
      [~,min_index]=min(circulation_data);
      time_based_on_en_cond(environment_index)=time_data(min_index);
   end
```
time_at_maximum_circulation_strength = max(time_based_on_en_cond);

end

1.15 Determine Minimum and Maximum Time for Described MCC

This code uses function w_07_Function_Calculate_Min_Max_Time_at_MCC in order to find the multiple minimum and maximum time (dynamic time separation) for a certain value of circulation.

maximum_circulation_strength = [41 41 41 41 41 41];
max_time = zeros(1,size(maximum_circulation_strength,2));
min_time = zeros(1,size(maximum_circulation_strength,2));
time_at_95_percentile = zeros(1,size(maximum_circulation_strength,2));
for calculate_index = 1:size(maximum_circulation_strength,2);

[w_07_Function_Calculate_Min_Max_Time_at_MCC(maximum_circulation_strength(calculate_index),number_of_sets_of_data,wake_behavior_at_standard_times)];
end
1.16 Function to Specify Maximum Circulation Capacity for Each Aircraft and to Select the Corresponding Neural Network Depending on the Specified Leading Aircraft Group

This code uses function w_07_Function_Calculate_Min_Max_Time_at_MCC in order to find the multiple minimum and maximum time (dynamic time separation) for a certain value of circulation.

```
function [neural_network,circulation_strength_m2_per_s]= leading_and_follower_specs(aircraft_group_leader,aircraft_group_follower)
load neural_network_GA_dep
load neural_network_GB_dep
load neural_network_GC_dep
load neural_network_GD_dep
load neural_network_GE_dep
load neural_network_GF_dep
load neural_network_GA_arr
load neural_network_GB_arr
load neural_network_GC_arr
load neural_network_GD_arr
load neural_network_GE_arr
load neural_network_GF_arr

%Define leading aircraft

% if (aircraft_group_leader == 1)
if(strcmp(aircraft_group_leader,'GA_arr'))
    neural_network = neural_network_GA_arr;
```

end

if(strcmp(aircraft_group_leader,'GB_arr'))
    neural_network = neural_network_GB_arr;
end

if(strcmp(aircraft_group_leader,'GC_arr'))
    neural_network = neural_network_GC_arr;
end

if(strcmp(aircraft_group_leader,'GD_arr'))
    neural_network = neural_network_GD_arr;
end

if(strcmp(aircraft_group_leader,'GE_arr'))
    neural_network = neural_network_GE_arr;
end

if(strcmp(aircraft_group_leader,'GF_arr'))
    neural_network = neural_network_GF_arr;
end

if(strcmp(aircraft_group_leader,'GA_dep'))
    neural_network = neural_network_GA_dep;
end

if(strcmp(aircraft_group_leader,'GB_dep'))
    neural_network = neural_network_GB_dep;
end

if(strcmp(aircraft_group_leader,'GC_dep'))
    neural_network = neural_network_GC_dep;
end

if(strcmp(aircraft_group_leader,'GD_dep'))
    neural_network = neural_network_GD_dep;
end

if(strcmp(aircraft_group_leader,'GE_dep'))
    neural_network = neural_network_GE_dep;
end
if(strcmp(aircraft_group_leader,'GF_dep'))
    neural_network = neural_network_GF_dep;
end

% DEFINE MAXIMUM WAKE CIRCULATION CAPACITY

if(strcmp(aircraft_group_follower,'GA_arr'))
    circulation_strength_m2_per_s =  602;% 350;
end

if(strcmp(aircraft_group_follower,'GB_arr'))
    circulation_strength_m2_per_s =  556;%300;
end

if(strcmp(aircraft_group_follower,'GC_arr'))
    circulation_strength_m2_per_s =  400;%525;%250;
end

if(strcmp(aircraft_group_follower,'GD_arr'))
    circulation_strength_m2_per_s =  350;%490;%200;
end

if(strcmp(aircraft_group_follower,'GE_arr'))
    circulation_strength_m2_per_s =  300;%490;
end

if(strcmp(aircraft_group_follower,'GF_arr'))
    circulation_strength_m2_per_s =  275;%436;
end

if(strcmp(aircraft_group_follower,'GA_dep'))
    circulation_strength_m2_per_s =  700;%808;%350;
end

if(strcmp(aircraft_group_follower,'GB_dep'))
    circulation_strength_m2_per_s =  458;%300;
end

if(strcmp(aircraft_group_follower,'GC_dep'))
    circulation_strength_m2_per_s =  400;%458;%250;
if(strcmp(aircraft_group_follower,'GD_dep'))
circulation_strength_m2_per_s = 350; %458; %200;
end

if(strcmp(aircraft_group_follower,'GE_dep'))
circulation_strength_m2_per_s = 320; %458; %185;
end

if(strcmp(aircraft_group_follower,'GF_dep'))
circulation_strength_m2_per_s = 300; %298 ;% 175;
end

end

1.17 Wake Behavior Test: Simulation Data vs. Neural Network

Compare dynamic time separation between data and nn; for the same input conditions.
This code will use previously created neural networks and functions in order to calculate dynamic time
separation between leading and following aircraft and test data from simulation vs calculations from
neural network.

```
clc
clear all
load wake_behavior_simulation_output_GA_ARR_A388_12M_12E_6W_6T

% NEURAL NETWORK STATISTICAL TEST
```
% Statistical test for neural network MSE for all the data.
% Calculate MSE for training indices during the neural network between the
% real data which is called y_value_for_regression vs data from neural network which
% is called y_from_nn

% When running each neural network the traning indices must be saved.
load training_indice.mat % indices from neural network

total_square = 0;
for i= 1:size(traning_indices,2)
    y_from_nn  = sim(neural_network,(x_value_for_regression(traning_indices(i),:))');
    total_square  = total_square + (y_from_nn -
    y_value_for_regression(traning_indices(i)))^2;
end

MSE = total_square/size(x_value_for_regression,1);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% 1 ST SCENARIO (DRAW ALL CURVES OF DATA VS NN)
% DEFINE LEADING AIRCRAFT GROUP AND CONDITIONS
aircraft_group_leader = 'GA_arr';

% DEFINE AIRCRAFT GROUP follower:
% 3; % this category clasifies aircraft from super heavy(A or 1) to light (F or 6)
aircraft_group_follower = 'GD_arr';

% USE FUNCTION TO DRAW MULTIPLE CURVES OF CIRCULATION STRENGHT VS TIME FOR
% DATA VS NEURAL NETWORK. This function will draw curves for same inout
% conditions it sees on wake bahavior data.
draw_nn_to_dts_multiple_curves(wake_behavior_at_standard_times,...
    number_of_sets_of_data,aircraft_group_leader,aircraft_group_follower);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% 2ND SCENARIO (FOR ARRAY OF GIVEN INPUTS; DRAW CURVES OF DATA VS CURVES NN)
% COMPARE NEURAL NETWORK AND DATA NON NORMALIZED

% DEFINE LEADING AIRCRAFT GROUP AND CONDITIONS
aircraft_group_leader = 'GA_arr';

altitude_condition_array = [15.2400 45.7200 76.2000 106.6800 137.1600 167.6400 198.1200 228.6000];

aircraft_mass_kg = [250900 263190 275470 287750 300030 312310 324600 336880 349160 361440 373720 386010];

% DEFINE CURRENT CONDITIONS
edr_value_m2_per_s3 = [0 0.0007 0.0014 0.0022 0.0030 0.0051 0.0072 0.0111];

wind_value_m_per_s = [0 3 6 9 12 15];

temperature_value_kelvin = [253.1500 273.1500 293.1500 313.1500 333.1500 353.1500]; % [323.1500 333.1500 343.1500 353.1500 363.1500];

% DEFINE AIRCRAFT GROUP follower:
aircraft_group_follower = 'GD_arr';

for altitude_index = 1:size(altitude_condition_array,2)
    for edr_index = 1:size(edr_value_m2_per_s3,2)
        for wind_index = 1:size(wind_value_m_per_s,2)
            for temp_index = 1:size(temperature_value_kelvin,2)
                for mass_index = 1:size(aircraft_mass_kg,2)
                    draw_nn_to_dts_input_specified_curves(wake_behavior_at_standard_times,...
                        number_of_sets_of_data,aircraft_group_leader,aircraft_group_follower,...
                        altitude_condition_array(altitude_index),...
                        edr_value_m2_per_s3(edr_index),...
                        wind_value_m_per_s(wind_index),...
                        temperature_value_kelvin(temp_index),...
                        aircraft_mass_kg(mass_index));
                end
            end
        end
    end
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% 3RD SCENARIO (FOR GIVEN INPUTS ONE CONDITION ;
% DRAW CURVE OF DATA VS CURVES NN AND CALCULATE THE MSE

% DEFINE LEADING AIRCRAFT GROUP AND CONDITIONS
aircraft_group_leader = 'GA_arr';

altitude_m = 45.7200; % 15.24; % GB 15.2400 45.7200 76.2000 106.6800 137.1600
167.6400 198.1200
aircraft_mass_kg= 275470; %141970; % GB 1.7985 1.8866 1.9746 2.0626
2.1507 2.2387 2.3268 2.4148 * 1.0e+05

edr_value_m2_per_s3 = 0.0014; % GB 0.0014 0.0022 0.0030 0.0051 0.0072
0.0111
wind_value_m_per_s = 3; % 0 2 4 6 8 10

temperature_value_kelvin = 273.1500; %298; % GB 313.1500 323.1500 333.1500
343.1500 353.1500 363.1500

%DEFINE AIRCRAFT GROUP follower:
aircraft_group_follower = 'GD_arr';

min_circulation_strength_right_m2_per_s =
min([wake_behavior_at_standard_times(1).circulation_strength_right_m2_per_s(:)]);

for row_index = 2:number_of_sets_of_data
    min_time_row =
    min([wake_behavior_at_standard_times(row_index).circulation_strength_right_m2_per_s(:)]);
    if (min_circulation_strength_right_m2_per_s > min_time_row)
        min_circulation_strength_right_m2_per_s = min_time_row;
    end
end

% FIND THE MAXIMUM CIRCULATION STRENGTH FOR THE CONDITIONS SPECIFIED ABOVE
for row_index = 1:number_of_sets_of_data
    if(abs(wake_behavior_at_standard_times(row_index).altitude_m - ...
        altitude_m) > 1e-2)
        continue;
    end
    if(abs(wake_behavior_at_standard_times(row_index).edr_value_m2_per_s3 - ...
        edr_value_m2_per_s3) > 1e-2)
        continue;
    end
    if(abs(wake_behavior_at_standard_times(row_index).wind_value_m_per_s - ...
        wind_value_m_per_s) > 1e-2)
        continue;
    end
end

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continue;
end
if(abs(wake_behavior_at_standard_times(row_index).temperature_value_kelvin - ...
    temperature_value_kelvin) > 1e-2)
    continue;
end
if(abs(wake_behavior_at_standard_times(row_index).aircraft_mass_kg - ...
    aircraft_mass_kg ) > 1e1)
    continue;
end

max_time_row =
max([wake_behavior_at_standard_times(row_index).circulation_strength_right_m2_per_s(:)
    ]); 

array_data_circulation_strength =
[wake_behavior_at_standard_times(row_index).circulation_strength_right_m2_per_s(:)];
    array_data_time = [wake_behavior_at_standard_times(row_index).time_s(:)];
end

%%% Remove duplicate from array_data_circulation
%%% Remove 0 value, only keep the first one
for index_array_circulation = 1:size(array_data_circulation_strength,1)
    if(array_data_circulation_strength(index_array_circulation) < 1e-2)
        number_of_line_to_remove = size(array_data_circulation_strength,1)-
        index_array_circulation;
        for iteration_0_removal=1:number_of_line_to_remove
            array_data_circulation_strength(index_array_circulation+1)=[];
            array_data_time(index_array_circulation+1)=[];
        end
        break;
    end
end

% array_circulation_strength=
linspace(min_circulation_strength_right_m2_per_s,max_time_row,10);
array_circulation_strength= array_data_circulation_strength;
array_time_s = zeros(size(array_data_circulation_strength,1),1);
for index_to_draw_cir_vs_time =1:size(array_data_circulation_strength,1)

    % DEFINE MAXIMUM WAKE CIRCULATION CAPACITY
    [neural_network,circulation_strength_m2_per_s]= ... 
    leading_and_follower_specs(aircraft_group_leader,aircraft_group_follower);

    % FUNCTION TO TRANSFORM THE INPUTS TO NORMALIZED INPUTS FOR THE NEURAL 
    % NETWORK: [output]=function_name(input)

    [altitude_m_norm,edr_value_m2_per_s3_norm,wind_value_m_per_s_norm,temperature_value_kelvin_norm,aircraft_mass_kg_norm, circulation_strength_m2_per_s_norm] = 
    wake_behavior_nn_transformation_input(altitude_m,edr_value_m2_per_s3,wind_value_m_per_s,temp_valuekelvin,aircraft_mass_kg,array_circulation_strength(index_to_draw_cir_vs_time), aircraft_group_leader);

    % REDEFINE PARAMETERS AND INJECT INTO NEURAL NETWORK.
    inputs_to_find_time=[altitude_m_norm edr_value_m2_per_s3_norm wind_value_m_per_s_norm temperature_value_kelvin_norm aircraft_mass_kg_norm circulation_strength_m2_per_s_norm];

    %PREDICT RESULTS
    wake_dynamic_time_separation_normalized = 
    sim(neural_network,inputs_to_find_time'); % net variable depends on the variable we are saving.
    % We will use neural network for leading aircraft which is the generator.

    % CALL THE FUNCTION TO TRANSLATE THE OUTPUT FROM THE NN (wake dynamic separation) % WHICH IS NORMALIZED INTO NON NORMALIZED TIME SEPARATION
    array_time_s(index_to_draw_cir_vs_time)= ... 

    wake_behavior_nn_transformation_output(wake_dynamic_time_separation_normalized)

end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% PLOT DATA VS NEURAL NETWORK FROM INITIAL DEFINED CIRCULATION TO MAXIMUM
% DEFINED CIRCULATION
% Filter the data from initial_time_value_seconds to
% final_time_value_seconds in order to plot the data vs neural network and
% then calculate the MSE and display on a figure
%%%Process the data from time 60 to 240 only
initial_circulation_value_m2_per_s = 250 ;
final_circulation_value_m2_per_s = max(array_circulation_strength)+ 1e-6;

%%%Find the index to crop data

for initial_circulation_index = 1:size(array_circulation_strength,1)
  if(array_circulation_strength(initial_circulation_index) < initial_circulation_value_m2_per_s)
    break;
  end
end

for final_circulation_index = 1:size(array_circulation_strength,1)
  if(array_circulation_strength(final_circulation_index) < final_circulation_value_m2_per_s)
    break;
  end
end

array_circulation_strength=array_circulation_strength(final_circulation_index:initial_circulation_index );
array_time_s = array_time_s(final_circulation_index:initial_circulation_index);
array_data_circulation_strength = array_data_circulation_strength(final_circulation_index:initial_circulation_index );
array_data_time=array_data_time(final_circulation_index:initial_circulation_index );

%PLOT NEURAL NETWORK VS DATA FOR ALL CONDITIONS
% CALCULATE MSE AND INCLUDE AS COMMENT IN PLOT
% Include conditions (automatic with varaibles) in comments or plot title
% Create subplot changing conditions with same generator aircraft
figure
plot(array_circulation_strength,array_time_s,'+', ...
     array_data_circulation_strength,array_data_time,'*');
xlabel('Circulation (m^2/s)','Fontsize',18);
ylabel('Time (s)','Fontsize',18);
set(gca,'XTick',0:60:240);
grid on;
title('Data vs Neural network','Fontsize',12); %Aircraft group leader
legend('ANN', 'DATA')%,'120 sec');
xlim([initial_circulation_value_m2_per_s ,max(array_circulation_strength))];

%%%%%Calculate MSE
total_square_error = 0;
total_square_error_real=0;
min_time = 0;
max_time = 240;

for index_array_time = 1:size(array_time_s,1)
    difference_between_data_and_nn = abs(array_time_s(index_array_time) - ...
                                    array_data_time(index_array_time));
    normalized_difference = (difference_between_data_and_nn-min_time)/(max_time-
                        min_time);
    total_square_error = total_square_error + normalized_difference^2;
    total_square_error_real = total_square_error_real +
    difference_between_data_and_nn^2;
end

MSE = total_square_error/size(array_time_s,1);
MSE_real= total_square_error_real/size(array_time_s,1);

%ADDITION TO TXT TO PLOT CREATED ABOVE.
%text(340,200,['MSE = ',num2str(MSE_real)]);
text(370,105,['Root error = ',num2str(sqrt(MSE_real))]);

text(340,180,['Normalized MSE = ',num2str(MSE)]);
text(370,100,['Normalized Root error = ',num2str(sqrt(MSE))]);
text(370,90,['altitude, edr, wind, temp, mass'])
text(370,85,['num2str(altitude_m), ' ',num2str(edr_value_m2_per_s3),'
        ',num2str(wind_value_m_per_s), ' ',num2str(temperature_value_kelvin),'
        ',num2str(aircraft_mass_kg)])
% saveas(gcf,'Data_vs_ann','epsc');