

Improvements to Airport Systems Capacity and Efficiency Using Computer Models and Tools

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## ABSTRACT

This thesis presents two aspects of air transportation systems, capacity and efficiency. The first study improved a runway capacity simulation model for estimating the capacity of airports under various conditions. The main contribution of this study was to develop a simulation model which is able to analyze different airports with individual aircraft types. Many air traffic regulations were added to the simulation model to give more realistic results to the potential users of the model. Analysis of different separation systems between aircraft pairs show that the capacity of airports can improve by using more efficient separation systems specially under tough weather conditions. One of the outputs of the study, is an upgraded user interface which can be used by airport authorities for estimating their facilities' available capacity under different scenarios.

The second study represents a new method for estimating unimpeded taxi times for taxing airplanes at airports. This study focused specifically on 6 large airports in the United States and the real ground radar data for all of the movements at those facilities. By tracking the real trajectories of every operation, the taxing behavior of each flight was analyzed. A standalone application was designed to summarize the flights information at each airport and represent the taxing behavior. The results show that using the ground radar data at airports can represent the taxing behavior in the highest fidelity.

# Improvements to Airport Systems Capacity and Efficiency Using Computer Models and Tools

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## ABSTRACT (General Audience)

The federal aviation administration predicts an ongoing growth in aviation industry over the following 20 years. The number of passengers using air transportation systems will increase annually in the next 20 years. Therefore, the airports will be more crowded and a higher number of operations will occur at those facilities. An accurate prediction of airports' capacities can help the authorities to improve the airports appropriately. This will lead to an efficient aviation system which does not suffer severely from long delays. The contribution of the first study in this thesis was to help the process of predating airports' capacities under various conditions by utilizing a computer model. As a result, a user interface was designed to help airport planners choosing their desired airports and estimating the maximum capacity under different operational conditions. An accurate prediction of airport capacity, can be useful for future designs and improvement plans.

The second part of this thesis, represents a new methodology for analyzing the behavior of airplanes while moving at airports. Every flight operation starts its journey at the origin airport and finishes its journey at the destination airport. It is very important to analyze the behavior of each airplane while it is moving on the ground at the origin or destination airport. Therefore, parameters like taxing duration, waiting duration, average taxi speed can be used to evaluate the taxing performance of the airplanes. This study extracts the critical parameters of airplanes' behavior at airports to help the planners evaluating the ground performance of each airport.

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## 1. Introduction

The Federal Administration Aviation (FAA) performs annual forecasts of future aviation demand. The overall trend in aviation demand has changed drastically in the past 10 years, with flat demand after the recession period between 2007-2009 which had a negative effect on the aviation industry. The FAA embarked in the development of the next generation system operational developments with use of computer systems for handling flight operations. At the same time, the capacity of airports continues to be the limiting component in the aviation system capacity. The capacity of an airport is affected by the operations on runways, taxiways, and apron areas. Strategies for improving the capacity of airports can be studied by using modelling and simulation.

This study contains two different topics related to airport capacity and airport efficiency. In the second chapter the author studied many effective parameters on airports capacity. This chapter is mainly about the improvements performed to a Monte Carlo runway capacity model and then examining many parameters to estimate the runway capacity at airports. The result of the improvements is packaged as a standalone computer model which has a user interface and can be used for running 250 airports in the national airspace system with various simulation parameters. This tool which is called RUNSIM version 2.00, is a useful simulation model for helping aviation authorities in estimating airports' capacities under different conditions.

The third chapter focuses on the development of a taxi event extractor, which tries to summarize critical moments of each operation at airports to estimate the taxiing time of the aircraft at airports. This study introduces new methods of estimating taxi times and analyzing taxiing behavior of airplanes at airports.

## 2. Airport Capacity Model (Version 2.0.0)

### 2.1. Introduction

Airport capacity continues to be an important topic in the development of the next generation aviation system (NextGen). FAA predicts an annual 1.9% increase in commercial and general aviation operations in the next 20 years (1), additional passenger demand results in more flights, airport ground movements, and busy days at airports. A quick method to estimate airport capacity under diverse operational conditions is of interest of FAA and airport modelers. Airport capacity is affected by weather, number of gates, aircraft fleet mix, operational procedures, nearby airport traffic and others. A combination of these factors can reduce airport capacity, causing delays which affects both passengers and airlines.

Nowadays the solution for capacity issues is more likely, an efficient system design. The construction of building new airport infrastructure is very costly. Improving the operational systems at existing airports can be considered as a more reasonable solution. Airport operational improvements include: applying optimum separation between airplanes for different operations, designing tools for guiding pilots in bad weather to recover the capacity, applying new separation rules which are compatible with different weather conditions, and allowing simultaneous runway operations in closely-spaced runways.

In this study, we describe enhancements to the runway capacity model developed by the Air Transportation Systems Laboratory (ATSL) at Virginia Tech for Nasa Langley Research Center (2). The runway capacity model was developed to estimate the capacity of 250 airports in the U.S. under different aircraft separation rules and weather conditions. A key constraint in airport runway capacity is the mandatory airspace separation between arrival and departure operations.

Large spacing between flights are mandated for safety reasons. When aircraft flies the lift generated by the wings creates powerful wake vortices that can affect trailing aircraft.

At the request of the FAA Wake Office, we developed RUNSIM model to estimate the capacity of U.S. airports under current and proposed wake vortex separation criteria.

## 2.2. Problem Definition

The main objective of this study is to develop a tool to measure runway capacity benefits of future concepts of operation. At the request of the Federal Aviation Administration (FAA), we modified the first version of the runway capacity simulation model developed at the ATSL. The FAA is conducting studies to develop new criteria to categorize aircraft into new wake categories. The objective is to reduce airspace separations to improve runway capacity. The runway simulation model has been modified to account for the new RECAT criteria and also to include wind effects.

## 2.3. Literature Review

There are numerous methods to estimate airport runway capacity. Pu developed a Monte Carlo simulation model to estimate runway capacity (2). Most of the documentation review is focused on the features of the model. The initial version of this model which is called Quick Response Runway Capacity Model (RUNSIM), employs Monte Carlo Simulation in a stochastic process to generate flights for arrivals and departures to estimate throughput for arrivals and departures (3). Figure 1 represents a sample output of RUNSIM v.1.00.

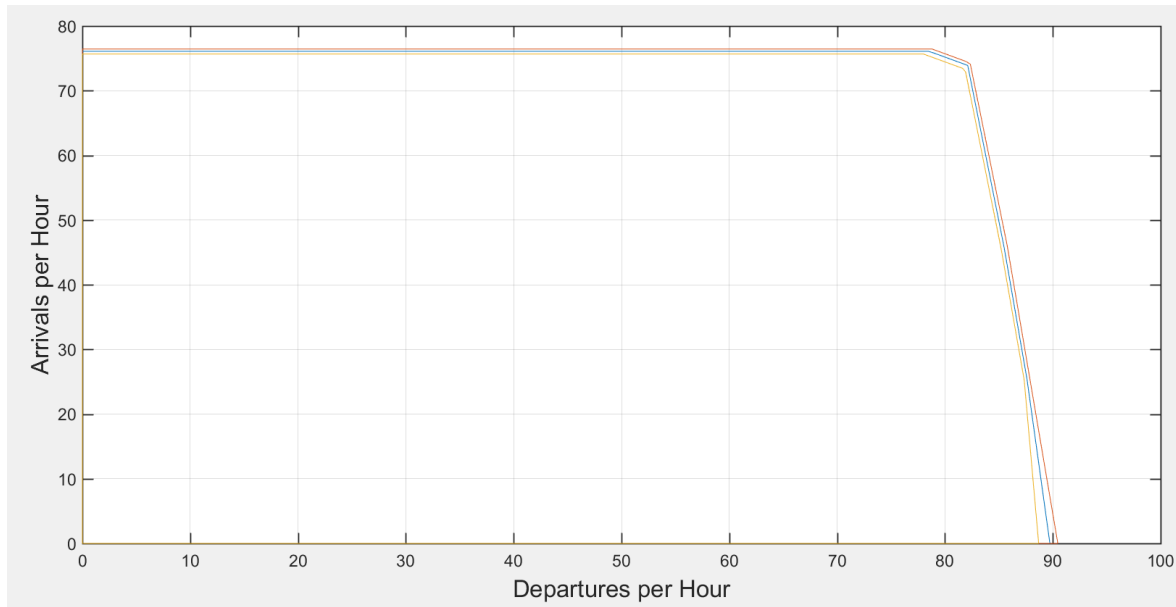


Figure 1. Sample Output of the RUNSIM model, Arrival-Departure Diagram for Los Angeles International Airport Operated Under Instrumental Meteorological Conditions (IMC).

### 2.3.1 Review of RUNSIM Version 1.0.0

The first version of the model can analyze airports with up to three dependent runway configurations, two weather conditions and a limited number of aircraft groups. The available wake groups of the model are:

- 1- Legacy wake categories with five different wake classes of aircraft. The legacy wake categories are based on maximum takeoff weight and wingspan (4). The five groups are: small, large, Boeing 757, heavy, and super heavy. The criteria of these categories are represented in Table 1:



Table 1. Legacy Aircraft Wake Categories Used by FAA.

Aircraft Wake Group	Small	Large	B757	Heavy	Super Heavy
Maximum Takeoff Weight (MTOW) (lb)	$\leq 41,000$	$41,000 < \text{and} < 300,000$	Boeing 757	$\geq 300,000$	Airbus A388 Antonov AN225

2- Re-categorization Phase 1 (RECAT1) grouping uses aircraft maximum takeoff weight and wingspan to categorize airplanes into six groups labeled A to F. The six groups are shown in Table 2.

Table 2. Aircraft RECAT Phase1 Wake Categories Used by FAA (6).

Grouping Name	MTOW (lb)	Wingspan (feet)
A	$\geq 300,000$	$> 245$
B	$\geq 300,000$	$175 < \text{and} \leq 245$
C	$\geq 300,000$	$125 < \text{and} \leq 175$
D	$< 300,000$	1) $125 < \text{and} \leq 175$
		2) $90 < \text{and} \leq 125$
E	$> 41,000$	$65 < \text{and} \leq 90$
F	$< 41,000$	$\leq 125$
	$< 15,500$	Regardless of Wingspan a Powered sailplane

- 3- Personalized grouping which enables user to enter random airplane groupings based on maximum takeoff weight and wingspan. The selection of groups considers both parameters within certain ranges of numbers.

RUNSIM v.1.00 models two visual range conditions:

- 1) Visual Meteorological Conditions (VMC) which allows visual flights rules (VFR) with pilots able to space themselves on final approach. This condition requires a visibility range higher than 3 nautical miles and 1000 feet ceiling height.
- 2) Instrumental Meteorological Conditions (IMC) which mandates the pilot to fly under instrumental flights rules (IFR) in which the aircraft separation is enforced by air traffic control. This condition occurs when the visibility range is less than 3 nautical miles and ceiling lower than 1000 feet.

In RUNSIM v.1.00, the weather parameters affect the model selection of airspace separation criteria. Other weather conditions including wind speed or wind direction are not available in the first version of the model.

The RUNSIM model uses minimum separation matrices accepted by FAA to run the simulation and estimate maximum throughput (4). For legacy wake categorization grouping the model uses separations shown in Table 3 and for RECAT Phase 1 uses separations shown in Table 4.

Table 3. Arrival-Arrival Separation Matrix in Nautical Miles for Legacy Wake Categories in IMC Conditions.

Leader/Follower	Super	Heavy	B757	Large	Small
Super	MRS	6	7	7	8
Heavy	MRS	4	5	5	6
B757	MRS	4	4	4	5
Large	MRS	MRS	MRS	MRS	4
Small	MRS	MRS	MRS	MRS	MRS

Note: MRS: Minimum Radar Separation

Table 4. Arrival-Arrival Separation Matrix in Nautical Miles for Re-Categorizations Groups in IMC Conditions.

Leader/Follower	A	B	C	D	E	F
A	MRS	5	6	7	7	8
B	MRS	3	4	5	5	7
C	MRS	MRS	MRS	3.5	3.5	6
D	MRS	MRS	MRS	MRS	MRS	5
E	MRS	MRS	MRS	MRS	MRS	4
F	MRS	MRS	MRS	MRS	MRS	MRS

MRS: Minimum Radar Separation

One important limitation of the RUNSIM model version 1.0.0 is the static nature of the aircraft groups. There are five legacy groups and six in RECAT Phase 1. Future concepts of operation may establish separation using time-based separations.

For departure separations the model uses the numerical values shown in Tables 5 and 6.

Table 5. Departure-Departure Separation in Seconds for Legacy Wake Categories in IMC Conditions.

Leader/Follower	Super	Heavy	B757	Large	Small
Super	180	180	180	180	180
Heavy	120	120	120	120	120
B757	120	120	120	120	120
Large	60	60	60	60	60
Small	60	60	60	60	60

Table 6. Departure-Departure Separation in Seconds for Re-Categorization Phase I Groups in IMC Conditions.

Leader/Follower	A	B	C	D	E	F
A	60	180	180	180	180	240
B	60	120	120	120	120	210
C	60	60	60	120	120	180
D	60	60	60	60	60	120
E	60	60	60	60	60	60
F	60	60	60	60	60	60

RUNSIM Version 1.00 can estimate the runway capacity of airports without an Air Traffic Control (ATC) tower. For those facilities the separation matrices used are based on the empirical observations.

RUNSIM model version 1.0 uses a Monte Carlo stochastic process for simulating flights. The model supports multiple runway configurations including parallel independent runways, close parallel runways, intersecting runways, and a combination of both intersecting and parallel runways. The model can estimate the runway capacity of most of the current runway configurations found at 250 airports in the National Airspace System (NAS).

### 2.3.2. Review of other Runway Capacity Models

Other runway capacity models were reviewed in order to understand their handling of various aircraft groups and separation criteria.

Models are basically divided into two main categories (5):

- 1) Analytical models which use series of equations for calculating the hourly capacity.

According to Airport Cooperative Research Program (ACRP) report 79 (7), this category

of models includes the FAA Airfield Capacity Model (the ACM), Logistics Management Institute (LMI) runway capacity model, and Boeing Co. Airport Capacity Constraints Model (7).

- 2) Simulation models use random processes to simulate random variables to estimate runway capacity in a more realistic fashion. Many of the current runway capacity simulation models use Monte Carlo techniques for generating streams of arrival and departure and then calculating the capacity. Examples of these models are the Jeppesen-Boeing Total Airspace and Airport Modeler (TAAM), the FAA Airport and Airspace Simulation Model (SIMMOD), and MITRE's Corporation *runway* Simulator.

The features and capabilities of each model were studied. The cost and time required for running analytical models are considerably lower than simulation models. The Airport Cooperative Research Program (ACRP) report 79 summarizes the features and capabilities of various runway capacity models and defines their attributes and limitations. The following paragraphs describe some of the features of each model.

#### *2.3.2.1 Table Lookup Model*

This model is defined as Level 1 model among runway capacity models. The main usage of a lookup table model to estimate capacity for small airport masterplans which have no-significant capacity. These tables are constrained to runways capacity only and need a simple configuration with aircraft fleet mix to produce runway capacity results.

#### *2.3.2.2 Excel Spreadsheet Model of Advisory Circular 150/5060-5*

This model is recognized as Level 2 among runway capacity models. The required inputs for this model are the runway configuration, runway exit locations, aircraft fleet mix, and the percentage of arrivals.

#### *2.3.2.3 Airfield Capacity Model (ACM)*

This model is an analytical runway capacity model which has more capabilities than lookup tables or excel spreadsheet models. This model has been used in many airport studies performed by the FAA. This model uses the runway configuration, aircraft fleet mix assigned to each runway, ATC separation rules, runway occupancy times, and aircraft performance characteristics to estimate runway capacity. This model has been replaced by MITRE Corporation *runwaySimulator* model (8).

#### *2.3.2.4 MITRE Corporation RunwaySimulator*

This model is considered a Level 4 model among runway capacity models. It uses analytical and simulation methods to extract the maximum runway capacity of each selected airport configuration. Most of the current FAA airport arrival-departure capacity diagrams for different airports are produced using this model. This model is limited to runway operations and does not simulate movements in taxiways or gates.

#### *2.3.2.5 SIMMOD, ADSIM, TAAM, and AIRTOP*

These models present the highest level of fidelity in airport simulations (Level 5). The user can model the operations based on their flight schedule at airport. Inclusion of gates, taxiways, and runways is possible in these models. The main logic for these models is to calculate the

operational delay at different points of the airspace or ground network of an airport. These models allow users to select variable groups for wake separation in the simulation.

## 2.4. Quick Runway Capacity Model Version 2.00

### 2.4.1 Input Parameters

One of the most critical features needed in the development of a runway capacity model is the capability of selecting different aircraft types used in the analysis. The Federal Aviation Administration is interested in modeling the wake vortex features of individual aircraft types operating in the National Air Space System (NAS). Therefore, the runway capacity model should be able to accommodate individual aircraft behavior of a potential large fleet mix.

#### *2.4.1.1 Aircraft Fleet Mix*

The fleet mix of airplanes using the facility is a critical input to any runway simulation model. A realistic estimate of the fleet mix at the airport can be obtained from recent historical records approved by FAA. For this analysis we use data archived by the Bureau of Transportation Statistics (9). The data source is the T-100 segment table for different air carriers (9). It contains a summary of all the flights operated at U.S. airports from domestic or overseas origins. The data has flight IDs, airplane types, origin and destination airports, and also the time of the operations. The data applies to all domestic and foreign carriers. There are 408 different airplane types in the T100 airplane data set. The fleet mix for each airport is extracted from the T100 data source for the past three years (years 2014-2016). A sample format of the extracted fleet mix of for the LaGuardia airport is represented in Table 7.

Table 7. Summary of Planes Operations at LaGuardia Airport (LGA) in Year 2016.

Airplane Types	Number Of Operations
Raytheon King Air A100	2
Pilatus PC-12	3
De Havilland DHC8-400 Dash-8	28
Boeing 717-200	8,867
Boeing 737-700/700LR	19,034
Boeing 737-800	22,485
Boeing 737-400	39
Boeing 737-300	213
Boeing 757-200	127
Boeing 757-300	345
Boeing 767-300/300ER	40
Canadair RJ-200ER /RJ-440	18,074
Canadair RJ-700	28,266
Boeing 737-600	1,854
McDonnell Douglas DC-9-15F	2
Canadair CRJ 900	23,704
Gulfstream G150	2
McDonnell Douglas DC9 Super 80/MD81/82/83/88	11,257
McDonnell Douglas MD-90	5,365
Bombardier CRJ 705	166
Gates Learjet Lear-31/35/36	1
Embraer ERJ-175	32,710
Embraer-145	16,641
Embraer 170	17,361
Embraer 190	18,780
Cessna 510 Mustang/560XL Citation Excel	2
Airbus Industrie A320-100/200	25,734
Airbus Industrie A319	10,085
Airbus Industrie A321	7,202
Boeing 737-900ER	2,886

Previously, in RUNSIM v.1.00, individual aircraft types were grouped in legacy wake categorization or RECAT phase1 categorization for calculating the fleet mix. The new version of the model is able to consider each specific airplane as a unique group. In this way the fleet mix for each airport is calculated based on the total number of operations of each aircraft divided by total operations at that airport. The final fleet mix file for each airport contains the percentages of



annual operations of each aircraft type. during the whole year at the airport. A comparison between traditional fleet mix calculation and the new method used in RUNSIM v.2.00 is represented in Figure 2.

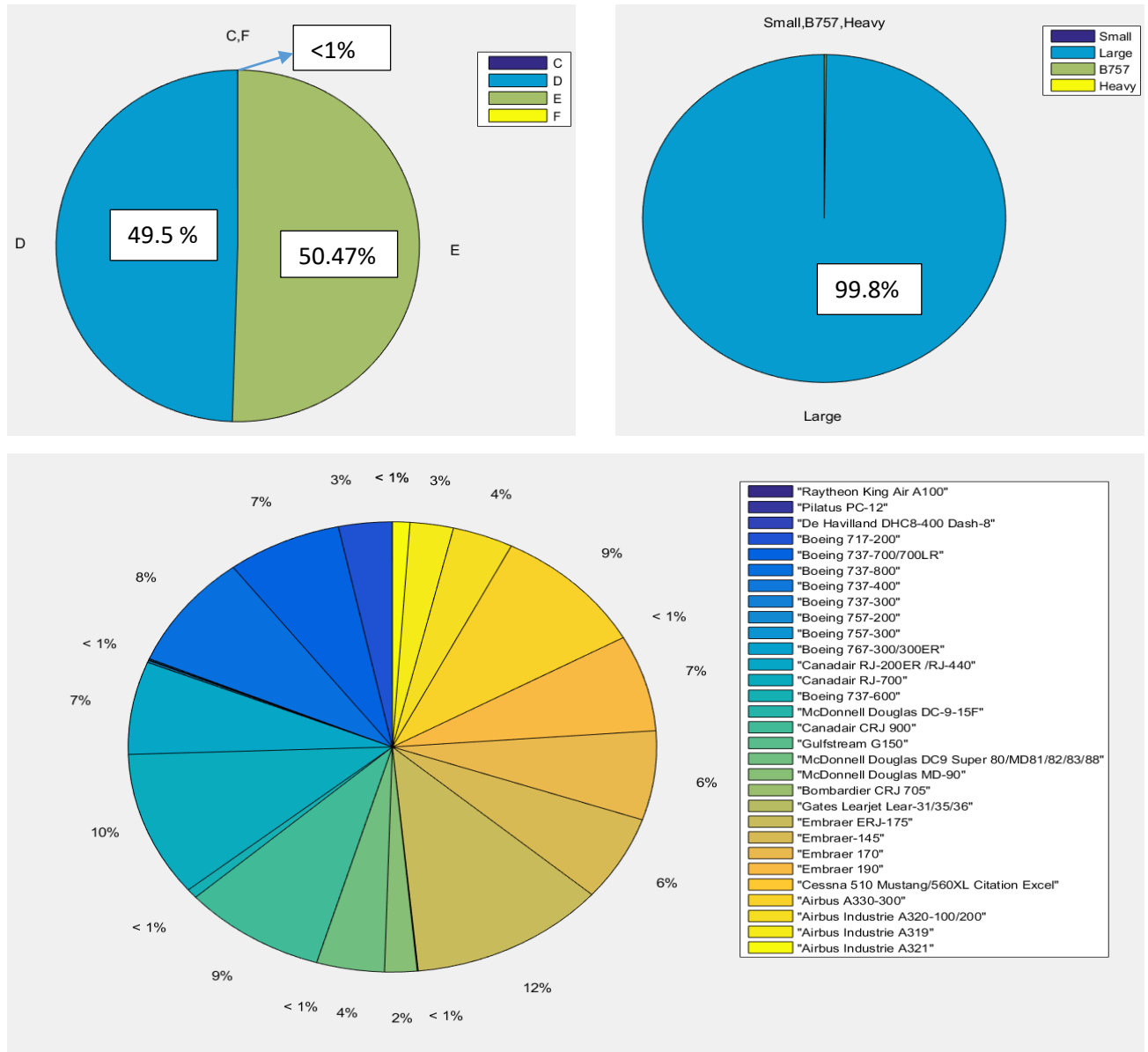


Figure 2. LaGuardia Airport (LGA) Fleet Mix in RECAT System Top Left, in Wake System Top Right, and in Individual Aircraft Types Below.

Figure 2 shows the LaGuardia airport fleet mix at year 2016, which is calculated in three different methods. The first two methods which are represented in top figures are the base

methods for calculating the fleet mix in RUNSIM v.1.00 and many other simulation models. Most of those models extract the fleet mix based on FAA legacy wake vortex grouping criteria or RECAT phase 1. The new method for calculating the individual aircraft type fleet mix is represented at the bottom of Figure 2. For the example presented there are 32 aircraft types operated at LaGuardia airport in the year 2016. 32 individual airplane groups comprise the fleet mix of the airport. The runway capacity analysis is more reliable if we simulate each specific aircraft type, because the FAA has defined recent wake criteria (RECAT Phase 2) based on many individual aircraft types. Moreover, by looking at the top section of Figure 2 we can see that legacy wake grouping criteria is not fully capable of drawing a detailed picture of airplanes which operate at the facility.

The variety of aircraft fleet mixes operating at the top 30 busiest airports in U.S. are shown in Figure 3.

The top 30 airports carried 70% of the total commercial operations in year 2016 among United States airports. After reviewing the current fleet mix at the top 30 airports, an interesting point about the percentage of different wake groups was noticed. All of these 30 airports in the United States, have more than 67% of their annual fleet mix, considered as legacy wake group large. There are more than 60 distinct aircraft in the large category. A simulation model that treats individual behavior offers higher fidelity in the simulation and thus could improve the runway capacity estimates.

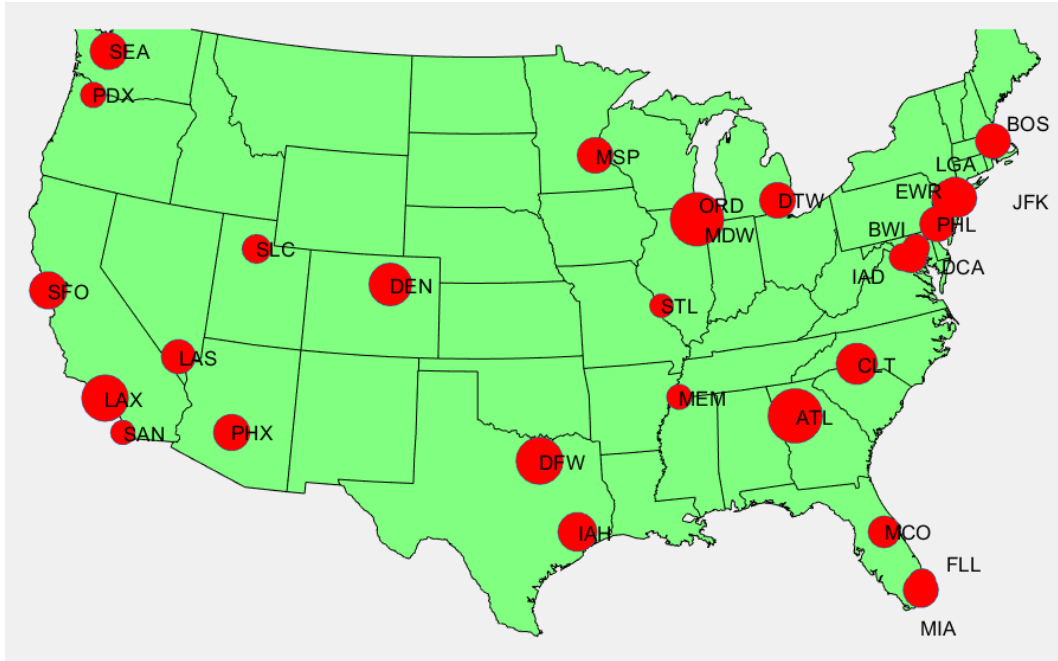


Figure 3. Top 30 Busiest Airports in U.S. Based on 2016 Operations.

Note: Size of the circles shows the number of operations in compare with other facilities.

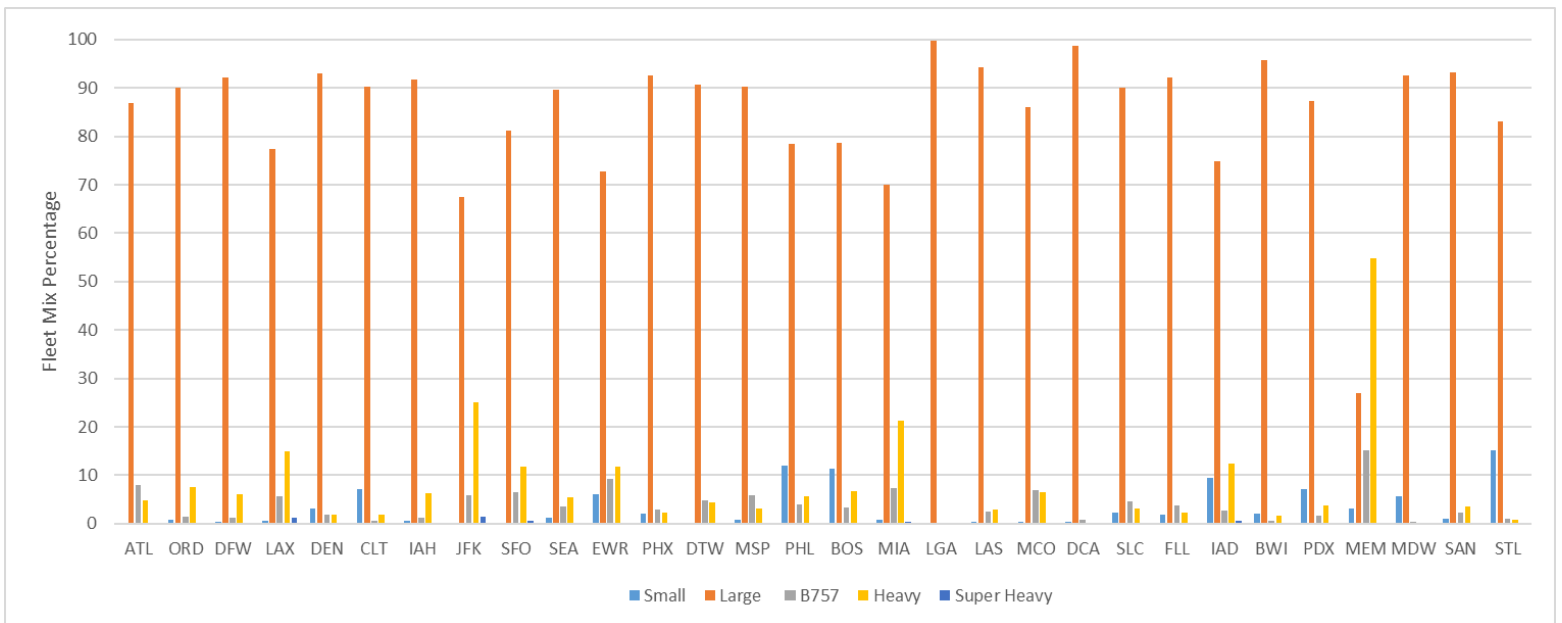


Figure 4. Top 30 U.S. Busiest Airports in 2016, Legacy Wake Groups.

As it is shown in Figure 4, all of the top 30 airports in U.S. have high percentages of large aircraft in their annual fleet mix. LaGuardia airport has the highest percentage of large aircraft

with 99.81% of its fleet mix. The heavy aircraft group is the second largest (percentagewise) wake legacy group. Memphis has the highest percentage of heavy airplanes in the U.S. with 54.86% of its fleet mix. There are a few airports in the country with super heavy class aircraft (which is Airbus A388). John F. Kennedy airport in New York has the highest number of super heavy operations in U.S. with 1.54% of its feet mix. The super heavy and the B757 wake groups contain one type of aircraft in the group. Other wake groups include many airplanes with a ranges of wingspans and maximum takeoff weights. Consider Figure 2 that shows the legacy wake group large with 22 different airplanes flying at LaGuardia airport. Having distinct aircraft performance will improve the estimate of airport capacity. It is recommended to include each airplane individually for every simulation scenario.

The benefits of analyzing aircraft individually will be discussed in simulation methods and methodology chapter which is chapter 2.4.2.

Table 8 summarizes the distinct large and heavy aircraft types operations at the top 30 busy airports in the U.S., and represents the number of airplanes which are recognized as LARGE or HEAVY wake group. Table 8 shows the benefit of modelling airports with individual aircraft performance characteristics as most airports have multiple airplanes in each wake group with various physical aspects.

Table 8. Summary of the Number of Aircraft Types at the top 30 Airports of U.S (Year 2016, Data).

Airport Name	Total Airplane Types	Number of LARGE Planes	Number of HEAVY Planes
'ATL'	58	30	19
'ORD'	64	28	25
'DFW'	56	27	19
'LAX'	76	31	27
'DEN'	57	30	17
'CLT'	54	30	13
'IAH'	63	31	19
'JFK'	66	29	29
'SFO'	62	30	23
'SEA'	54	28	19
'EWR'	67	33	21
'PHX'	45	24	11
'DTW'	57	30	18
'MSP'	62	28	16
'PHL'	66	31	17
'BOS'	76	35	21
'MIA'	79	33	27
'LGA'	32	22	3
'LAS'	63	33	15
'MCO'	57	29	19
'DCA'	25	18	3
'SLC'	49	24	12
'FLL'	61	31	16
'IAD'	74	34	19
'BWI'	63	31	14
'PDX'	51	28	12
'MEM'	50	28	10
'MDW'	47	26	1
'SAN'	52	27	14
'STL'	50	29	10

### 2.4.1.2 Approach Speed

The aircraft approach speed in the arrival procedure is an important simulation parameter used in runway capacity models. In the first version of the RUNSIM model there were 5 legacy wake groups or 6 RECAT groups. Each group had a representative approach speed which was calculated based on the weighted average approach speeds of the aircraft defined in each group. This method is only an approximation of actual aircraft operations. After studying many samples of Airport Surface Detection Equipment (ASDE-X) data, and analyzing the approach speed of different airplanes within 10 nautical miles from the runway thresholds, we found considerable variation in the airplanes approach speeds. For distinct aircraft this is shown graphically in Figures 5, 6, and 7.

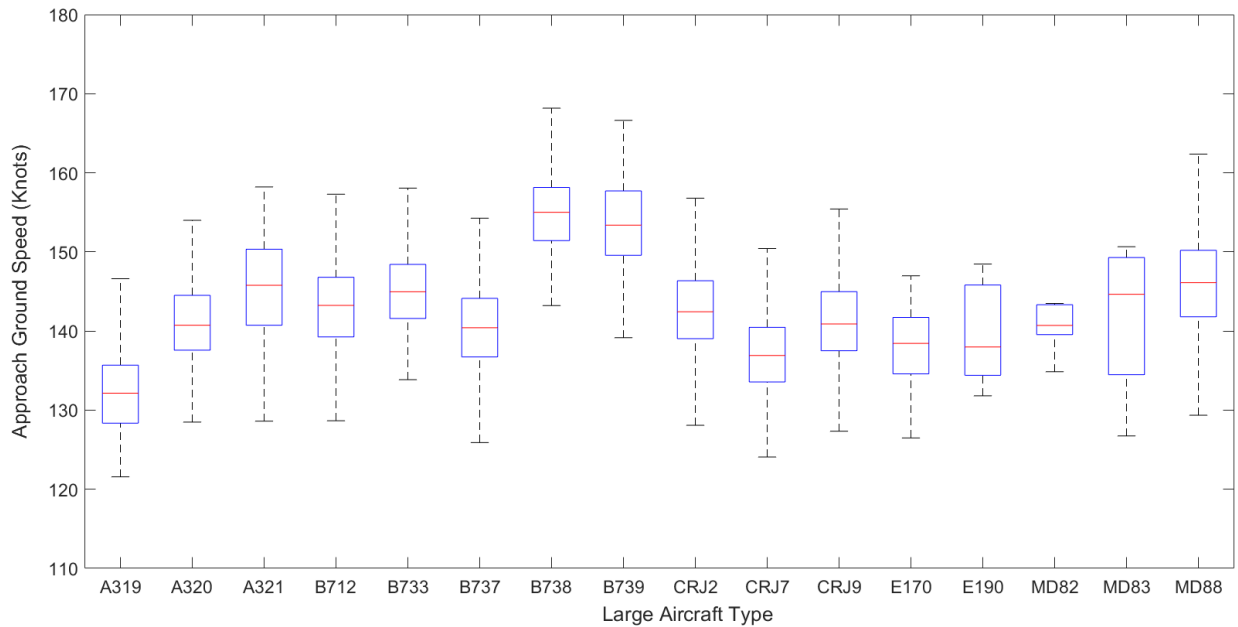


Figure 5. Variability of Approach Speeds Extracted from ASDE-X Data for Large Aircraft operations at U.S. Airports.

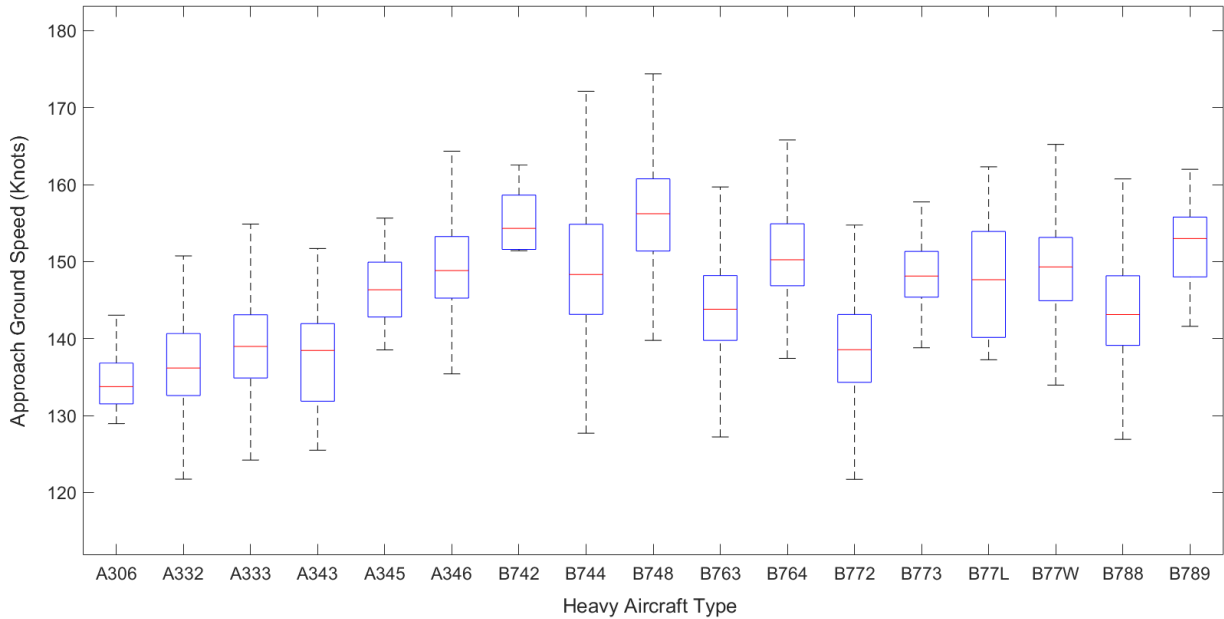


Figure 6. Variability of Approach Speeds Extracted from ASDE-X Data for Heavy Aircraft operations at U.S. Airports.

Figures 5 to 6 show the variability of approach speeds among different airplanes belonging to similar wake groups. Referring to Table 8 the high number of large and heavy airplanes at most of the top 30 airports in U.S., produces substantial variations in approach speed profiles that can only be modified using individual aircraft performance. For the remaining three legacy wake groups super heavy, B757, and small with small fleet mix percentages, the variety of approach speeds within each group will not play a considerable role in estimating the airport hourly throughput. Nevertheless, approach speeds for these groups were extracted from the same ASDE-X data source. Not every large hub airport at U.S. has super heavy aircraft operations. To study super heavy operations, we used JFK and LAX airport data. The approach speed profiles for Airbus A380-800 are represented in Figure 7. Figure 7 contains data for several months for JFK airport. Flights which had illogical speed values due to data drops or bad data were eliminated from the analysis.

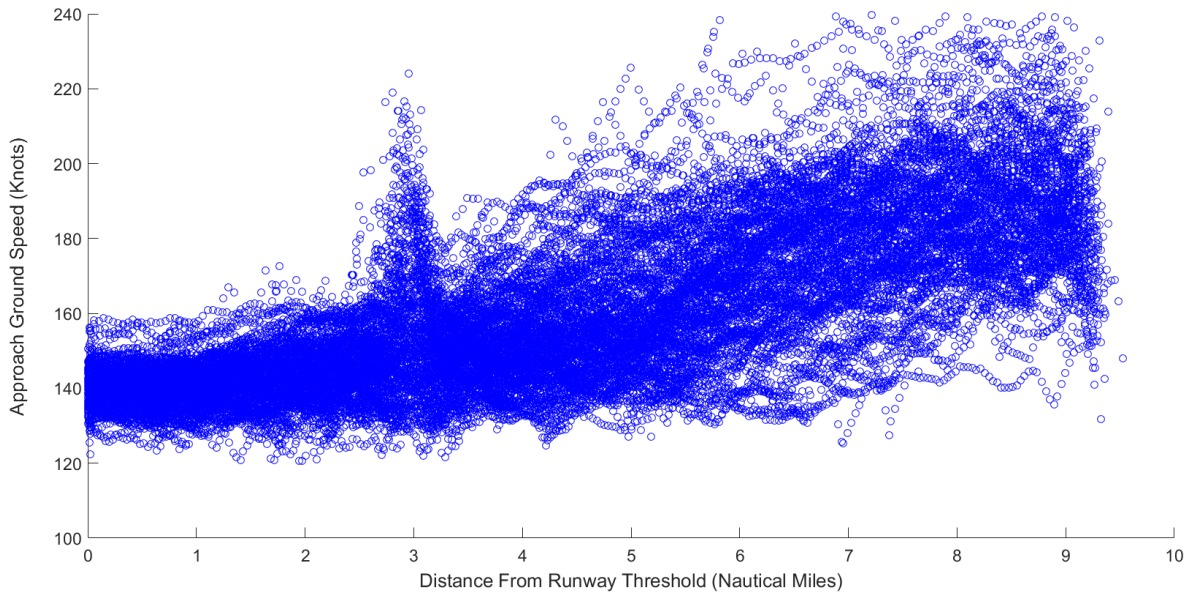


Figure 7. Speed Profiles of Airbus A380-800 Landing at JFK Airport.

#### 2.4.1.3 Runway Occupancy Time

Another important parameter that can influence runway capacity is the Runway Occupancy Time (ROT). ROT is the time an aircraft (arrival or departure) spends on the runway. Runway occupancy times can be estimated for individual aircraft types. Different aircraft have different runway occupancy times (ROT), because their braking systems are different, their different approach speeds, and pilots may have motivation practices based on the location of cargo or passenger gates that affect the runway exit taken. Figure 8 shows a sample of arrival flights to runway 08L at Atlanta airport. The figure shows that many runway exits are used due to various purposes. The motivations of taking a specific exit on a runway are independent of the technical aspects of reducing speed and vacating the runway quickly.



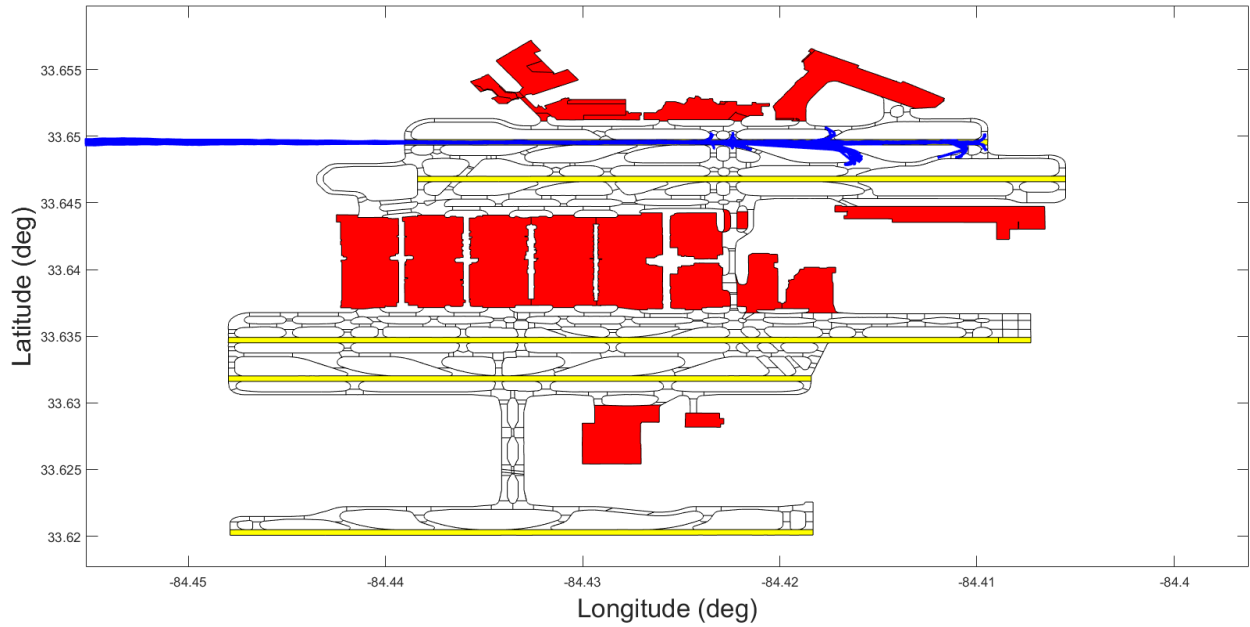


Figure 8. Arrivals at Runway 8L in ATL Airport Taking Various Exits.

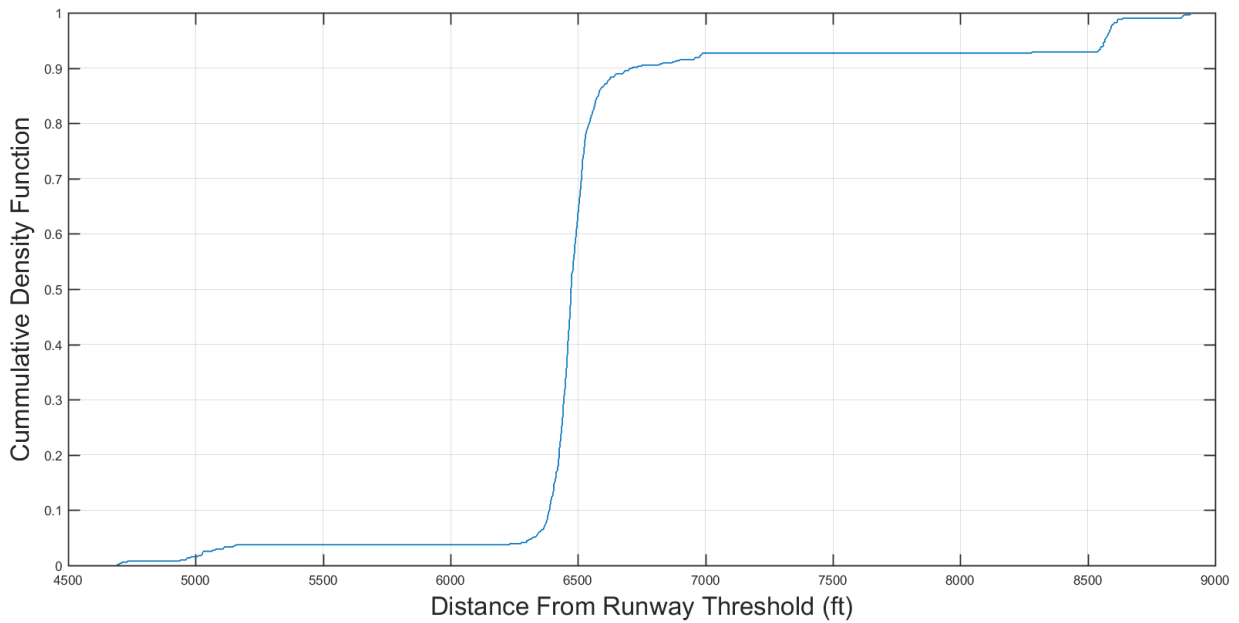


Figure 9. Cumulative Density Function Plot of Exit Locations for Arrivals on Runway 8L at ATL Airport.

Figure 9 represents the cumulative density graph of the distance measured from runway threshold to different exits taken by arrivals to runway 08L at Atlanta airport. Many factors can affect the runway occupancy times. The ROT values vary from airport to airport and from aircraft type to aircraft type. In order to do realistic simulation results it is recommended to extract the runway occupancy times for all of the aircraft operating at the airport. The runway occupancy data in the runway capacity model is extracted from ASDE-X data. The procedure is to define the time when the plane passes the runway threshold and subtract it from the time where the airplane exits the runway. This process requires the definition of a runway polygon used to estimate aircraft positions inside the runway.

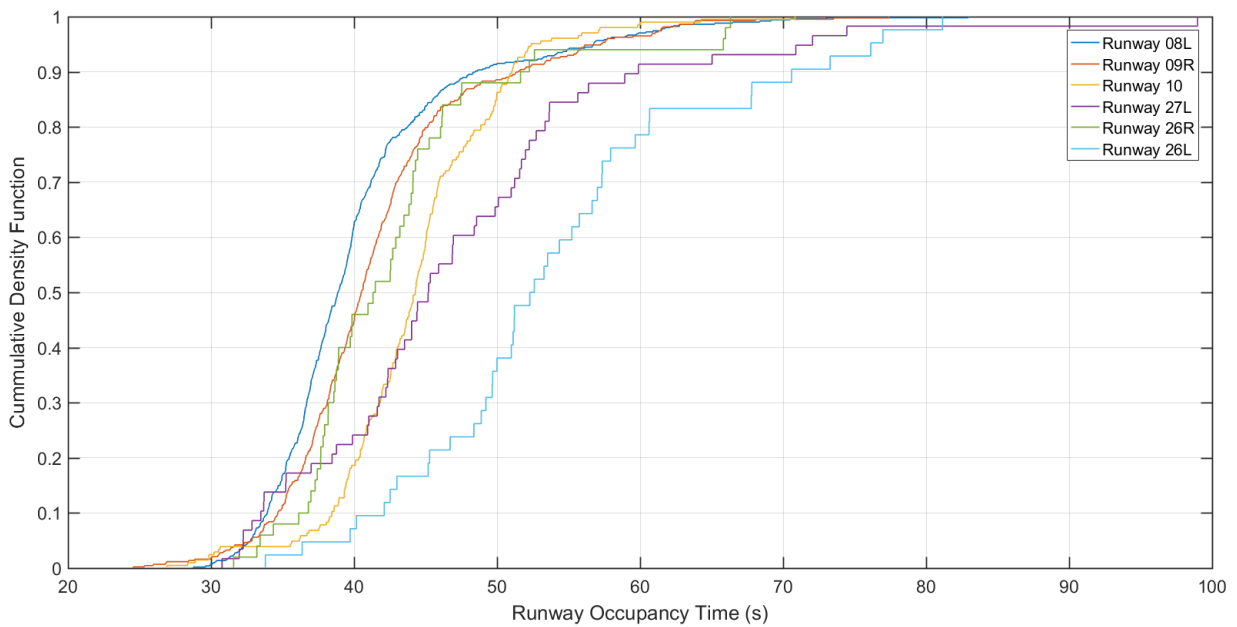


Figure 10. ATL Different Runways Cumulative Distribution Functions Plot, Representing the ROT Values for Various Arrivals.

Figure 10 shows the variability of ROT for different runways at the Atlanta International Airport. This shows the stochastic nature of ROT. The variations are explained by the fleet mix, runway length and runway exit locations.

#### *2.4.1.4 Air Traffic Control and Separation Rules*

Air traffic separation rules are fundamental in simulation models. Air traffic rules contain operational procedures for separating airplanes in order to keep runway operations safe and efficient. Air traffic control rules are likely to evolve in the future. Most of the air traffic control (ATC) rules are the same between RUNSIM version 1.00 and version 2.00. The most important separation rule which is significantly different between the mentioned versions of the RUNSIM is about airplanes' separation methods. RUNSIM model version 1.00 includes the accepted static separation matrices for legacy wake groups and RECAT phase 1 wake categorization, used by FAA. Version 1.00 also enables the user to define its desired groups by defining ranges of wingspan and maximum takeoff weight and their associated wake vortex separations. This feature allows the introduction of new airplanes in the model, however the process of categorizing airplanes in different wake groups based on their wingspan and maximum takeoff weight is not within the interest of capacity analysis anymore. FAA is interested in considering each individual airplane in its own wake group, therefore it would be preferable to let the user pick real operating airplanes at the airports and then let the user defining the separation method as well.

There are multiple separation matrices which are used in the second version of RUNSIM model.

##### *2.4.1.4.1 RECAT 1 Individual Separation Matrix*

Table 4 which shows the arrival-arrival separation matrix in IMC conditions and it is based on RECAT phase1 used by FAA, is the main source for the individual separation matrix in RUNSIM model version 2. There are 193 airplanes in the model aircraft database which every of them are assigned to one of the current RECAT phase1 groups. Using the RECAT phase1

categories and the separation cells of Table 4, a big matrix with 193 rows and columns (193\*193) was created to be used for any individual aircraft simulation runs using RECAT phase1 criteria. The same procedure was repeated with departures referencing to Table 6.

#### 2.4.1.4.2 RECAT 1.5 Separation Matrix

FAA released a RECAT 1.5 separation matrix based on the wake studies using Southern California TRACON fleet mix. This center collects many data for airplanes' wake vortices, thus they released a new version of RECAT separation matrices for Arrival-Arrival condition. The new matrix had couple of replaced cells with new numbers and a new RECAT group labeled as group G. Group G basically refers to those airplanes which are not showing up many times at U.S. airports or there is not sufficient information about their wake behaviors. Table 9 represents the RECAT phase 1.5 separation matrix.

Table 9. RECAT 1.5 Arrival-Arrival Separation Matrix in Nautical Miles.

Leader/Follower	A	B	C	D	E	F	G
A	MRS	4.5	6	7	7	8	7
B	MRS	3	4	5	5	6	5
C	MRS	MRS	MRS	3.5	5	6	5
D	MRS	MRS	MRS	MRS	MRS	4	5
E	MRS	MRS	MRS	MRS	MRS	MRS	5
F	MRS	MRS	MRS	MRS	MRS	MRS	5
G	5	5	5	5	5	5	5

Note: Red cells show the cells which are lower than the similar cell in RECAT phase1 matrix.

Blue cells show the cells which are bigger than the similar cells in RECAT phase1 matrix.

Airplanes in group G vary from airport to airport. The studies on the behavior of those planes is still continuing, however Table 9 has not ever selected to be the reference separation matrix for air traffic controllers.

#### 2.4.1.4.3 RECAT 2 Individual Separation Matrix

FAA has studied the wake behavior of 123 different aircraft types by using antennas and data collectors at busy airports' runway thresholds in United States. The results of the wake study defined distance-based separations between pairs of 123 studied aircraft. A 123 by 123 separation matrix was produced based on those results. The implementation of this matrix into a runway capacity model requires the capability of running simulation scenarios for individual aircraft grouping. Since the latest RECAT 2 matrix does not use a specific procedure for categorizing airplanes inside a limited number of groups and treat each individual aircraft type as a standalone group, the runway capacity model should be able to have simulated airplanes based on aircraft data base with a minimum size of 123 planes inside it.

32% of the cells in the FAA RECAT2 matrix are zeros. This means that 2,417 aircraft pairs are not separated in RECAT2 system based on the wake vortex effect. This shows the importance of having a clear and precise vision over the runway occupancy times for different airports, since this parameter will be replaced to the separation in case the model finds a zero value inside the matrix. Therefore, for designing safe and efficient systems, accurate data for each type of airplane which is not affected by wake vortex force and should be separated based on the runway occupancy time must be available. None of the airplanes from RECAT groups A, B, and C are among those pairs as the leader. This implies that the heavier airplane groups still have considerable wake vortex strength to affect aircraft behind them.

Figure 11 illustrates the percentage of different arrival pairs which do not have specific separation values in FAA RECAT2 separation matrix. These pairs are given zero as their separation values which means that the runway occupancy time for the leader should be considered as the minimum practical separation. RECAT group F has the highest percentage of

zeros in the separation matrix. Group F includes small general aviation aircraft that do not generate strong wakes. The reason that the percentages of zero cells among group E planes are lower than group D planes, is that there are 33 different aircraft in group D in the RECAT Phase2 matrix, while there are only 25 aircraft in RECAT group E in the separation matrix.

Figure 11 clearly shows that most of the airports in United States with high fleet mix of RECAT groups B,D, E, and F will be considerably affected by the new individual separations if the runway occupancy times for the groups D, E, and F are drastically different than the previous separations in RECAT1 system.

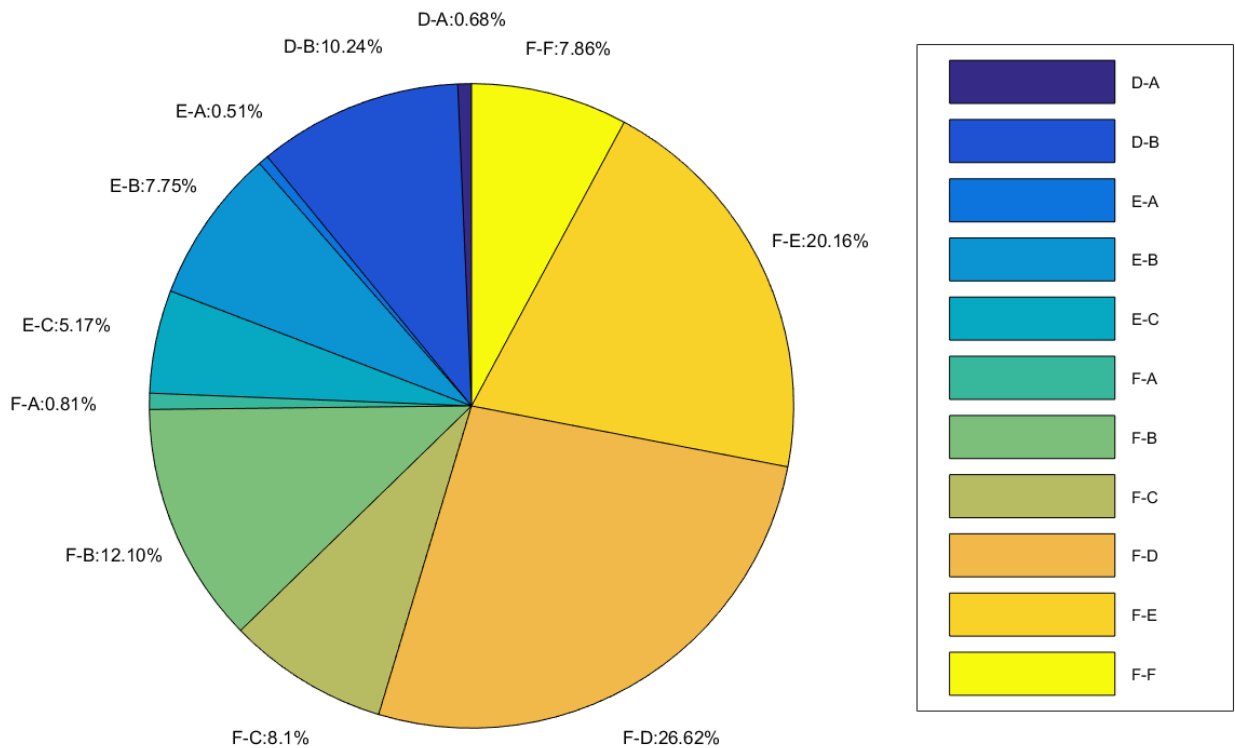


Figure 11. Percentage of Different Arrival Pairs Which Have Zero in Their Separation Cells in FAA RECAT2 Matrix.

This shows that under the RECAT2 separation system, runway occupancy times will take a more important role than before.

#### 2.4.1.4.4 Time Based Separation Matrix

One of the most important aspects in aviation world which causes considerable delays and challenges for landings is wind. Heavy headwind at many airports reduces the number of arrivals considerably. There is an on-going study to consider the possible solutions for retrieving the lost capacity under heavy headwind and that's using the time based separation instead of distanced based separation (10). This idea is coming from Euro Control and NATS UK which started implementing the time based separation procedure at London Heathrow airport since 2015 (11). Figure 12 represents the time based separation matrix which is used by NATS UK.

		Follower					
		Super Heavy	Heavy	Upper Medium	Lower Medium	Small	Light
Leader	Super Heavy A380	#	135s	158s	158s	158s	158s
	Heavy ≥ 136000 kg	#	90s	113s	113s	135s	158s
	Upper Medium > 104000 & < 136000 kg	#	#	68s	90s	90s	135s
	Lower Medium > 40000 & ≤ 104000 kg	#	#	#	#	68s	113s
	Small > 17000 & ≤ 40000 kg	#	#	#	#	68s	90s
	Light ≤ 17000 kg	#	#	#	#	#	#

Figure 12. NATS UK Time Based Separation Matrix.

Note: # Signifies that separation for wake turbulence reasons alone is not necessary. The six groups defined in Figure 12 are very similar to the six groups of the RECAT system defined by FAA in terms of the maximum takeoff weight. The FAA does not have a time based separation matrix, therefore the input file for the computer model is similar to what is used by NATS UK.

#### *2.4.1.5 Wind*

Wind is an important factor in aviation operations. The direction of wind defines the heading of the runways at an airport, and every day the selected runway configuration by the ATC tower is defined by the direction of blowing wind. The absolute headwind or tailwind do not make severe difficulty for the pilots, however crosswinds make the operations (specifically landings) more challenging for pilots.

In the first version of RUNSIM there is no wind option provided for the user, therefore the assumption is that operations are conducted with no wind in the simulation and the approach speeds are constant, unless the user changes them manually. In the second version of RUNSIM the number of selected airplanes can exceed the number of traditional wake groups, and many airports have multiple runway headings, therefore it is a time consuming and inaccurate process for the user to change all the approach speeds relevant to the wind components, therefore a wind procedure has been programmed and added to the second version of RUNSIM that estimates the headwind condition for every flight operation considering the runway heading used. The new procedure estimates the ground speed of the aircraft which affects the runway capacity. Figure 13 presents the calculation of aircraft approach speed considering wind.



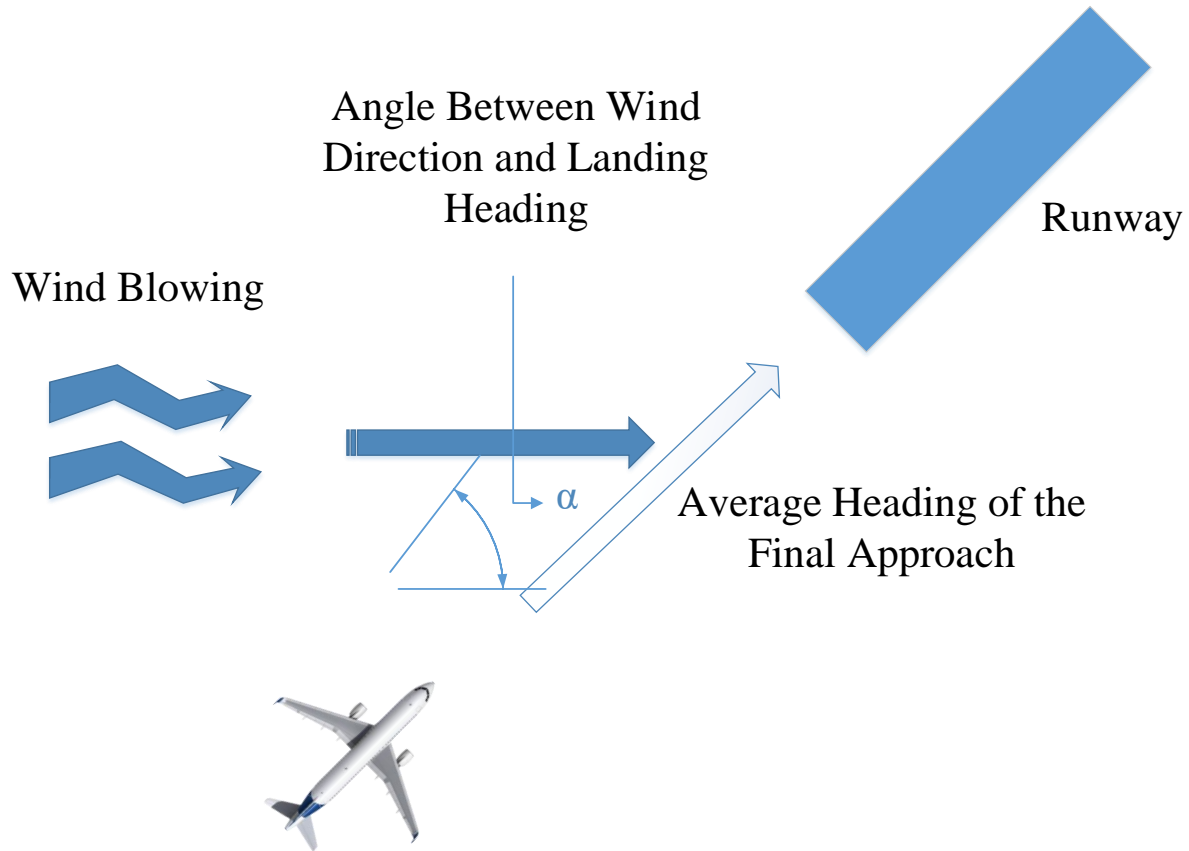


Figure 13. Wind Effect on the Approach Speed in the RUNSIM V.2.00 Model.

Users are able to enter wind speed and heading in the second version of RUNSIM. Ground speed is calculated from the set of equations shown in Equation 1 (12):

$$\text{Headwind} = \cos (\text{Wind Heading} - \text{Average Link Heading}) * \text{Wind Speed}$$

$$\text{Crab Factor} = 1 - \frac{\text{Wind Speed}^2 - \text{Headwind}^2}{\text{Approach Speed}^2}$$

$$\text{Ground Speed} = (\text{Approach Speed} * \text{Crab Factor}) - \text{Headwind}$$

Equation 1. Wind Speed Calculations.

## 2.4.2 Simulation Methodology

This section explains the methodology used by RUNSIM v.2.00 to simulate different operations at airports. Figure 14 shows the work flow used in RUNSIM v.2.00.

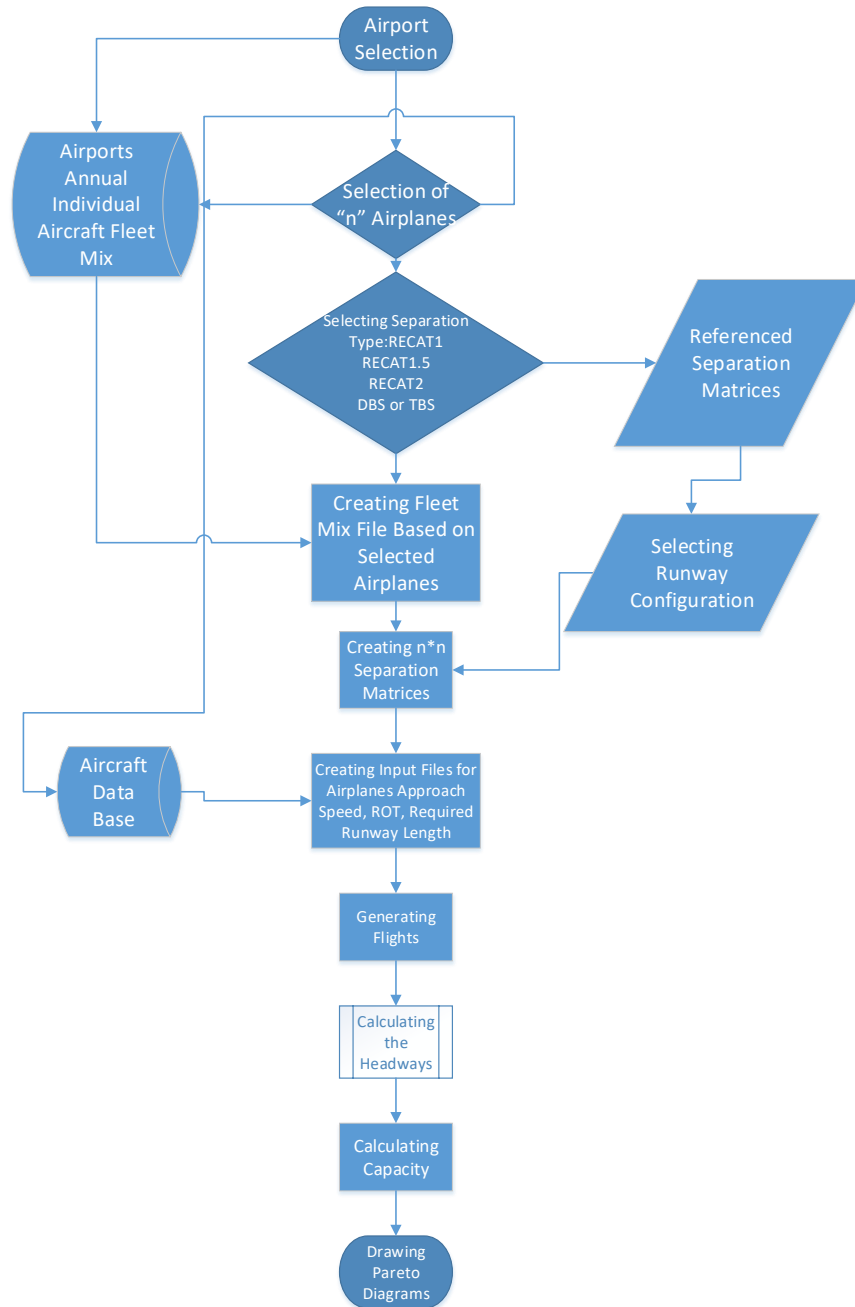


Figure 14. RUNSIM Version 2.00 Work Process Flow Chart.

A database of 193 aircraft is provided to enable the user selecting its desired airplanes from. The database contains aircraft names, legacy wake label, RECAT phase1 label, average and standard deviation of approach speed, average runway occupancy times and standard deviation, and minimum required runway length for landing and take-off.

A list of 250 airports is provided for the user to choose the desired facility from. This list contains the top 250 airports in the NAS. After selecting the airport, a list of all of the aircraft types which operated at that airport during year 2016, is presented to the user. The user has the option to delete or add aircraft in the simulation.

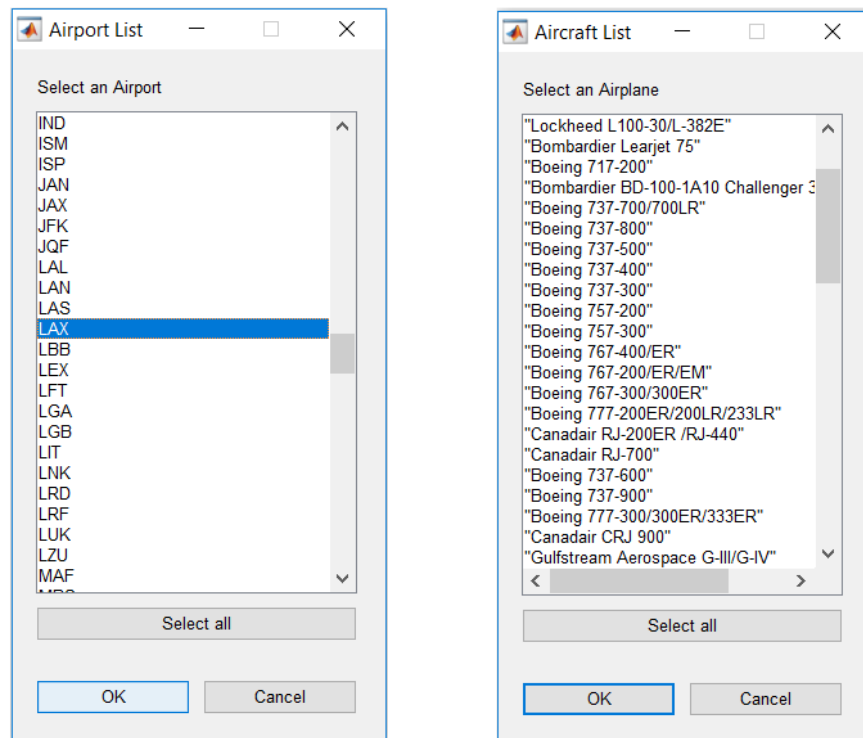


Figure 15. RUNSIM V.2.00 User Interface to Select the Airport and Aircraft in the Simulation.

Figure 15 shows the dialog boxes which let the user to select the airport and airplanes to start the simulation with. RUNSIM v.2.00 model can run airports with various separation scenarios.

Based on the selected separation type, the model creates n-by-n (number of selected aircraft by the user for each airport) separation matrices (for both Arrival-Arrival and Departure-Departure) for different simulation scenarios. Figure 16 shows a sample of a separation matrix with 12 aircraft selected by the user.

Individual\_Separation =

	B190	B737	B738	B735	B734	B733	B752	B753	B772	A343	A345	A388
B190	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
B737	4	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
B738	4	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
B735	4	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
B734	4	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
B733	4	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
B752	4	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
B753	4	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
B772	6	5	5	5	5	5	5	5	3	3	3	2.5
A343	6	5	5	5	5	5	5	5	3	3	3	2.5
A345	6	5	5	5	5	5	5	5	3	3	3	2.5
A388	8	7	7	7	7	7	7	7	4.5	4.5	4.5	2.5

Figure 16. Example of a Separation Matrix for 12 Distinct Aircraft Types, Using the RECAT 1.5 Separation System.

The model uses the created separation matrices among the other simulation parameters to start generating the random flights from each individual group. The required files for each run are as following:

- 1- Arrival-Arrival separation matrix
- 2- Departure-Departure separation matrix
- 3- Runway configuration for arrivals and departures (like: Arrivals 09L)
- 4- Airport runway information (latitude, longitude, heading, length, etc.)
- 5- Fleet mix percentage for each aircraft
- 6- Groups names (which are aircraft names in the new version of the model)
- 7- Selected aircraft approach speeds, runway occupancy times, and required runway lengths

8- Simulation parameters for random number generation and technical ATC rules

The most important difference of running individual aircraft grouping and traditional aircraft grouping (legacy wake categorization or RECAT phase1), is the procedure of generating random flights. For calculating the hourly throughput, the headway between each pair of successful landings is calculated. This headway is calculated from a set of equations which are selected based on the relationship of the following and leading airplanes' approach speeds. Figure 17 shows an example headway for two arriving airplanes in the model.

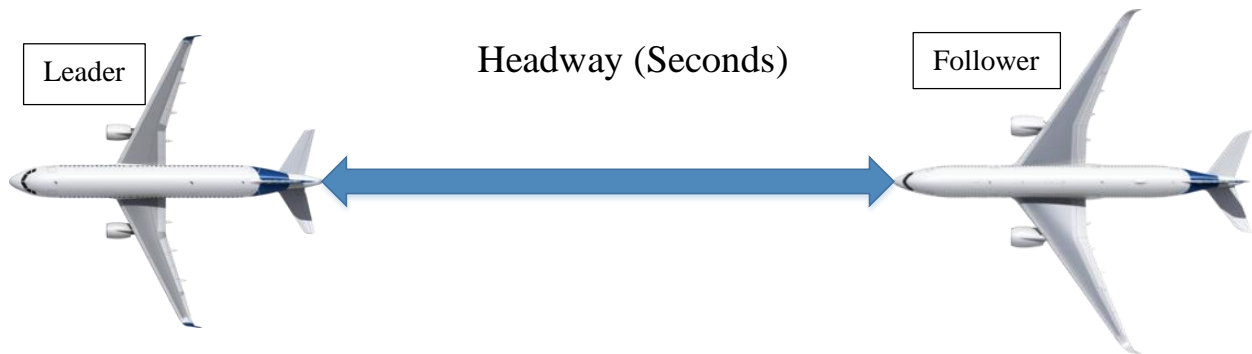


Figure 17. Headway Between the Follower and the Leader Airplanes in Runway Capacity Model.

If the approach speed of the leader is greater or equal than the approach speed of the follower, a condition called as an opening case, the error free headway between the leader and follower is calculated using Equation 2:

$$\text{Error Free Headway} = \frac{\text{Minimum Separation}}{\text{Follower Approach Speed}} + (\text{Common Approach Length}) * \left( \frac{1}{\text{Follower Approach Speed}} - \frac{1}{\text{Leader Approach Speed}} \right)$$

Equation 2. Error Free Headway Between Arrivals for Opening Case.

If the approach speed of the follower is greater than the approach speed of the leader, this condition is called as a closing case, and the error free headway can be calculated from the Equation 3:

$$\text{Error Free Headway} = \frac{\text{Minimum Separation}}{\text{Follower Approach Speed}}$$

Equation 3. Error Free Headway Between Arrivals for Closing Case.

Also a position error buffer is always added to the error free headway to estimate the actual headway between successful arrivals. Most of the times the added buffer for closing case is zero, however the formula that is used for calculating buffer for opening is dependent on the approach speeds of the leader and follower. Therefore, the estimated headway which leads to the final hourly capacity is highly dependent on the approach speeds of the leading and following airplanes. When we run the individual grouping scenarios, the closing and opening cases can vary more often than running for limited traditional wake groups. For example, if we generate 1000 sample flights with legacy wake groups for a busy airport in United States, we can expect from the fleet mix studies that the majority will be airplanes from wake group large or RECAT phase1 group D. Therefore, the most probable pairs of the same groups will be airplanes of group D following each other. Whenever a D-D pair shows up, because the approach speed for the whole group is a unique number, the headway will be calculated as an opening case, however running with multiple individual groups will represent the unique approach speed of each individual airplane for itself and it gives a more realistic simulation of what happens in the real world. Note that using any distribution for the whole legacy wake group or RECAT phase1 group can't produce the desired approach speed for each aircraft inside those groups, since it was

mentioned earlier that each individual aircraft type can have a distribution for its approach speeds itself. Figure 18 clearly shows that within each wake group, the airplanes can show up with various approach speeds.

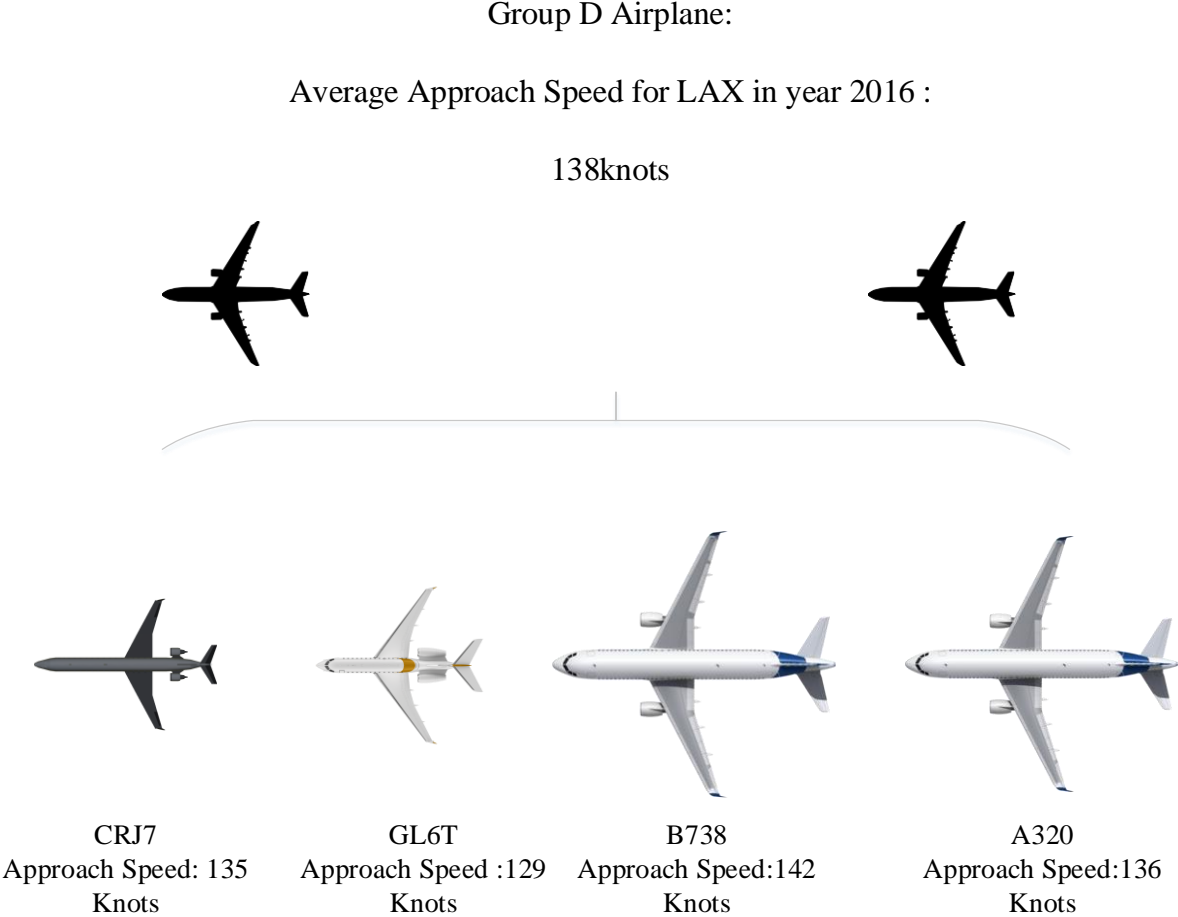


Figure 18. An Example to Show How Different Approach Speeds Occur in the Same Wake or RECAT Group.

Moreover, for the cases that airport authorities run the facility with mix mode operations (both arrivals and departures on one runway), the runway occupancy time will have the same effect.

Therefore, the first benefit of analyzing with individual aircraft grouping is the increased accuracy of the results of the simulation. The important point for running the individual grouping

is to generate more random numbers since the preference is to simulate more groups and the number of groups can exceed to 50 different airplanes for some big airports in United States, therefore modelling for at least 1000 flights is recommended to have a close estimation of airplanes presence at airport to their real fleet mix percentage. Figure 19 represents the differences between running ATL, LAX, and ORD under IMC conditions with RECAT phase 1 separation system in 6 RECAT groups and individual aircraft grouping.

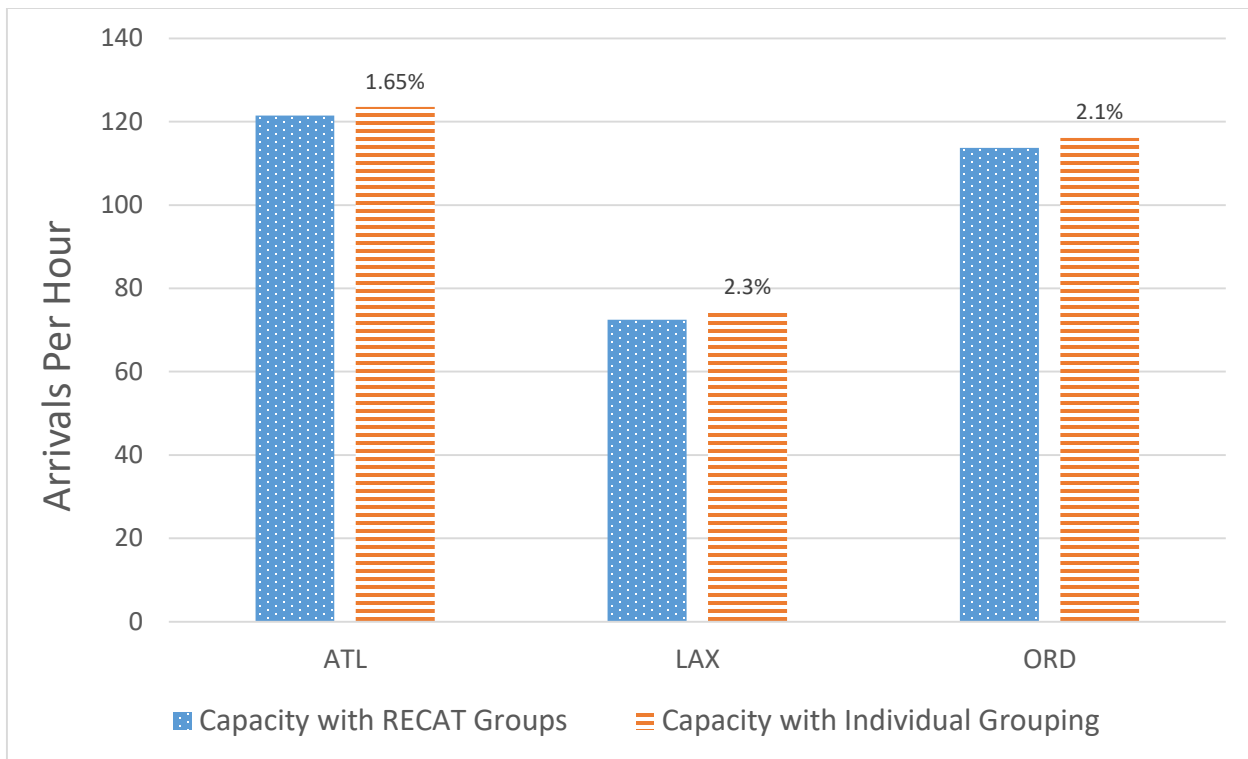


Figure 19. Differences Between Estimated Arrivals Throughput Running 3 Airports of U.S. with RECAT Grouping and Individual Grouping in IMC Conditions.

Differences in simulation results shown in Figure 19 are relatively mild, however this figure shows that even running with the same separation criteria, the estimated maximum number of arrivals at each facility would be different if a different grouping method would be selected.



### 2.4.2.1 (123\*123) Individual Separation Matrix

The individual separation matrix released by FAA for 123 different aircraft types, has separation values which are believed to be safe and optimum between each pair of airplanes. In the wake behavior study done by FAA, some of the separation cells are announced as they are not factored by wake vortex forces generated by the leader airplane. This means that the separation between those pairs is not implemented by considering the wake vortex effect, therefore there should be another parameter to be used for defining the separation between those pairs.

The most reasonable parameter for defining the separation between arrival airplanes is their runway occupancy time. If there would be a separation cell in the individual separation matrix which doesn't have a specific value assigned, it can be inferred that the runway occupancy time of the leader airplane can be used as a separation reference time for the controllers. The reason which makes the mentioned point valid, is that runways can't be occupied by two operating airplanes simultaneously, therefore the controller should let the leader airplane vacate the runway and then let the follower airplane to land.

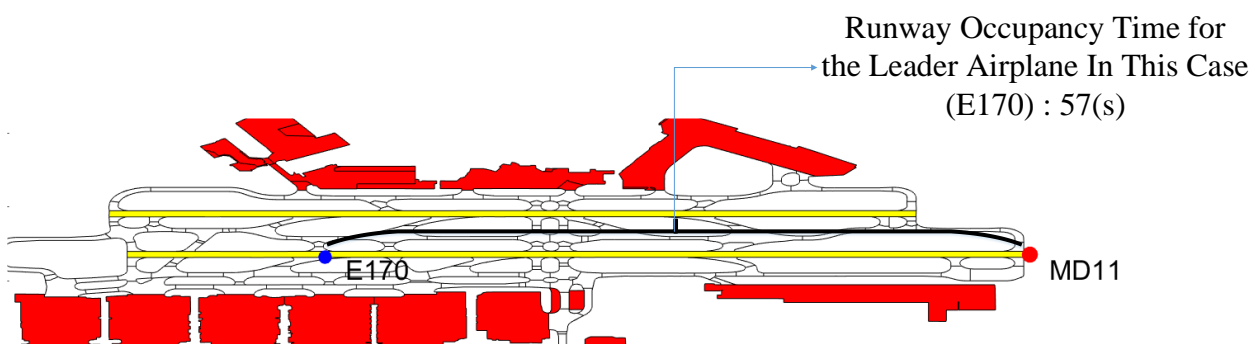


Figure 20. Example of an Arrival Pair Which Doesn't Have a Specific Separation Value in FAA RECAT 123\*123 Matrix.

Figure 20 shows a real arrival pair happened on runway 26L at ATL airport on 2015-07-16. In this case a MD11 is following an E170 to arrive at runway 26L, however based on the FAA individual separation matrix for RECAT phase2, the separation between those airplanes would be zero the wake vortex effect of Embraer E170 doesn't have significant effect on the McDonnell Douglas MD11 flying path. This means that air traffic controllers can separate those vehicles as close as they desire, however it is unsafe and against the FAA operation rules to have two operating airplanes operating on a runway simultaneously. Therefore, the earliest time for the MD11 as it is shown in Figure 20 to arrive at runway threshold, is the time that E170 has already vacated the runway. This time profile shows the fact that in such situations the runway occupancy time of the leader airplane should be applied as the separation between arrival planes. This process is programmed in RUNSIM model v.2.00 and is used for not only the cases that the separation matrix doesn't refer to a specific separation value, but also in those cases that the runway occupancy time for the arrival would be larger than the converted separation value in the matrix.

#### *2.4.2.2 Time Based Separation*

In Figure 12, the time based separation matrix which is used at London Heathrow airport is shown. This new capability is added to the computer model to estimate the capacity of United States' airports under heavy headwind conditions with time based separation method. For running an airport with time based separation, the user will choose whatever airplane(s) that he/she desires to choose from the flying list of airplanes at the selected airports or the general list of airplanes provided in the model. Then, the model will create the separation matrices based on the

referenced time based separation matrix which is shown in Figure 12. Figure 21 shows a created sample of time based separation matrix by the model for 18 selected different airplanes.

Individual\_Separation =

	BE18	B738	B753	B764	B772	CRJ7	B773	CRJ9	MD82	E145	E190	B77L	A333	A319	FA7X	B744	A346	B789
BE18	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70
B738	113	70	70	70	70	68	70	68	70	68	70	70	70	70	68	70	70	70
B753	113	70	70	70	70	68	70	68	70	68	70	70	70	70	68	70	70	70
B764	135	90	90	68	70	90	70	90	90	90	90	70	70	90	90	70	70	70
B772	158	113	113	113	90	135	90	135	113	135	113	90	90	113	135	90	90	90
CRJ7	90	70	70	70	70	68	70	68	70	68	70	70	70	70	68	70	70	70
B773	158	113	113	113	90	135	90	135	113	135	113	90	90	113	135	90	90	90
CRJ9	90	70	70	70	70	68	70	68	70	68	70	70	70	70	68	70	70	70
MD82	113	70	70	70	70	68	70	68	70	68	70	70	70	70	68	70	70	70
E145	90	70	70	70	70	68	70	68	70	68	70	70	70	70	68	70	70	70
E190	113	70	70	70	70	68	70	68	70	68	70	70	70	70	68	70	70	70
B77L	158	113	113	113	90	135	90	135	113	135	113	90	90	113	135	90	90	90
A333	158	113	113	113	90	135	90	135	113	135	113	90	90	113	135	90	90	90
A319	113	70	70	70	70	68	70	68	70	68	70	70	70	70	68	70	70	70
FA7X	90	70	70	70	70	68	70	68	70	68	70	70	70	70	68	70	70	70
B744	158	113	113	113	90	135	90	135	113	135	113	90	90	113	135	90	90	90
A346	158	113	113	113	90	135	90	135	113	135	113	90	90	113	135	90	90	90
B789	158	113	113	113	90	135	90	135	113	135	113	90	90	113	135	90	90	90

Figure 21. Example of Time Based Separation Matrix for 18 Airplanes at ORD Airport Created by Model.

After the separation matrices are created by the model, at least 1000 flights are generated by the model (the number of random flights can vary) and the actual headway between each of the arrival pairs will be calculated using the values of the generated time based separation matrix cells. The point about the headway under time based method is that the model doesn't have to convert it to seconds by dividing the separation value to the approach speed of the follower airplane because the separation cells themselves are in the second scale. Therefore, the only equation that the approach speed may play a role would be the buffer error for opening cases. Since many times the buffer is equal to zero, basically the influence of approach speeds in time

based separation is dismissible. This means that for simulation models whatever value of wind used in running the simulation wouldn't change the maximum hourly throughput under time based separation system drastically. In the real world controllers estimate the proper approach speed which the airplanes need for having the required separation in time scale, and ask the pilots to fly with the calculated approach speeds. This process is done with computer systems entirely (28).

### 2.4.3 GUI

RUNSIM model v.1.00 was packaged and compiled as a standalone application in order to be ran on every computer. The source code is written in MATLAB and for compiling Visual Studio was used to make a user interface window in order to simplify working with the runway simulation model.

The upgraded version which is version 2.00 and is capable of running individual aircraft types, running RECAT phase2 123\*123 FAA separation, running RECAT phase1.5, and time based separation scenarios is added to the previous interface. Therefore, the old functions of the model are still accessible through GUI, but the new features have been added in order to be used by FAA Operation and Wake Offices.

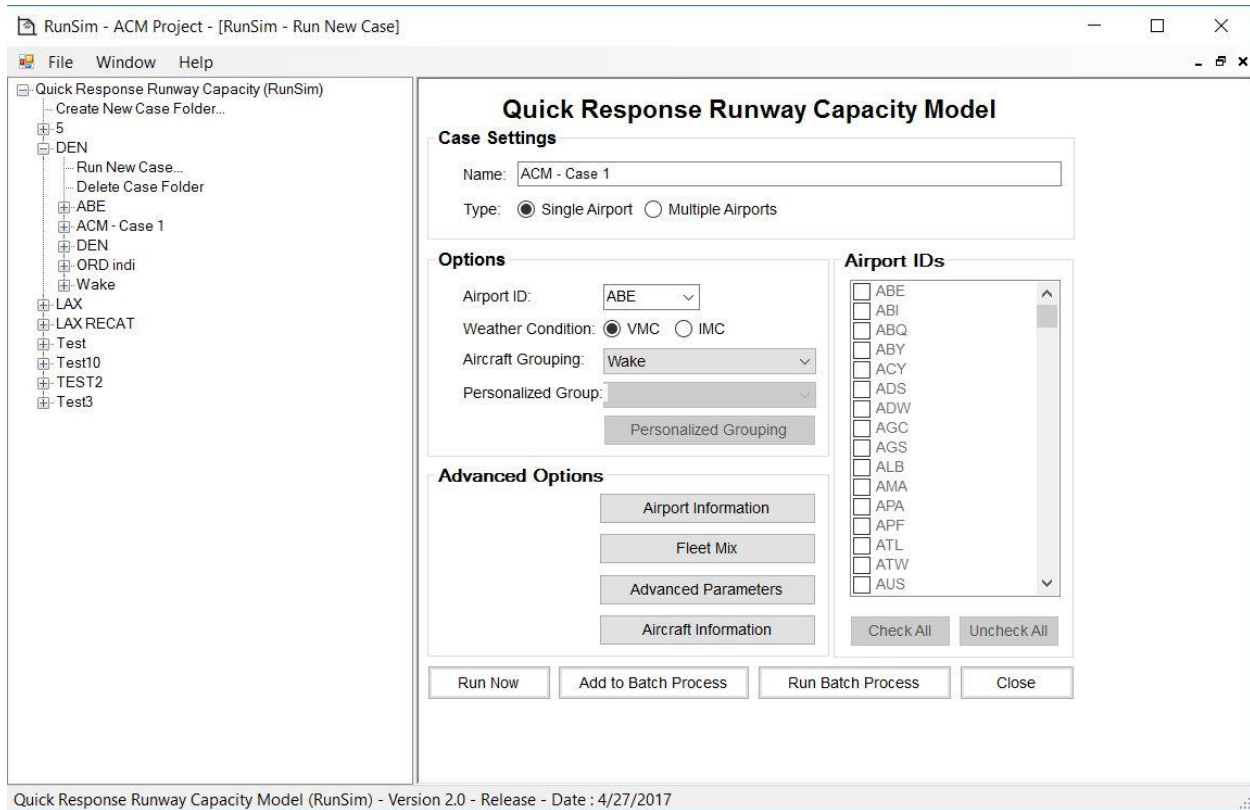


Figure 22. The Main Window of RUNSIM Model Version 2.00.

As it is shown in Figure 22, the user interface includes options for selecting airport(s), desired visual range conditions (IMC or VMC), Simulation type (different separation scenarios), and advanced options. The model has the capability of running batch mode for multiple airports with various simulation parameters. Each scenario has an input directory which includes the input data for airplanes and the separation matrices, and an output directory which the user can define after opening a new case. The results of the model are Pareto diagrams which show the maximum number of arrivals and departures and mixed operations for the facility. Figure 23, Figure 24, Figure 25, and Figure 26 show the other windows from the user interface version of the model.

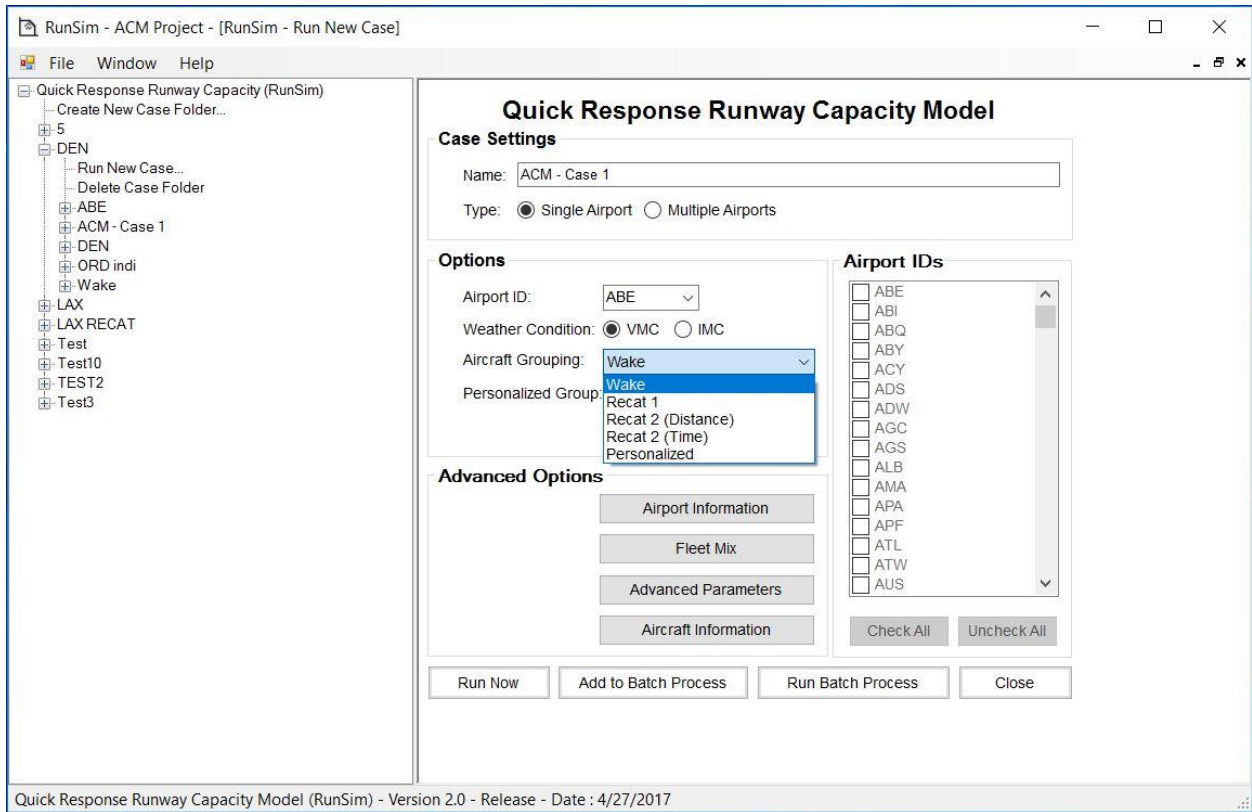


Figure 23. Different Running Options for Individual Aircraft Grouping Which is Added to the Model Recently.

	Mean Arrival ROT (s)	St.Dev Arrival ROT (s)	Approach Speed (knots)	Mean Dept ROT (s)	St. Dev Dept ROT (s)	Minimum Arrival Runway Length (ft.)	Minimum Dept Runway Length (ft.)
A346	78.921	13.654	153	78.921	13.654	6200	7200
A345	56.65	12.46	146	56.65	12.46	6200	7200
B773	55.838	12	145	55.838	12	6400	6700
B772	65	7.2	145	65	7.2	5900	6800
A343	57.377	9.0771	138	57.377	9.0771	5600	6200
A333	70	10.5	150	70	10.5	6400	6400
A332	70	10.5	150	70	10.5	6400	6400

Figure 24. Each Individual Aircraft Has Multiple Simulation Variables Which is Provided in Model.

Advanced Parameters

Minimum Separation Rules

IMC Conditions

Parallel Dependent Departures (ft)

Parallel Dependent Arrivals (ft)

Parallel Independent Arrivals (ft)

Parallel Stagger Rule (ft)

Parallel Independent Arr-Dept (ft)

3 Parallel Independent Arrivals (1000 ft. altitude)

3 Parallel Independent Arrivals (5000 ft. altitude)

4 Parallel Independent Arrivals (ft)

VMC Conditions

Parallel Independent Arrivals (ft)

Parallel Independent Arrivals (Legacy Groups V-VI) (ft)

Crossing Path Dependency Rule (nm)

Minimum Diagonal Distance Parallel (nm)

Minimum Intersect Arrival (nm)

Minimum Arrival-Departure Separation (nm)

Minimum Arr-Dept Close Parallel Separation (nm)

Minimum Separation Arr-Arr Table (nm):

Lead\Follower	A388	B748	B77L	B744	A346	A345	B773
A388	2.25	3.06	3.51	3.42	3.51	3.51	3.78
B748	1.8	1.8	1.8	1.8	1.8	1.8	2.07
B77L	1.8	1.8	1.8	1.8	1.8	1.8	1.8
B744	1.8	1.8	1.8	1.8	1.8	1.98	2.16
A346	1.8	1.8	1.89	1.8	1.89	2.07	2.25
A345	1.8	1.8	1.8	1.8	1.8	1.8	1.98
B773	1.8	1.8	1.8	1.8	1.8	1.8	1.8

Minimum Separation Dept-Dept Table (sec):

Lead\Follower	A388	B748	B77L	B744	A346	A345	B773
A388	54	162	162	162	162	162	162
B748	54	108	108	108	108	108	108
B77L	54	108	108	108	108	108	108
B744	54	108	108	108	108	108	108
A346	54	108	108	108	108	108	108
A345	54	108	108	108	108	108	108
B773	54	108	108	108	108	108	108

Mean Dept-Dept Time (s)

St. Dev. Dept-Dept Time (s)

Mean Exit Time (s)

St. Dev. Exit Time (s)

Common Approach Distance (nm)

Arrival Position Violation (s)

Cumulative Normal

Cumulative Normal - Parallel

Arr-Arr Pareto Points Multiplier

Model Run Parameters

Random Flights Simulated

No. of Iterations

Refinement Level

Default Values Done

Figure 25. Advanced Parameters Window Which Has the Individual Separation Matrices Based on Flying Airplanes at the Facility.

Wake Group	Operations (%)
B748	0.55
B77L	0.17
B744	0.72
A346	0.08
A345	0.03
B773	0.97
B772	1.55
A343	0.00
A333	0.12
A332	0.72
B789	0.00
B788	0.59
B742	0.01
MD11	0.19
B764	0.01
DC10	0.35
B763	1.32
B762	0.10
A306	0.20
A30B	0.03
B753	0.95
B752	0.59
A321	2.37
B739	5.73

Figure 26. Aircraft Fleet Mix Editor Window.

In the MATLAB source code of the model, there are dialog boxes which enable the user to pick whatever airplanes it desires to run the simulation for. There are two airplane databases which are used for this purpose.

1. The T100 segment aircraft database which is released by the Statistical Office of Department of Transportation.



2. The FAA airplane database which contains 123 aircraft types.

However, in the compiled version of code the list of airplanes which would be shown after selecting any airport are the ones from the T100 database that exist in the FAA database. This modification was done as not all the reported airplanes in T100 database are flying regularly at airports, therefore their effect on the facility fleet mix is negligible. Basically the user can put zero for the undesired airplanes' fleet mixes in order to remove them from the list of simulated planes. Figure 27 represents an example of ORD runway layout with assigned operations to each runway.

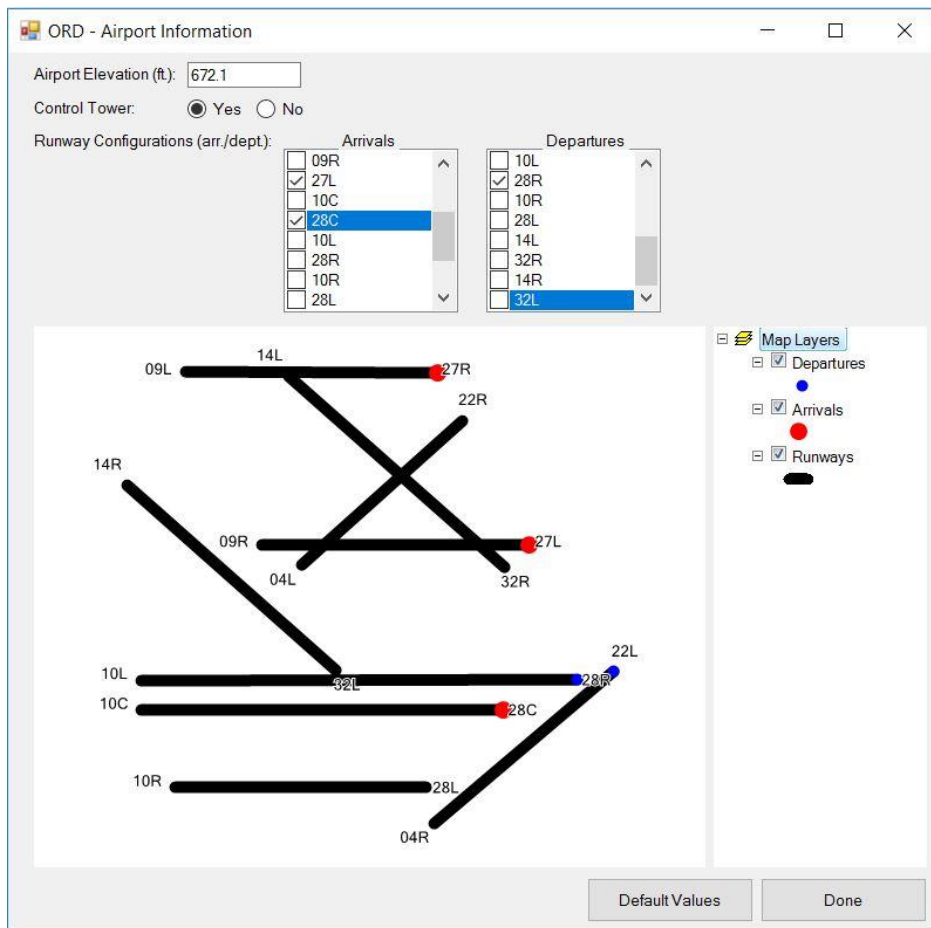


Figure 27. Sample of ORD Airport Geometric Layout and the Arrival/ Departure Runways which can be Studied.

## 2.4.4 Case Studies

This section reviews the most important capacity analyses which were done as deliverables of this study. The focus was basically on running different airports with different separation scenarios, however a few studies were done for various environmental conditions like wind (headwind and crosswind), and a few on more detailed simulation parameters like reduced separations or hourly fleet mix. Table 10 shows the scenarios that were studied on different airports.

Table 10. Different Scenarios Studied for Different Airports.

Airports \ Scenarios	ATL	ORD	LAX	CLT	DCA	DEN	LGA	BOS	JFK
Wake Grouping	✓	✓	✓	✓	✓	✓	✓	✓	✓
RECAT 1	✓	✓	✓	✓	✓	✓	✓	✓	✓
RECAT 1.5	✓	✓	✓	✓	✓	✓	✓	✓	✓
RECAT 2 (123*123 with zeros)	✓	✓	✓	✓	✓	✓	✓	✓	✓
RECAT 2 (123*123 with MRS <sup>1</sup> )	✓	✓	✓	✓	✓	✓	✓	✓	✓
Time Based Separation	✓	✓	✓	✓				✓	
With Head Wind	✓	✓	✓	✓				✓	
Hourly Fleet Mix Analysis			✓						

<sup>1</sup> MRS: Minimum Radar Separation of 2 nautical miles

Figure 28 shows the runway configurations for 8 studied airports which were used for completing different scenarios. Because the purpose of study was to extract the entire capacity profiles, all the airports were analyzed with the runway configuration which is heavily used at each facility based on the meteorological conditions.

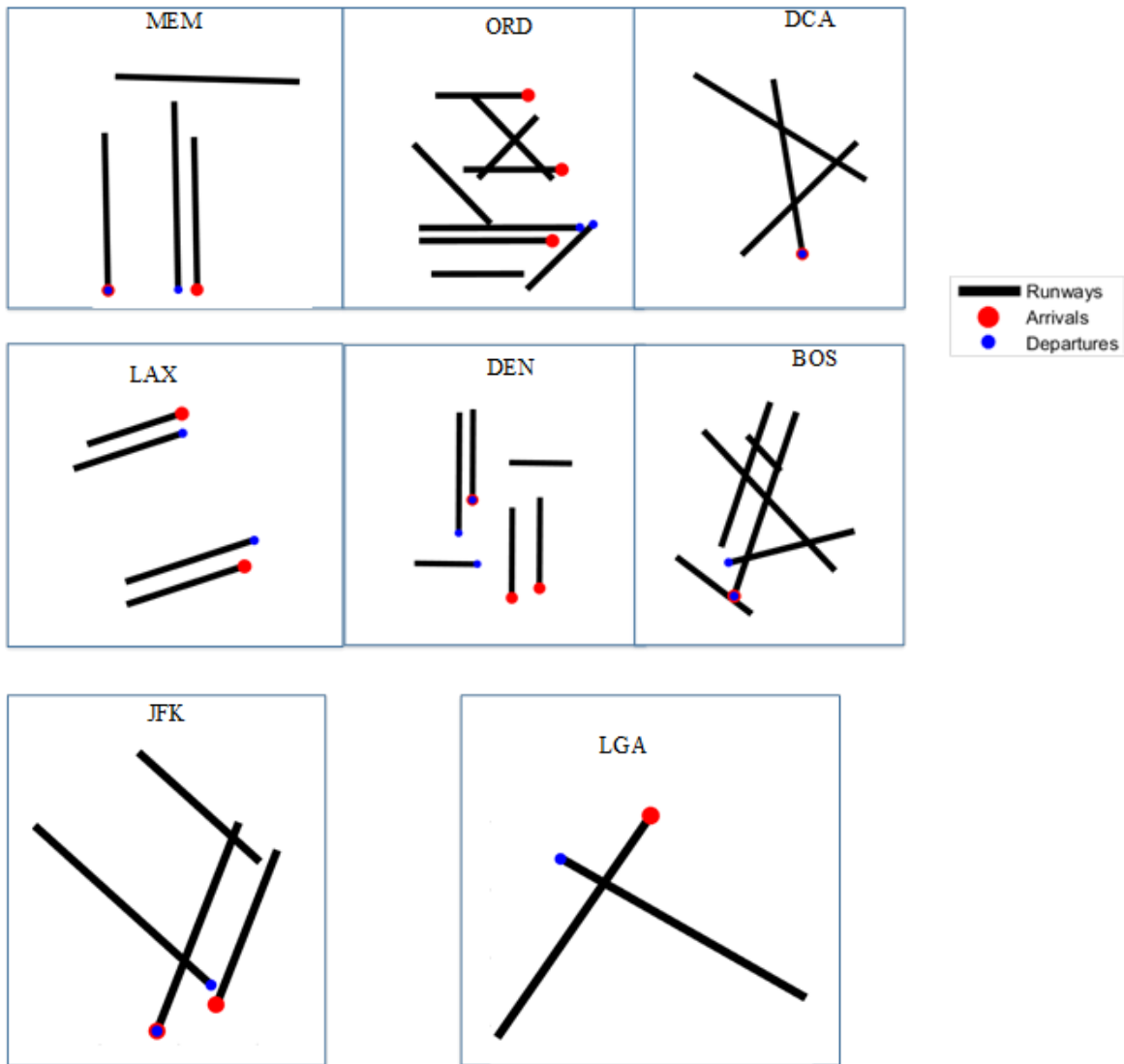


Figure 28. First Group of Studied Airports' Runway Configurations.

Initially a study over the differences between the capacities of top busy airports in United States under three different separation scenarios was done. The first separation scenarios studied for this purpose are: 1- Legacy grouping (wake categorization), 2- RECAT phase1 categorization, and 3-RECAT phase1.5 categorization.

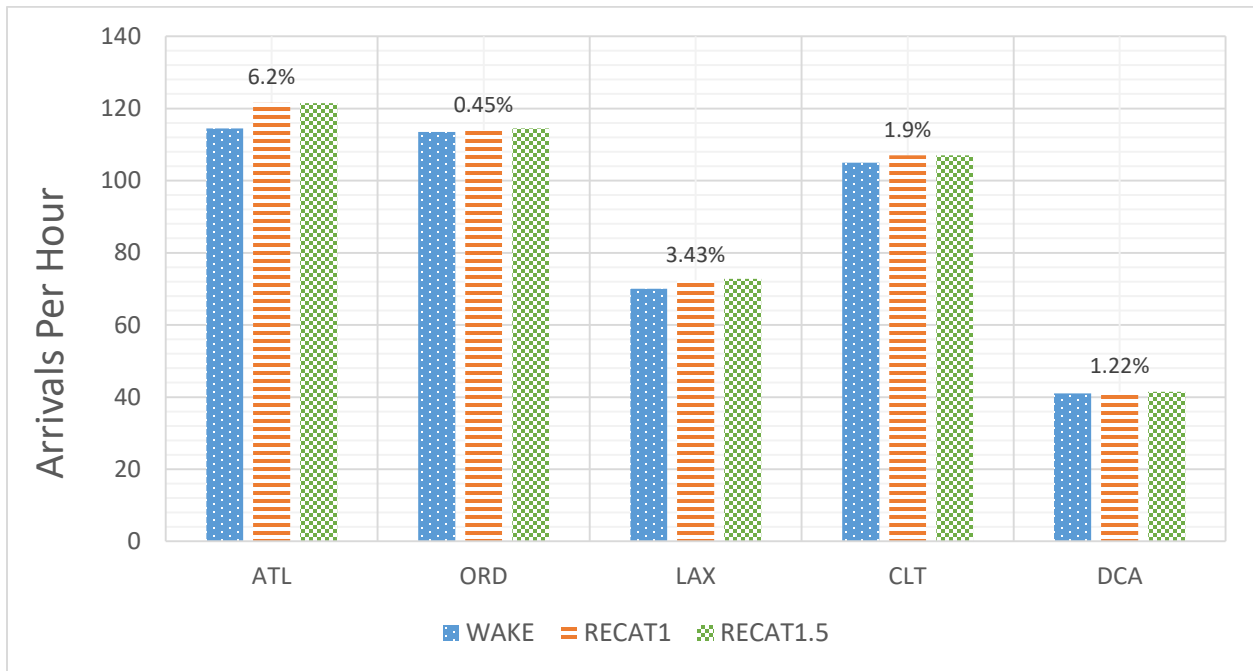


Figure 29. Different Airports Maximum Arrival Capacity Under Different Separation Groupings in IMC Conditions.

Figure 29 shows the estimated maximum arrival capacity for each of the mentioned airports under three different separation scenarios. These numbers are the first points which are drawn in every Pareto Diagram that the model produces. Many times the Pareto Diagrams are drawn with 5 points. Considering the maximum arrivals capacity, is beneficial for the times that there are independent arrival runways in the airport or there is no scheduled departure at the facility and controllers can focus on the arrival stream. These conditions happen rarely and expect couple of big airports around the country, the others have dependent arrival runways with departure

runways or air traffic controllers use runways in mix operation mode that handle both arrivals and departures. Therefore, not only the number of the runways, but also the runway configuration, dependency of operations on each other, and fleet mix percentages are among all the variables that have direct effect on each airports' capacity.

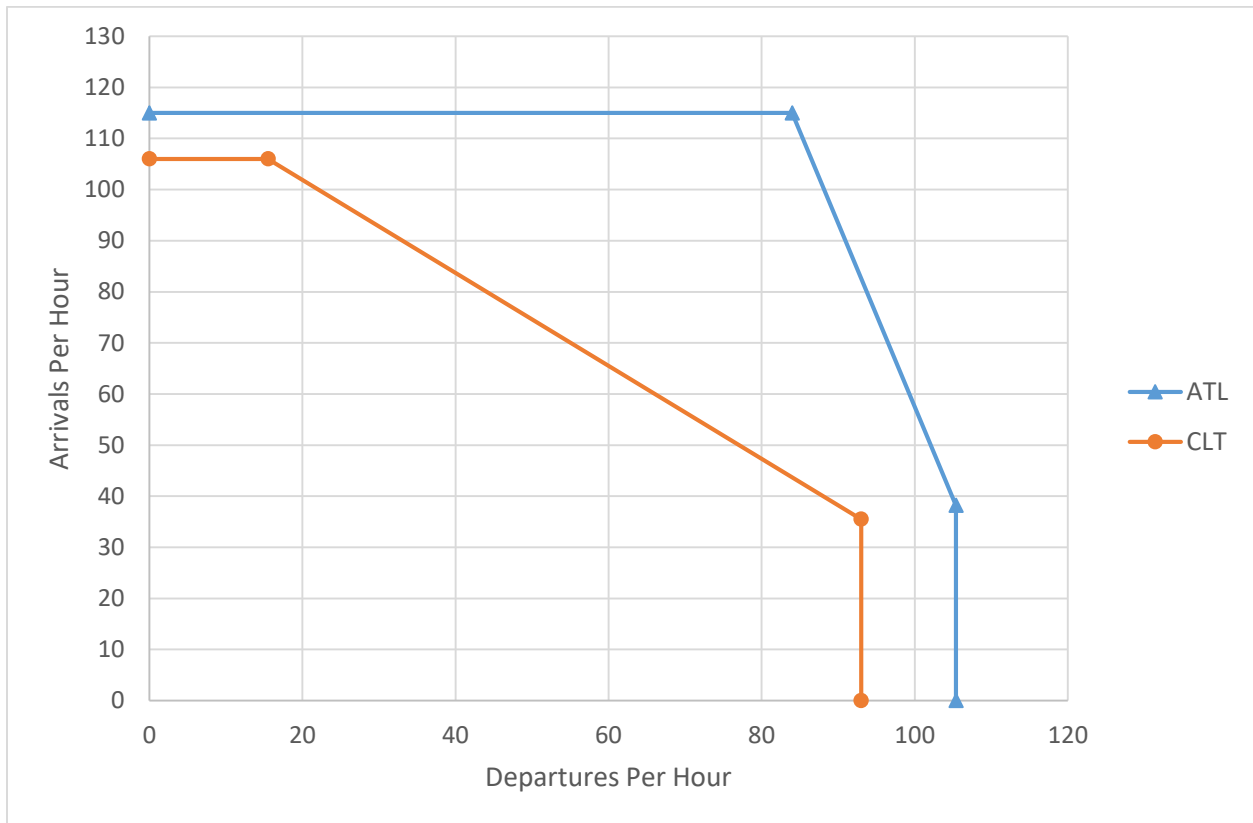


Figure 30. An Example Two Airports with Three Arrival Runways but Different Capacity Diagrams, ATL and CLT Pareto Diagrams Under IMC Conditions and Legacy Separation.

Figure 30 represents the capacity diagrams for Atlanta airport and Charlotte airport. As it is obvious although both facilities assign arrivals to three runways, ATL has a bigger covered area under its Pareto Diagram boundaries. The reason for this considerable difference between those facilities capacity rates, is that the runway configurations are different. ATL has three parallel independent arrival runways which are operating in segregated mode which mean only one type

of operation (which is arrivals) is assigned to them. However, CLT uses the two of the parallel runways in mixed operations mode (both arrivals and departures). Under mix mode operation the controllers assign departure flights between each arrival gaps which meet the departure separation criteria. This means that, when the airport is running operations with 100% priority on arrivals the hourly throughput might be close to ATL arrivals throughput, however by enlarging the arrivals gaps, the arrival capacity will reduce and this causes a steep drop in Pareto Diagram. Figure 31 shows the runway configurations of ATL and CLT.

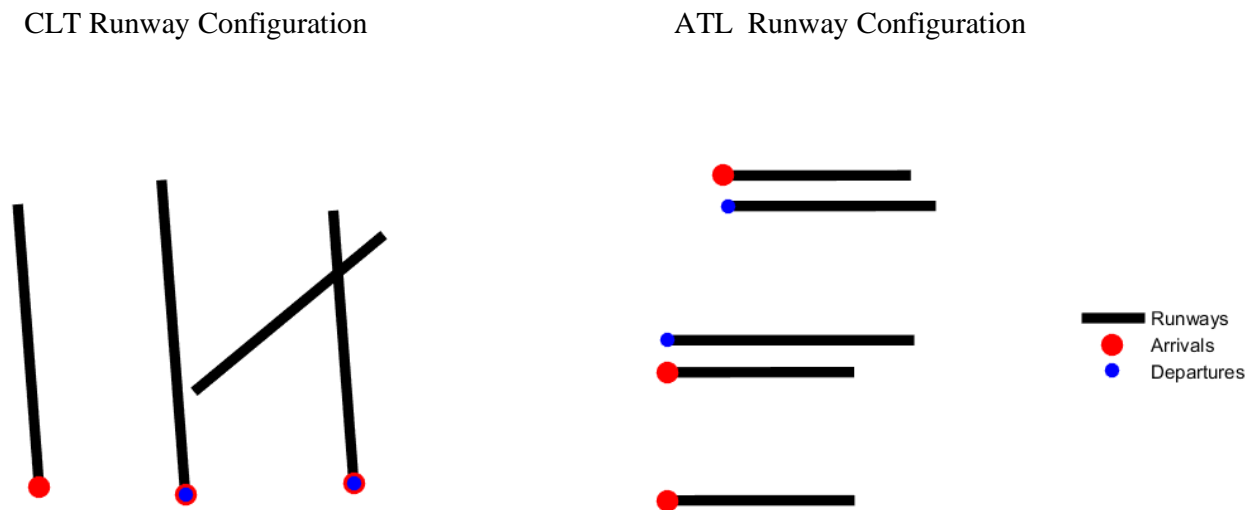


Figure 31. CLT and ATL Runway Configurations Used for Producing Results Shown in Figure 30.

The other point from Figure 30, is the difference between capacities under traditional legacy separations and RECAT1 (or RECAT1.5) separation systems. The gain in using each system is highly dependent on the fleet mix at each airport. For example, the gain in ATL is around 6% which is approximately 7 arrivals per hour. This beneficial rate is around 3% for LAX which is

around 3 arrivals per hour. Therefore, it is understandable that changing from the wake separation to RECAT can be beneficial.

The highest gain in changing from legacy system to RECAT phase1, happened in Memphis International airport. This airport has a unique fleet mix with more than 50% of heavy planes and 15% of Boeing 757s, as the facility is heavily used by cargo and post airplanes.

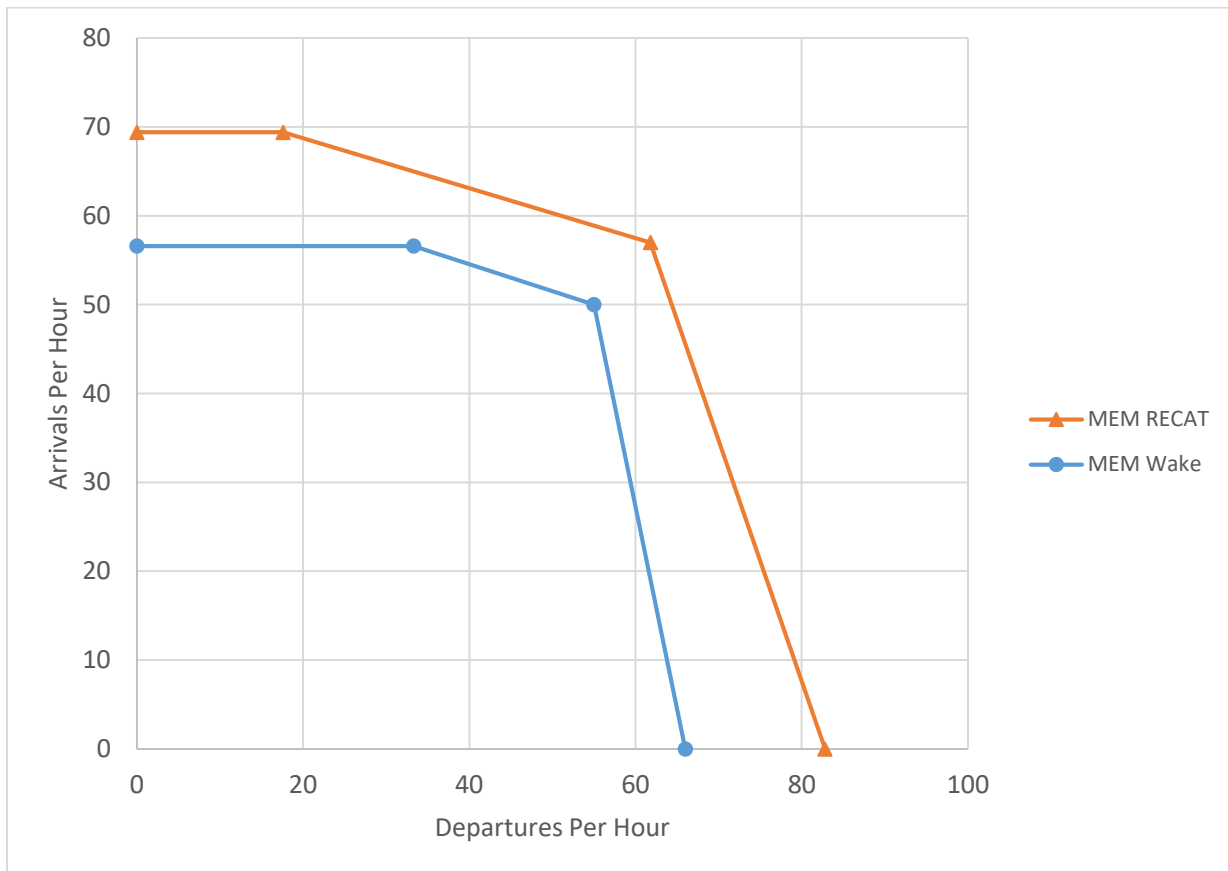


Figure 32. MEM Capacity Diagrams Under Two Different Separation Systems and IMC Conditions.

As it is shown in Figure 32 the maximum arrival throughput in Memphis airport increased 20% when the separation regulation changed from the traditional legacy system to the RECAT phase1 system.

The main focus of this study is to compare the results of the simulation model for individual grouping scenarios and different separation matrices which are recently released by FAA.

The first major study was done to review the capacity gain for top busy airports with individual aircraft grouping instead of running with known wake categories. For this purpose, the big separation matrix expanded from the 7\*7 RECAT phase1 separation matrix for 193 airplane types gathered in the aircraft database was used as the baseline for each scenario.

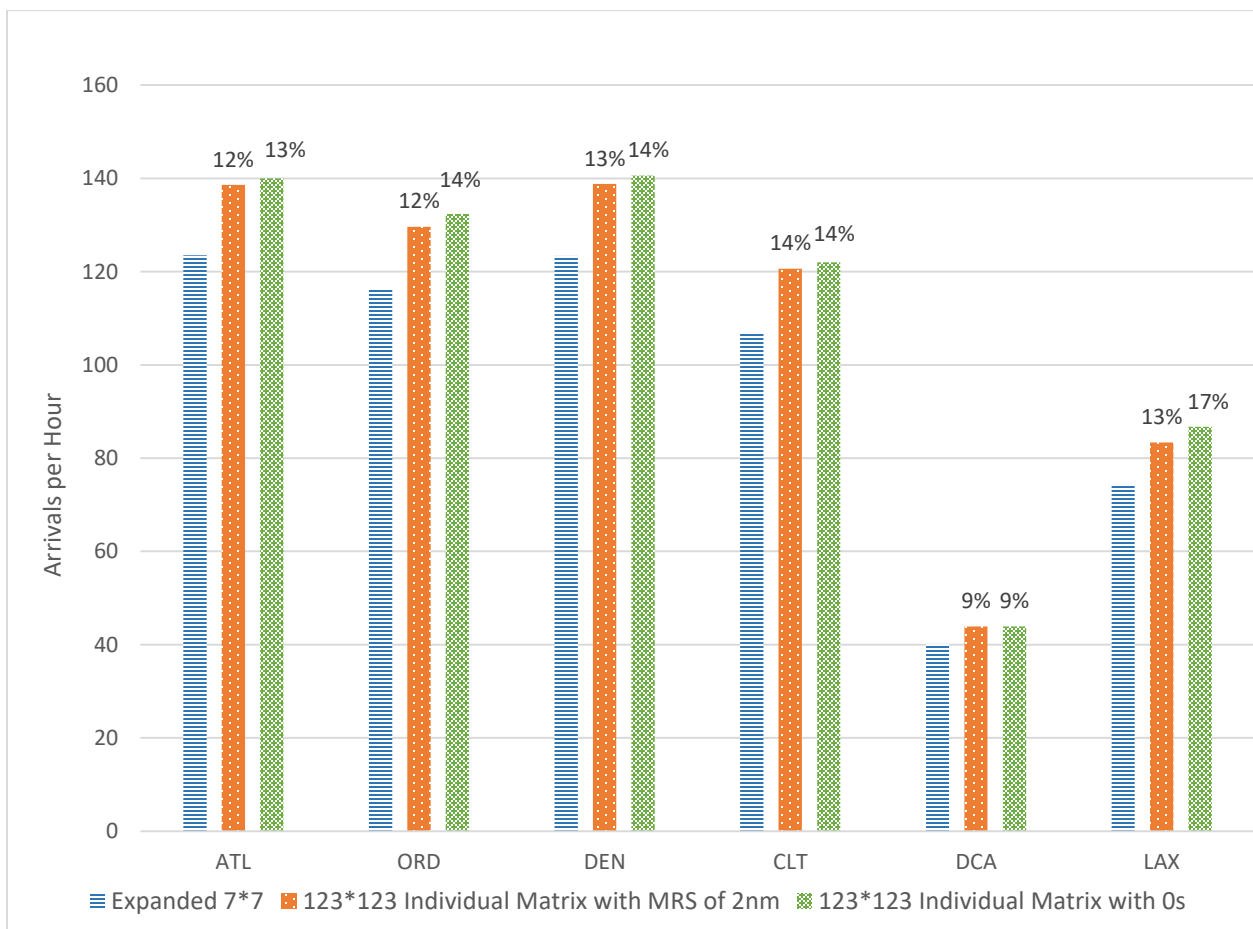


Figure 33. Maximum Arrival Capacity Under Three Individual Separation Scenarios.



Figure 33 shows a great capacity benefit for all of the studied facilities with RECAT phase2 separation matrix or 123\*123 Individual separation matrix. Most of the airports gained 10% more arrivals compare to the individual expanded RECAT phase1 separation. Since many cells in the RECAT phase2 matrix were zeros and they meant to be cells which are not defined based on the wake vortex forces of the leader airplane and the simulation model uses the runway occupancy time of the leader airplane, the safety of those values for separating 32% of the pairs inside the 123\*123 matrix wasn't clear to the research team. Then as a hypothetical scenario, all of the separation cells with zeros were replaced by the minimum radar separation in the RECAT phase2 system which is 2 nautical miles. The gain between the RECAT2 matrix analysis with zeros or with minimum radar separation of 2 nautical miles doesn't exceed 4% (which is for LAX case), which shows us that many times the estimated runway occupancy time for the leader airplane is almost equivalent to a distance of 2 nautical miles between the leader and the follower, however the approach speed of both leader and follower planes can change the situation and get them closer to each other.

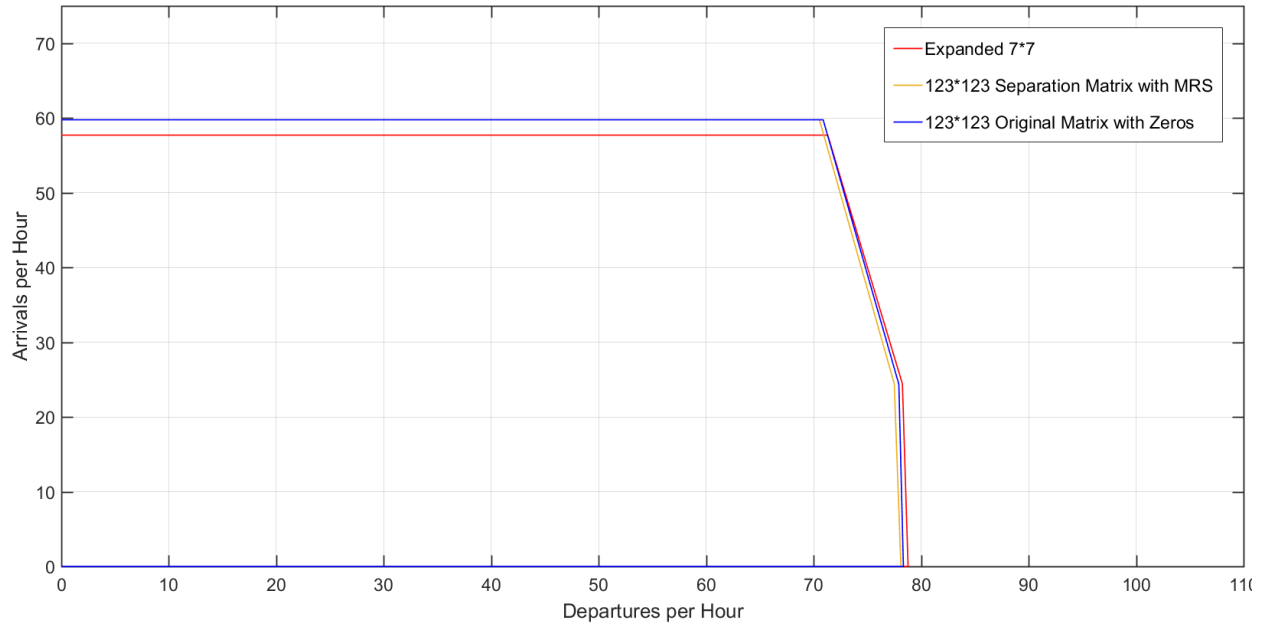


Figure 34. John F. Kennedy Capacity Profiles with Three Different Individual Separation Scenarios Under IMC Conditions.

Figure 34 shows the capacity analysis on JFK with three different individual separation scenarios. The capacity gained at this airport from changing to the RECAT phase2 system is approximately 4% which is the lowest among all the studied airports. After reviewing the fleet mix at JFK and the separation cells in 123\*123 FAA RECAT phase2 separation matrix, it makes sense that there shouldn't be an expectation of big capacity gain at JFK for changing separation systems, because this airport has a high number of heavy and super heavy airplanes in its annual fleet (1.5% super heavy and 25% heavy), the impact of the recent separation matrix on the airport arrivals capacity wouldn't be considerable. This result is predictable for every airport which has a high percentage of heavy and super heavy fleet, as a few separation cells in the RECAT phase2 matrix for airplane classes A, B, and C has considerable changes from the expanded RECAT phase1 matrix. Therefore, a considerable capacity change would be expected

for airports with many regional jets or narrow-body commercial planes. This can be inferred from Figure 33, that airports like ORD and ATL with many regional jets in their annual fleet will gain 12% benefit from changing the separation system to the RECAT phase2 individual matrix.

Earlier the effects of choosing different runway configurations on the final throughput of the airports were discussed. Another area of interest is airports with single runway or just one runway used for arrivals. The purpose is to see what will be the impact of using various separation scenarios on single arrival runway airports' capacities. Among the top 30 busiest airports in the United States with just one arrival runway under IMC conditions, SAN, LGA, and DCA are chosen for this capacity comparison study. San Diego (SAN) airport is the only one among the mentioned airports which has only one runway. The other two have 2 and 3 runways sequentially.

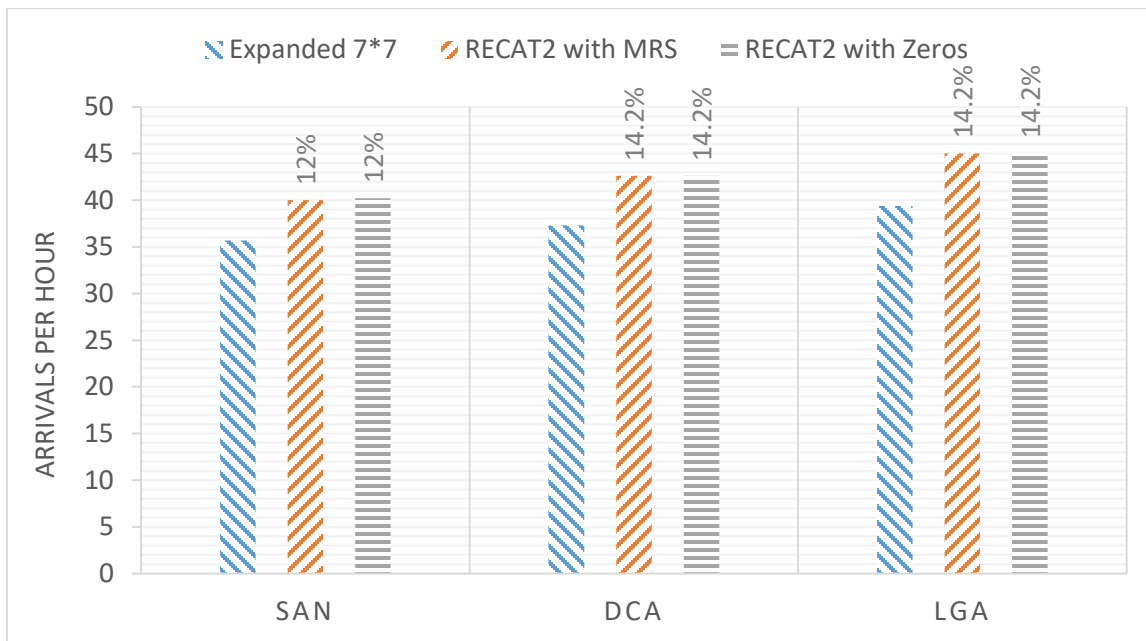


Figure 35. Arrivals Throughput for Studied Airports with One Arrival Runway Under IMC Conditions.

Figure 35 depicts that fact that even using one runway at studied airports, the capacities under various separation scenarios can be different. This difference in capacity or in the gain from changing to RECAT phase2 system is highly dependent on each facility's fleet mix and the intensity of arrival runway dependency on the departure runway.

The final airport which is studied to review the potential capacity gains after changing to RECAT phase2 separation system is Memphis International Airport. This airport gained 20% more operations from changing to RECAT phase1 system, therefore it would be interesting to analyze the capacity changes for a switch to RECAT phase2 system.

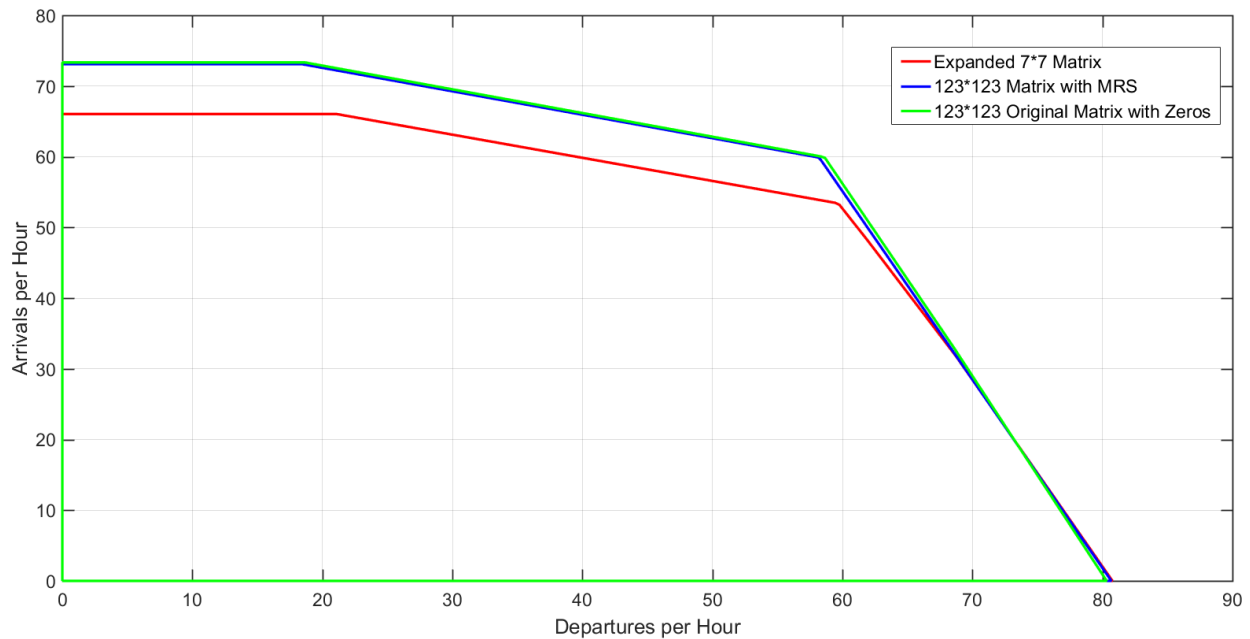


Figure 36. MEM Arrival Throughput with Three Different Individual Separation Systems Under IMC Conditions.

Figure 36 depicts the potential capacity gain for Memphis International Airport with RECAT phase2 individual separation matrix. The capacity improvement is not similar to the time that the airport migrated from the legacy system to RECAT phase1, moreover in compare to other big

airports in U.S. which have higher number of regional jets, this airport will probably gain fewer arrivals per hour. However, there are still 7 more arrivals (compare to expanded RECAT phase1) or 4 more arrivals (compare to RECAT grouping with just 6 groups), therefore there is still a potential growth in the number of arrivals. The gain for this airport after changing from RECAT phase 1 to RECAT phase2 matrix is around 11%.

One important factor in analyzing the airports' capacities, is their fleet mix. Most of the times the fleet mix used for simulating the operations at airports is based on their annual operations. Therefore, the whole number of each planes' operations during the year at the desired facility would be studied, and then based on the preferences of the user the fleet mix would be reported in traditional legacy and RECAT groups or in individual aircraft list. Meanwhile, we should pay enough attention to the changes of fleet mix in each time period. The changes in fleet mix pattern, are not considerably versatile through seasons or months. Even after reviewing the list of airplanes and airlines operating at big airports, it was noticed that the patterns of flight schedules are very similar on each day. However, the fleet percentages vary considerably during each day at different periods of time. Many big airports host heavy and super heavy planes during the early hours of the day for handling the cargo or international flights. Then during the middle of the day this fleet changes to narrow body airplanes or regional jets to meet the domestic demand at the facility. Therefore, it would be interesting to study the impact of hourly fleet mix change on airports' capacity profiles. For this purpose, the flights' schedule of Los Angeles airport during the third week of July of year 2015, were analyzed to study the changes in airports' capacities at different periods of time.

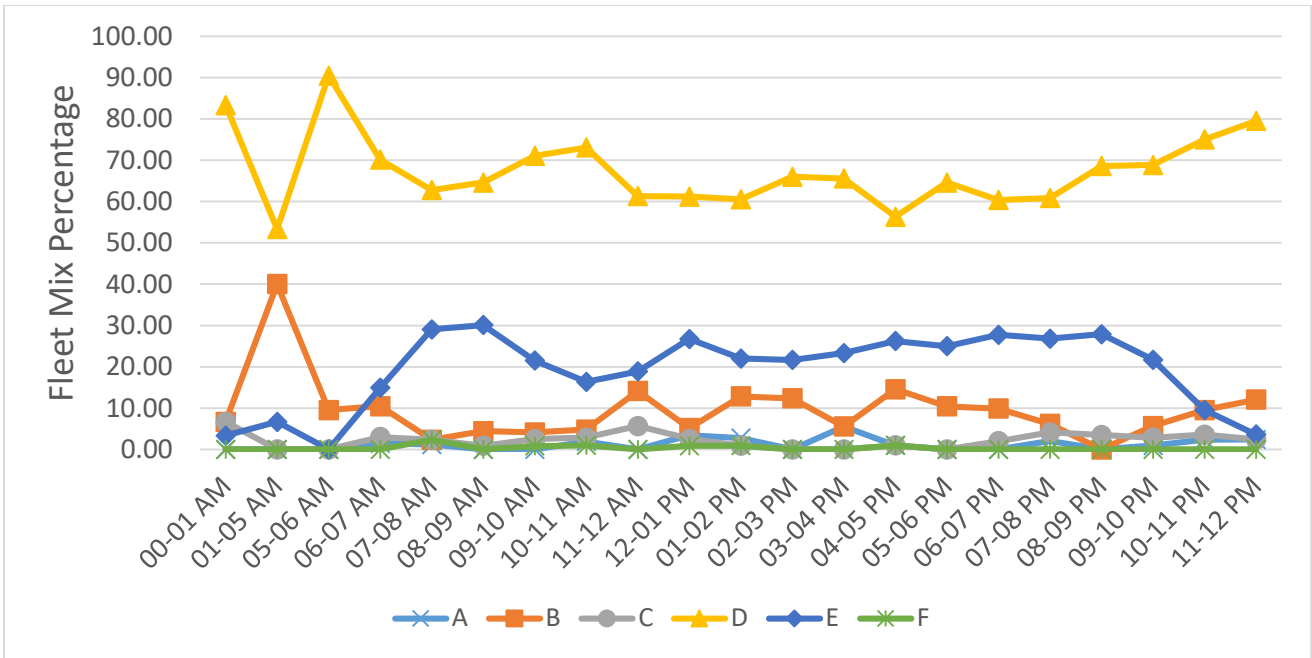


Figure 37. LAX RECAT Groups Fleet Mix Change at Different Time Periods During a Day.

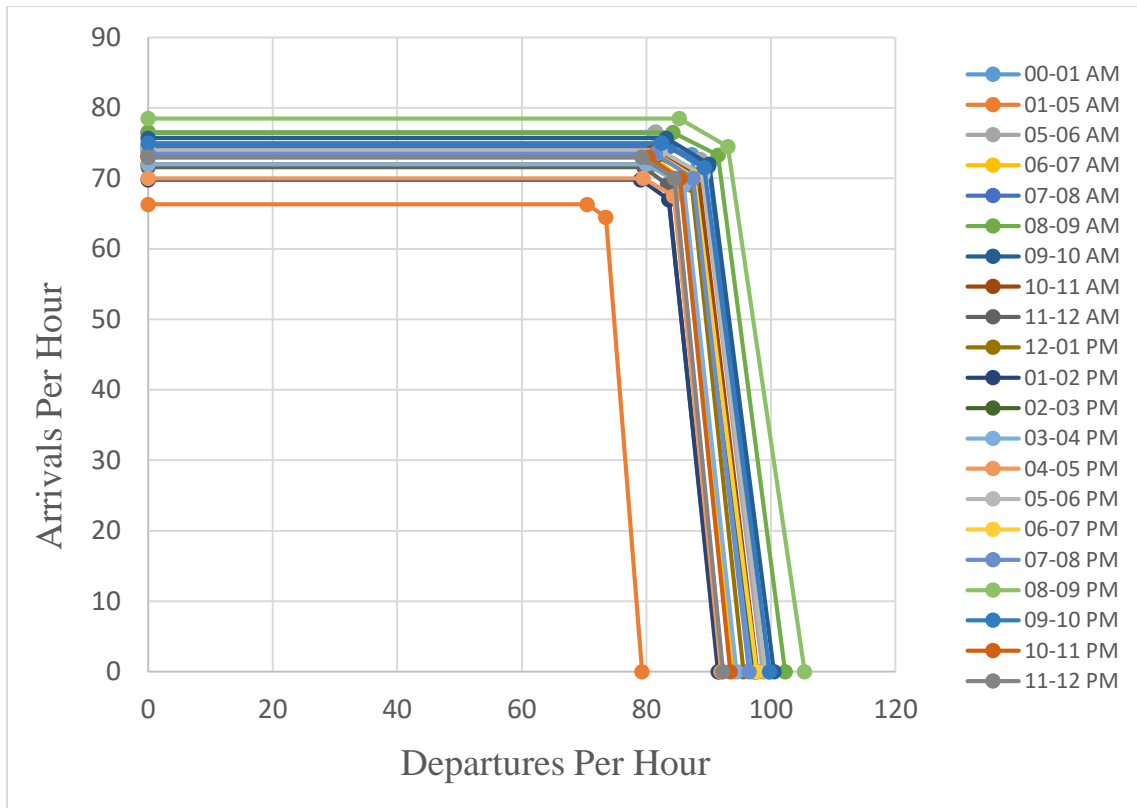


Figure 38. LAX Pareto Diagrams at Different Periods of Time During the Third Week of July 2015 Under IMC Conditions.

Figure 37 shows the changes in fleet mix percentages of 6 RECAT airplane categories at Los Angeles International airport during the day times of the third week of July 2015. The trend of each line represents the validity of predictions which were made prior to the analysis. The airport had high number of heavy airplanes during the early hours of the day which were cargo planes or international flights coming from abroad. RECAT categories E and D, are the dominant airplane groups at the airport and it is obvious that the time periods in the middle of the day are the times which those airplanes show up a lot. Even the percentage of super heavy group varies from time to time. The maximum percentage of super heavies is 5.6% which occurred during 3-4 PM. These changes in fleet mix result in different capacities which are shown in Figure 38. Figure 39 represents the summary of capacity analysis of LAX under IMC conditions for each hour of the day.

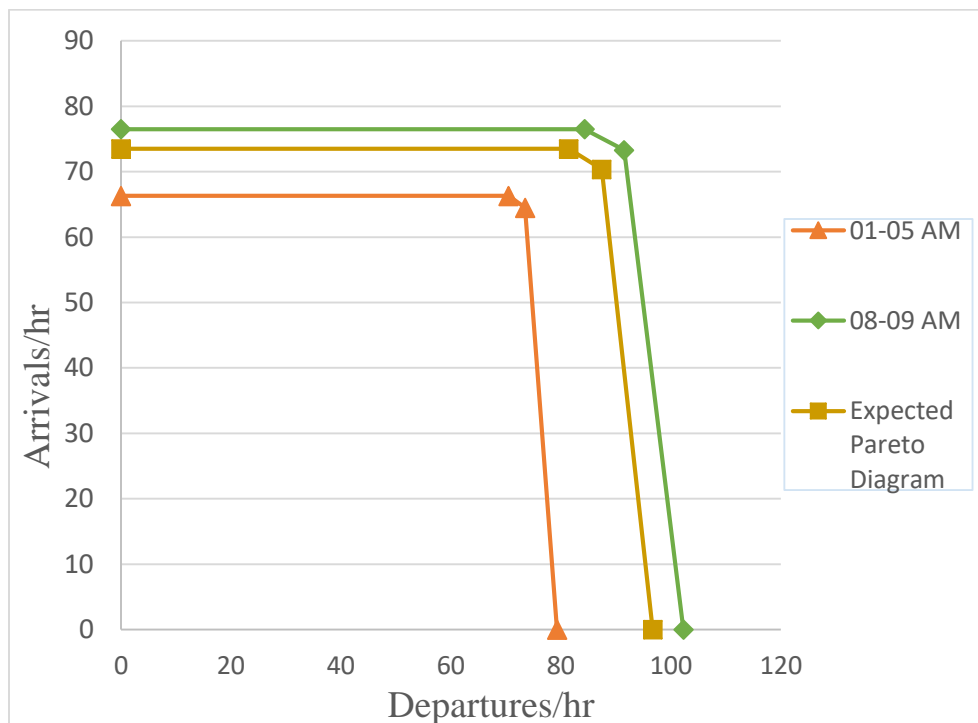


Figure 39. LAX Maximum, Minimum, and Expected Pareto Diagrams Based on Hourly Fleet Mix Studies Under IMC Conditions.

As it was mentioned before, wind can be a challenging aspect in aviation operations' world in terms of efficiency and safety. Heavy headwind can reduce the arrival capacity of an airport drastically. Heavy crosswind can not only reduce the arrival capacity, but also it may make trouble for pilots to land safely with one attempt, therefore the importance of modeling different aspects of wind (speed and direction) is not negligible when a fully capacity analysis for an airport is required to be done. Some airports were studied with hypothetical wind speed and directions under various separation systems to estimate the most optimum separation type under windy conditions. O'HARE International airport was studied with real wind data to estimate the capacity loss with heavy headwinds and different separation scenarios were tested for this airport for finding the optimum type. In the end a comparison between the fleet mix of London Heathrow airport and Chicago O'Hare was done, to compare the effects of running both airports with time based separation.

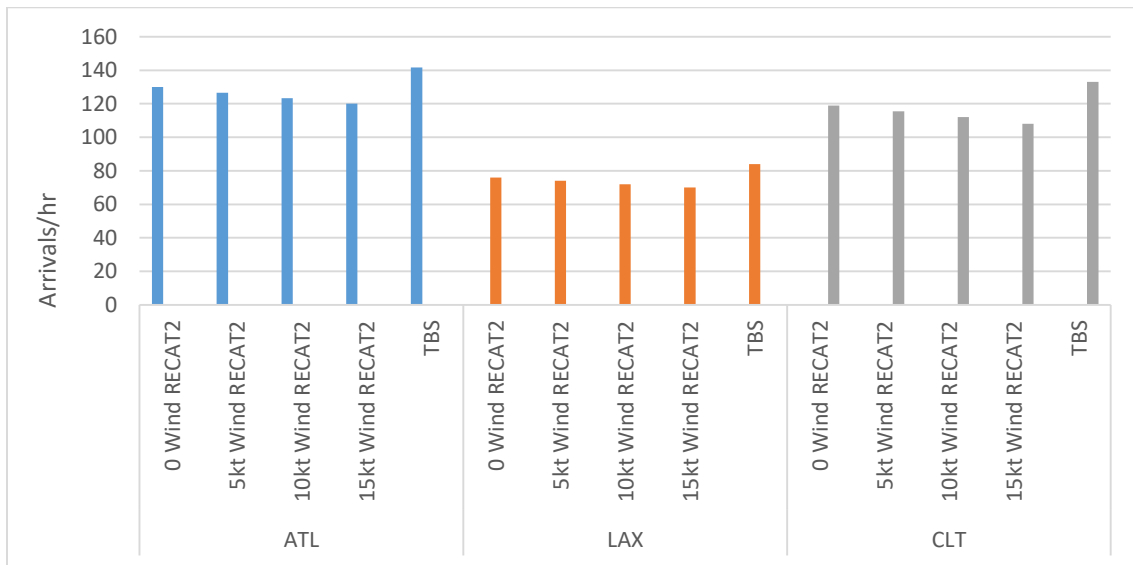


Figure 40. ATL, LAX, and CLT Arrival Throughput with Windy Condition and DBS<sup>2</sup>/ TBS<sup>3</sup> Separation System Under IMC Conditions.

<sup>2</sup> DBS: Distance Based Separation

<sup>3</sup> TBS: Time Based Separation



Figure 40 depicts considerable capacity gain with every wind speed for Time Based Separation system which is being used by NATS UK at London Heathrow airport. The point about TBS system is that whatever wind speed would be used in the simulation model, since the separation is already in time scale (seconds), the model doesn't have to consider the ground speed for converting the separation from distance scale to time, therefore the true ground speed wouldn't play significant role in the capacity estimation anymore. However, the numbers which are used in the main referenced table used by NATS UK and they're shown in Figure 12 seem very low, specifically for small airplanes following super heavy planes. This table has been used by controllers in London Heathrow since 2015, however the validity of those separation numbers and their safety are just checked for that specific airport.

Separating small airplanes followed by super heavy airplane with 158 seconds doesn't seem very safe unless there is a good proof from the real gathered data at runway thresholds at various airports. Moreover, many separation cells in NATS UK table are not defined based on wake forces and they are dominated by the leader airplane runway occupancy time, which is the same scenario as FAA 123\*123 separation matrix, but again enough attention should be paid to the safety of each of those cells.

A full study over ORD was done with all the wind speeds in the range of 3 to 21 knots to see what's the effect of headwind on the capacity of the airport. Almost 68% of the time the airport authorities run operations in the west flow, meaning that airplanes approach and depart from the east part of the airport towards the west. After that the ORD capacity with various wind values was compared with its capacity under TBS system and LHR fleet mix to see what are simultaneous effects of fleet mix change, wind, and change in separation system on the capacity gains in a facility.

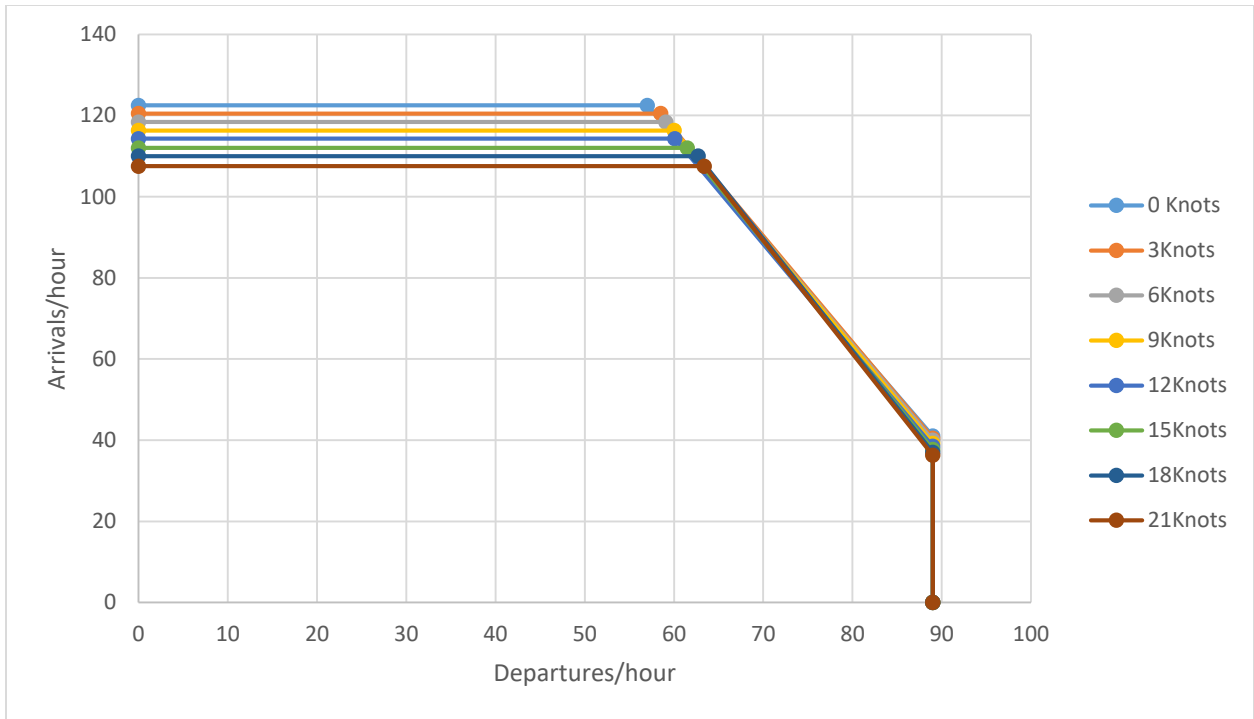


Figure 41. ORD West Flow Capacity Profiles with Various Wind Speeds and RECAT Phase2 Separation System Under IMC Conditions.

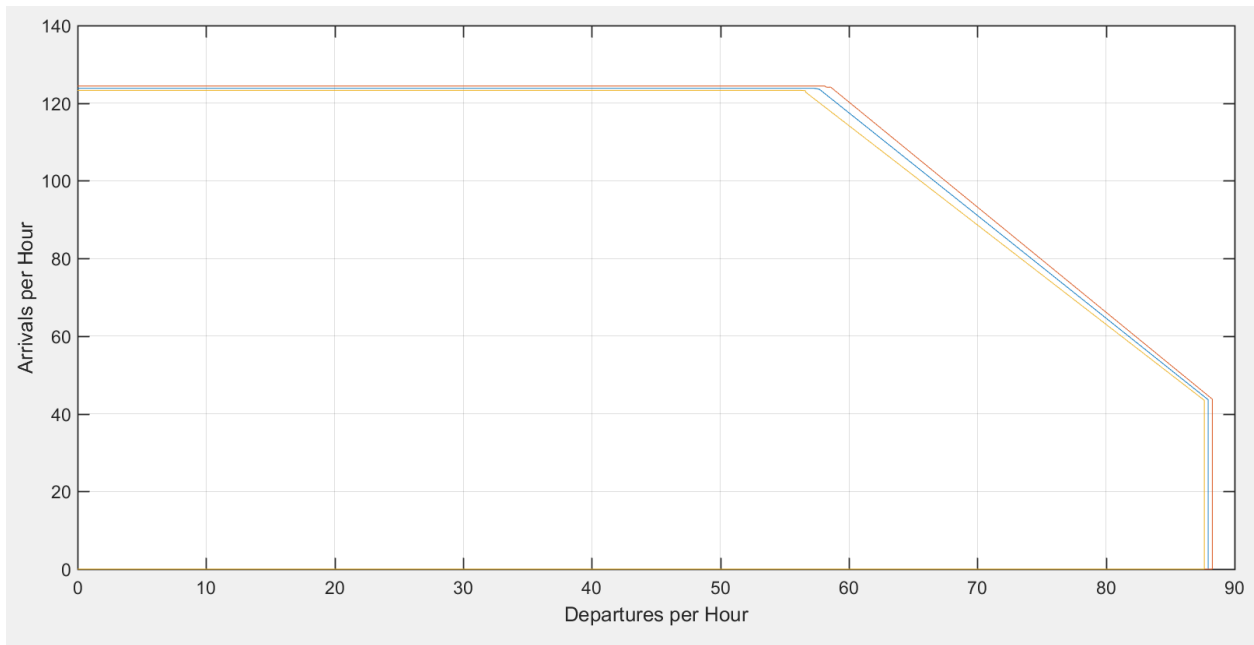


Figure 42. ORD Pareto Diagram Under TBS Separation System Under IMC Conditions.

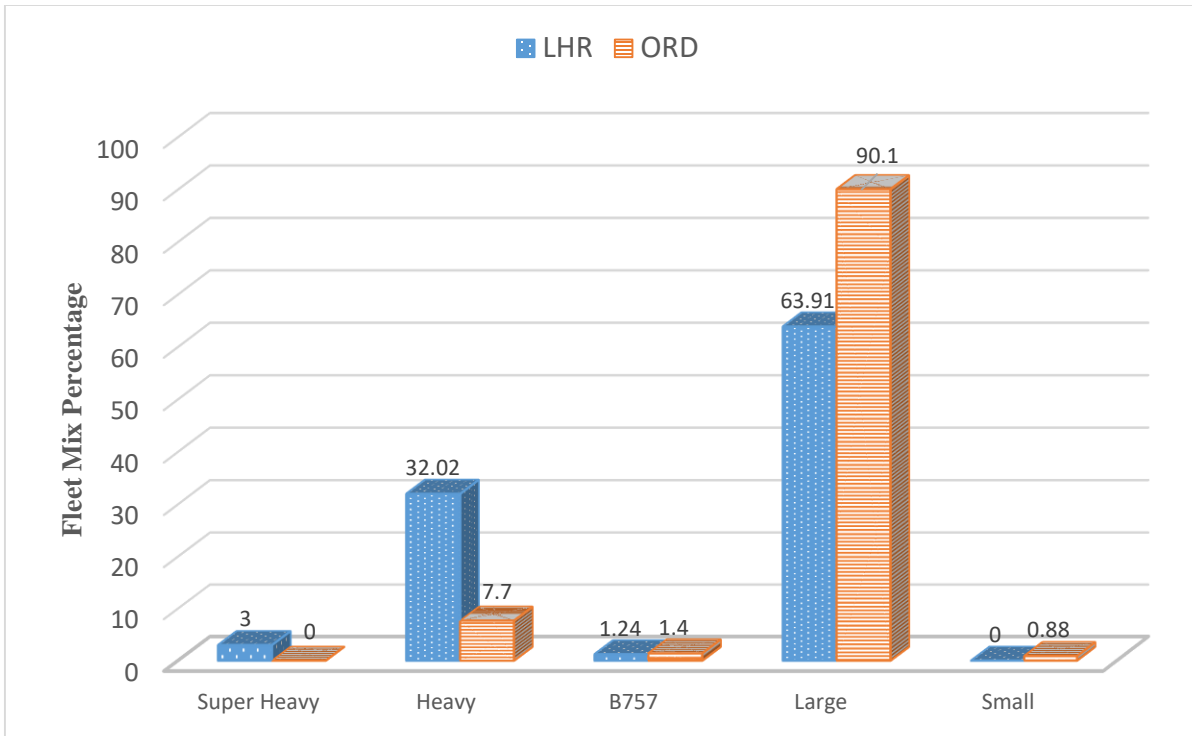


Figure 43. Fleet Mix Comparison Between Chicago ORD Airport and London LHR Airport.

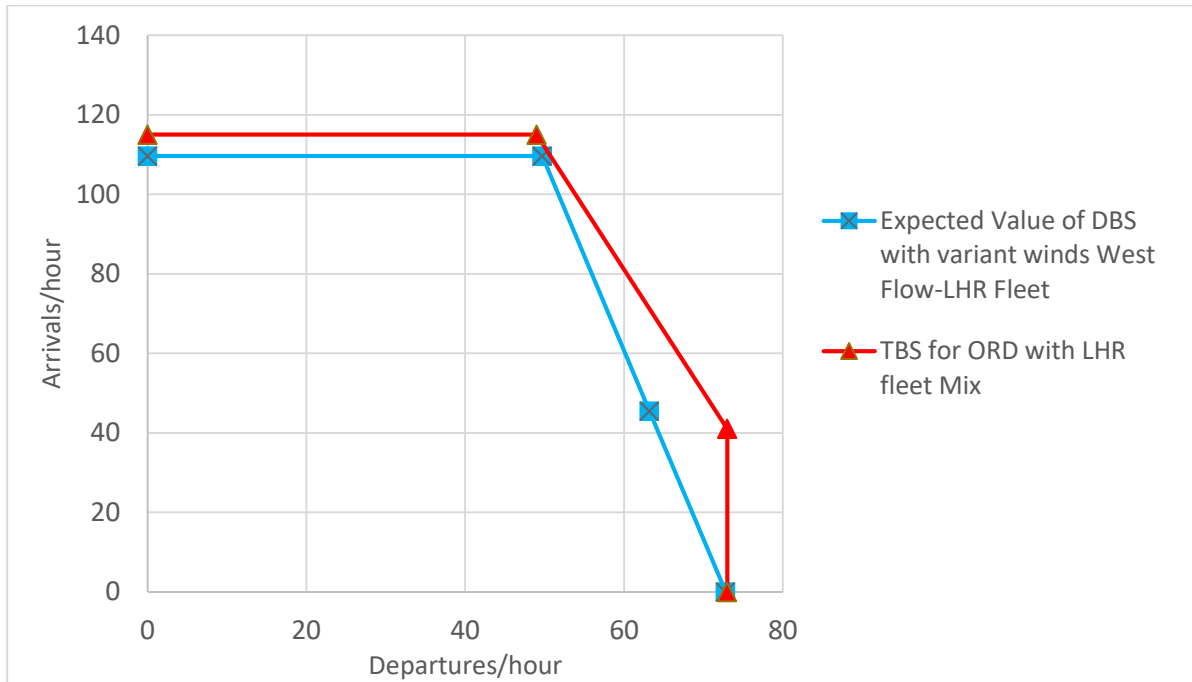


Figure 44. ORD Pareto Diagrams with Expected Value of Wind Values in Range of 3-21 knots and DBS, and TBS with LHR Fleet Mix.

Figure 41 represents multiple Pareto Diagrams at ORD under IMC conditions and FAA 123\*123 individual separation matrix, while the headwind value is increasing for each scenario. In average 2 arrivals are lost for every 3 knots of headwind.

Figure 44 shows that ORD airport with LHR fleet mix will have lower maximum arrival throughput, however the TBS system still gains around 6 more arrival flights per hour with every possible wind speed at the facility. Figure 42 represents a maximum arrival throughput of 123 operations per hour under TBS system and current fleet mix at ORD, while the expected value of arrival throughput considering the percentage of various wind speeds is around 118 arrivals, therefore again TBS system saves around 5 more arrivals per hour for this facility. The importance of using TBS can be magnified for the times that a headwind of 12 knots is blowing at the facility and with the FAA RECAT phase 2 separation system the facility loses at least 8 arrivals per hour, however the TBS system can retrieve the entire lost capacity.

Most of the case study section was focused on the ways that airports can rely on in order to increase their hourly capacity by reducing separations between arrivals or changing their separation systems. However, pushing the airports highly and trying to make the separations very close to the most optimum condition is not recommended all the times. Many events at airports may slow down the pace of operations, therefore considering the perfect condition for each day and trying to extract the highest capacity should be done very carefully in terms of safety. One of the routine signs of reducing the separations without considering other operational parameters, is the unsuccessful arrival or go around movement. This phenomenon happens when a plane is approaching the runway and tries to land, but the leader airplane is still on the runway and hasn't vacated that yet. At big airports in U.S. go around movements are seen couple of times during the day.

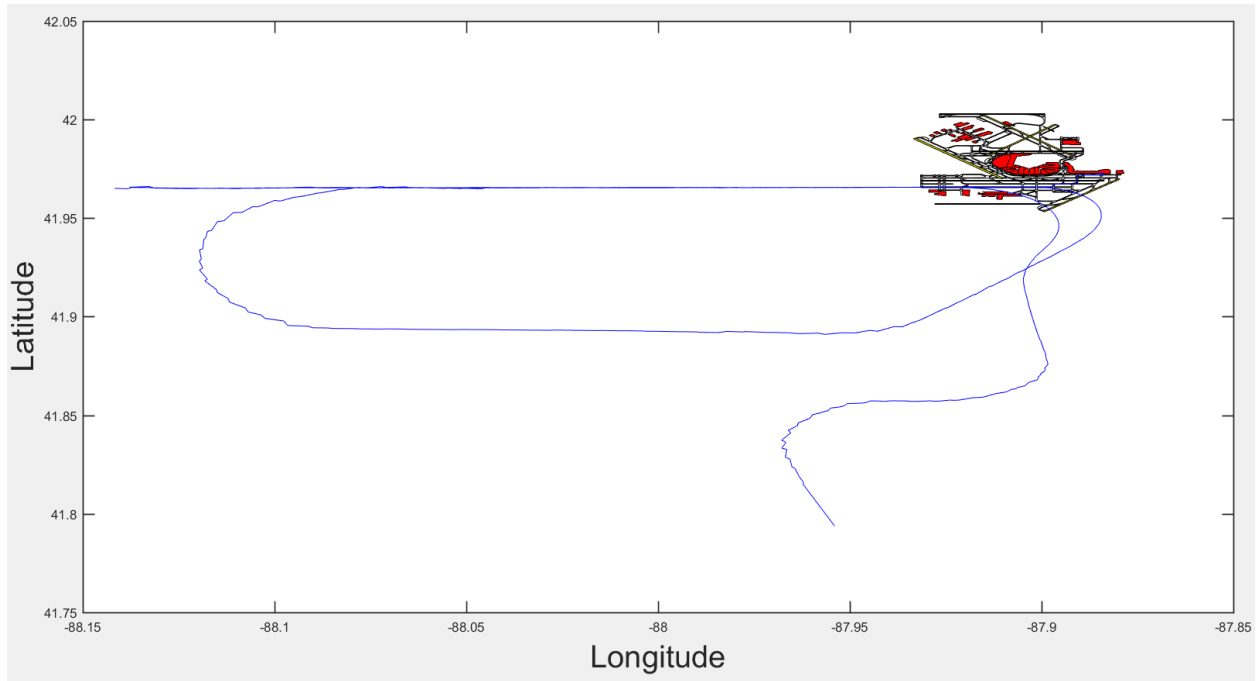


Figure 45. An Example of Two Go Around Movements by Heavy Airplanes at Chicago O'HARE Airport on One Day. (04/15/2017)

Figure 45 shows two go around operations at ORD airport on one day. Therefore, paying attention to all of the aspects of airport operations is a critical point for every improvement plan.

#### 2.4.5 Summary and Conclusion

Runway capacity model was developed in a way that it can help many airport authorities and decision makers in aviation industry to give them more realistic views of the potential growth that they can expect in near future. This tool provides the flexibility of analyzing many facilities with various runway configurations and separation rules, which can be beneficial for figuring out the inefficient systems, the possible capacity for increasing the number of operations, and many more functionalities which can be utilized during the planning phase of big airports improvement projects.

Analyzing airports with individual aircraft grouping would show the users of this simulation model a better scene of how aviation operations are happening in the real world. After doing all the safety studies, tools like RUNSIM v.2.00 can help researchers, airport authorities, FAA officials, and airlines to estimate the benefits of changing from current separation rules to more efficient ones. Although the results of this model shouldn't be treated as sufficient elements in any airports capacity estimation, the final outputs can draw the possible ways for beginning the changes and moving towards a more optimized system.

Reviewing terms like time based separations is the best example of the functionality of RUNSIM model, as it shows the potential benefits in capacity under heavy windy days for multiple airports. These analyses are way cheaper and safer than applying the new rules in the real system and giving them try and error procedures.

Since the aviation demand is going up again and many facilities across the country are reporting delays and inefficiencies in their operational systems, the usage of simulation models like RUNSIM can save time and money, and may potentially help the decision makers to optimize their operational systems.

#### 2.4.6 Recommendation

For future research it is recommended to study more runway configurations to be added to the capacity model. Currently there are many runway configurations which are supported by the model, however just like other runway simulation models when it comes to more than 4 runways or more than 3 dependent runways, the process would be baffling for the system and many of those complicated configurations are not supported by this model.

The dynamic separation procedures need reliable and robust studies on different airplanes wake vortex effects. Those studies are beyond the runway capacity issues and can get to more aerospace topics in detail. Having a reliable algorithm which could transfer the results of an aircraft wake vortex simulation model to the RUNSIM individual aircraft branch, would be very functional for the times that users want to test the effects of dynamic separation matrices on the airport capacity profiles. Those algorithms should be trained in a way that extract reliable separation values whenever a new pair of airplanes shows up for both departures and arrivals streams.

## 3. Taxi Event Extraction Model

### 3.1. Introduction

Every network in the transportation system is built from nodes and links. The way that those links and nodes are connected to each other and how the operations are being done at each node or on each link between the nodes, has considerable effect on the efficiency of the transportation system. Air transportation systems have the same make up as they are built from links showing every possible airway and air path that airplanes can fly through, plus the nodes in the system which are the airports. The quality of operations at airports can directly affect the total delay in the air transportation system. Airport operations include both the airside and the landside operations. Much of the focus for estimating the capacity of airports is on the airside operations and how the separations between each pair of operating airplanes can be reduced; however, there is another significant operation to analyze at airports which includes the taxiing phase of airplanes. This phase covers all movements of vehicles on the groundside of airports for getting to the gates from runways or leaving the gates and heading to the runways. Moreover, some other airplanes move around the airport and use different taxi lanes to go to their desired hangers. The analysis of these ground movements at airports is a critical part of analyzing and evaluating the airport operations. In many facilities, the ground movements of the airplanes or taxiing phase is the restricting parameter for the airport capacity due to reasons like inefficient taxi way design, inefficient exit design, and not having an effective monitoring system on the moving vehicles at the facility. Therefore, the analysis of the ground movement behavior of airplanes can be very helpful for airport designers, FAA authorities, airlines, and all the organizations which care about the efficiency of the operations at airports.



One of the functional parameters for evaluating the efficiency of ground movements at airports is the unimpeded taxi time (also known as nominal taxi time). The unimpeded taxi time is the time it takes an arrival or departure to taxi all the way to the gate (for arrivals) or to the runway (for departures) without any interaction with surrounding airplanes. In other words, when an airplane taxis at a facility without reducing its speed or stopping to let another airplane use a desired path (either runway or taxiway), this taxiing action is called unimpeded. Unimpeded taxi time is very important for estimating the best possible taxi times for all of the operations and can be used as a reference to compare with the other taxiing airplanes' behavior to evaluate the overall traffic condition at the airport.

The other benefit of analyzing the bottlenecks at the airports, where airplanes have to wait in queues for airplanes departing from a runway or getting to a passenger gate, is that the amount of fuel burn can be estimated to see how much fuel is wasted by waiting airplanes at airport. Since the environmental regulations and the fuel price are the main concerns of many federal agencies and airlines, having a realistic picture of ground operations at airport during taxiing phase can be very helpful.

Upon request of the Operation Office of Federal Aviation Administration, to develop a new method for calculating unimpeded taxi times at airports, a study on taxiing behavior of airplanes was completed to address the problem. Since there are ground radars installed at top airports in US, the flight trajectory of the majority of the flights at these airports are available. For this study, flights at 6 large airports at US were provided to be evaluated. The airports are: ATL, CLT, DEN, IAH, JFK, and ORD. The source of this data is the Airport Surface Detection Equipment (ASDE) which detects airplane's locations at each second and appends it with flight information like airplane type and flight ID. In the methodology section, a summary of the used

techniques for this study will be presented. Following by the methodology section, two summary tables are shown to summarize the conclusion of study on the six airports. Finally, validation plots for each airport are attached to show the accuracy of the parsed events by the programmed computer tool for analyzing the radar data.

### 3.2. Literature Review

For addressing the unimpeded taxi time estimation issues, many papers were studied to explore the current methodologies which are being used by corporations and government agencies to calculate the unimpeded taxi time and depict of ground movements at airports.

Zhang analyzed airports layout files in a funded project from FAA to create input files for ADSIM+, which is a simulation model for airports that calculates the delay for operations (13). The research was about converting the AIXM<sup>4</sup> data to link-node networks which could be read by ADSIM+ as input files for running airport simulation scenarios. In this process he used a sophisticated methodology by using ArcGIS application to convert AIXM files to structure files containing all the paths like runways, taxiways, and apron areas at airports. In his study he defined the possible exiting and taxiing paths for each airport, which can be used as reference taxiing paths. The graphics used in this study to represent the airport layouts are extracted from his study.

Currently the FAA Aviation Policy and Planning Office (APO), calculates the unimpeded taxi time by using a statistical analysis on the OOOI times (wheels on, wheels off, gate out, gate in) (14). They categorize the flights based on the operation type (arrival or departure), season of operations (4 seasons of the year or specific months), operating carrier, and the airplane's actual

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<sup>4</sup> Data which can be used for managing Aeronautical Information Services (AIS) data in digital format

and scheduled gate-off or gate-in times. Then the algorithm counts the number of airplanes which are ahead of the operating time of the airplanes which enters the defined queries on each sample file. After normalizing the data, a regression model is used to estimate the parameters for taxi-in and taxi-out times. Then by replacing the variables for each operation with 0 and 1 the unimpeded taxi time for each operation is calculated (14). The precision of this approach is at minute scale, while the real radar data is more accurate and can follow a track all the way to the fraction of a second. The other issue with this methodology is that the taxi times are defined based on the wheels off/ on time to the gate out/ in time. This definition is not very accurate for estimating taxi time, since the precise definition of taxi time does not include the runway occupancy time, but this method includes the runway occupancy time as well.

EUROCONTORL uses a similar statistical procedure for calculating unimpeded taxi time (15). Initially, they categorize the flights based on stand and location type (gates). After defining the operational runway, within each group a congestion factor is defined to count the number of other vehicles taxiing at the same time. Within each group a range from 10<sup>th</sup> to 90<sup>th</sup> percentile is made and sorted by the least congestion indices. Then a weighted average is used to calculate the differences between unimpeded taxi times which have the lowest congestion index, and the true taxi times. After several iterations, the flights with the lowest congestion index are selected as unimpeded flights. This method uses the statistics over the raw data without considering the real path that airplanes took while moving at the facility. Many times the taxi times look long; however, if one draws the trajectory of the airplanes, it might be inferred that the taxiing path was a long distance and was not interrupted by the rest of the traffic. Therefore, relying on the raw numbers cannot be reliable to figure out whether a plane slowed down or stopped during taxiing because of another plane or if the increased time was due to a longer distance.

Yu Zhang and Qing Wang (16) utilized a combination of the mentioned statistical methodologies. The parameters that they used included the taxiing routes and taxiing distances at the studied airport (LGA). The method of calculating these parameters were drawing lines over the airport map and estimating the possible taxi distances at the airport. After reviewing many flight trajectories from radar data, the pattern of many taxiing airplanes' behaviors can be understood. Most of the times the estimated taxi distances are considerably different than the length of the actual taxi paths that an airplane may travel through, as many times it was observed from the ASDE radar data that pilots take longer paths for letting the controllers to assign more operations on the active runways, or they travel multiple times on similar taxi ways to avoid waiting in queues. Srivastava (17), analyzed the radar data however the taxi distance is calculated by simply drawing a straight line from the runway exit used to the gates, which is not a reliable representation of the actual travelled distances.

Since most of the studied methods of estimating the unimpeded taxi times are statistical, not many articles were found to use computer models for extracting critical taxiing events at airports. Some researchers tried to visualize the data with available tools for drawing the airport layout, however they did not use the actual radar-reported movements.

Therefore, a computer tool which is able to analyze actual flight tracks, identify the operational runways, calculate the real taxiing time and distance, monitor the airplanes' timestamps and locations to understand where it stopped or reduced its speed and then eventually report all the mentioned parameters would be beneficial for future use.

### 3.3. Input Data

Part of the input data was provided by the FAA's Office of Performance Analysis which contained the processed radar data for six airports for dates 07/16/2015 and 07/17/2015. This data set comes from the Performance Data Analysis and Reporting System (PDARS) which is an integrated system that analyzes the operations in NAS<sup>5</sup>. A total of 27 airports around United States with ASDE-X radars are available in PDARS measurement tools as well. The structure of the data set includes the flights' information and track points. Each PDARS sample data contains fields related to both flying or moving objects near the airports. Each unique movement is categorized with track identifiers. The heading of each movement is unique and contains the type of operation, radar message type, flight key, flight ID, airplane (vehicle) type, starting time in seconds from 01/01/1970, and origin/ destination airport codes.

The data contains the specific information of each registered track point. A complete track data set for a movement includes: latitude and longitude of each track point, altitude in hundreds of feet for each track point, time tags in seconds, speed and acceleration for each track point, message type, and the heading of each track point. Figure 46 represents a sample of PDARS data latitude and longitude map for a set of flights at ATL. These track lines are drawn over the airport layout to draw a better picture for the reader. As it is obvious from the figure, many tracks are not complete and they showed up in remote locations from the main facility.

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<sup>5</sup> National Airspace System

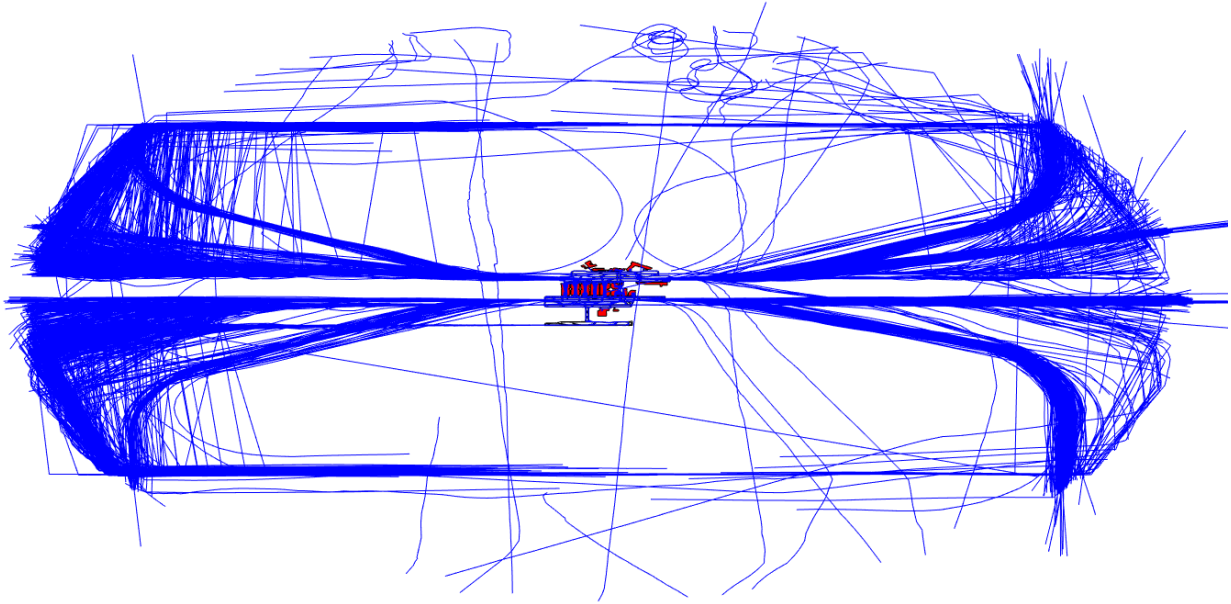


Figure 46. Sample of PDARS Data for One Day at ATL.

The PDARS samples for ATL, ORD, JFK, DEN, IAH, and CLT are the main input files for this study and also the standalone application which was developed by the author to analyze the data. The other input files include the runway configurations datasets created from prior airport layout studies and the FAA 56 days airport data set (18). The airport layout files contain the runway polygons coordination and each runway end name. The complementary airport data set contains the apron areas labels for airports.

### 3.4. Methodology

The main focus of the methodology section is on the development of a standalone application for FAA in order to extract the critical events during the taxi in and taxi out phases of an aircraft. This model identifies the operational runways as well, and reports each event with the real time

tag. The second goal of the methodology section is to define a new process of estimating unimpeded taxi times at airports. Since the process of calculating the unimpeded taxi time is done within the analysis of PDARS data and extracting other critical taxi events at airports, both procedures are explained simultaneously.

This model is a stand-alone application which was coded in MATLAB. The required input data for this model is PDARS data for airports which are known as IFF<sup>6</sup> files. The parser reads the comma separated files and tries to identify all the flights in those files. There are many fields in the PDARS files which can be extracted for each flight. The most important ones are:

- 1- Latitude of each registered track point
- 2- Longitude of each registered track point
- 3- Time tag of each operation which is reported in seconds from 1/1/1970
- 4- Altitude of each registered track point
- 5- Airplane type
- 6- Flight ID
- 7- Flight key

Every PDARS sample includes the trajectory of moving vehicles at airport, or airplanes which are taxiing to the hanger area. Those movements are not categorized as arrival or departure if there would not be a considerable change in their altitude profile. Therefore, for filtering all of the operations, once parsing the PDARS data the first track point altitude was compared with the average of rest of track points' altitudes. If the difference is lower than 20 feet (which is very low

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<sup>6</sup> Interchange File Format

height in compare with a full operation average altitude), that specific track would be eliminated from the data set in order to keep only the real operations (arrivals or departures).

There are many other fields in the IFF files which the event extraction parser does not need necessarily for extracting critical events. Speed and acceleration for each flight record can be found in the IFF files, however the accuracy of those reported numbers is not reliable at all, therefore those features of each flight are calculated by the model by using the time tag and location.

After parsing the input file, the event parser tries to extract the critical events for each successful operation (arrival/ departure) at the airport. A summary of each flight movement is then represented in the final output in a table format. The final output of the model has 25 fields which will be explained later.

An entire list of fields in the output file can be found in Appendix 1.

All of the extracted fields have their defined explanation in the data dictionary table.

In this chapter, the key fields which are extracted for each operation are explained.



### 3.4.1 Arrivals

The Figure 47 shows the critical events for each arrival flight:

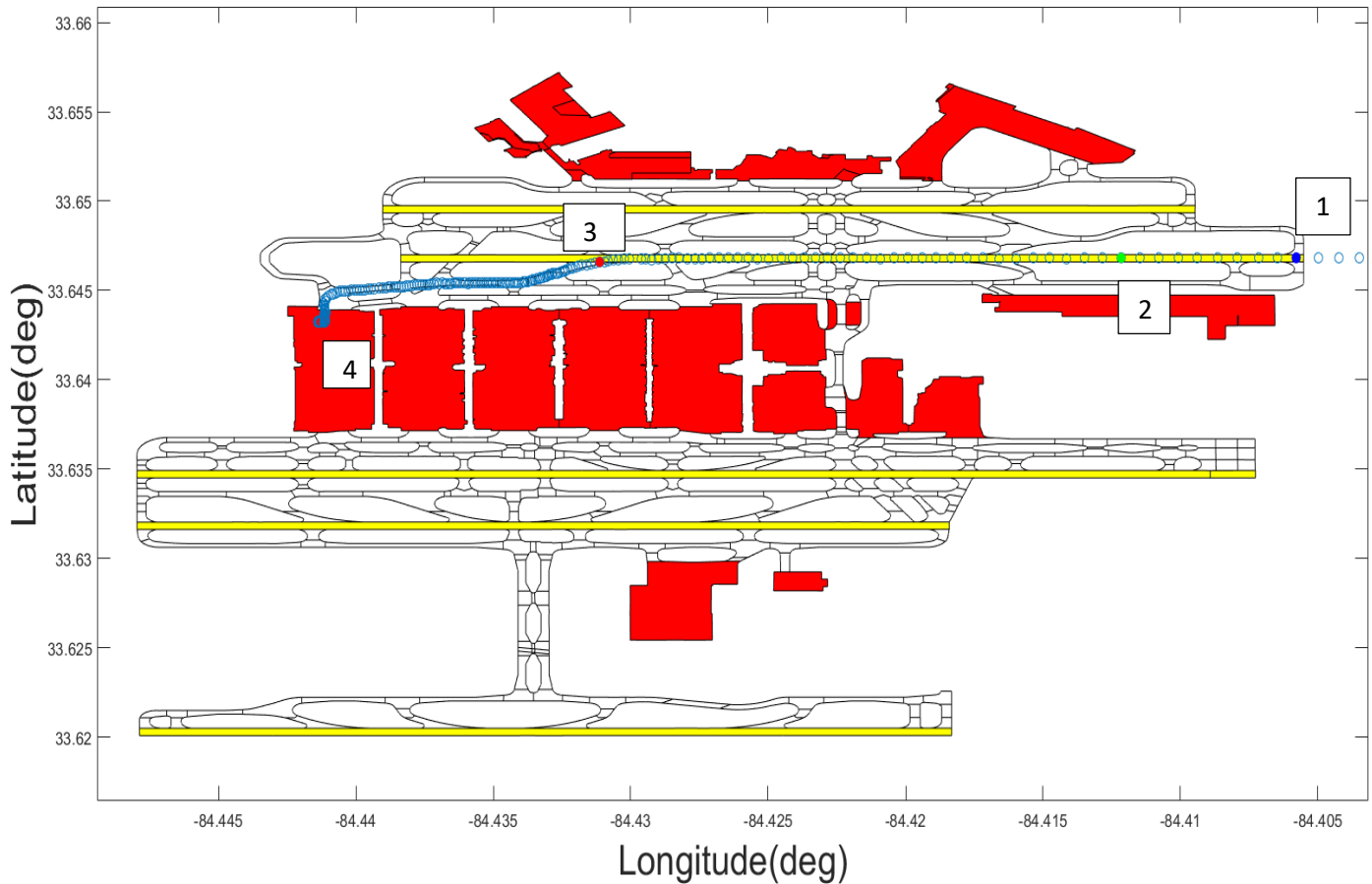


Figure 47. Sample of an Arrival Flight at ATL and the Important Events.

- 1- Operational runway: this field is extracted by checking the arrival track and finding the runway polygon that it landed in. The criteria for assigning an arrival flight to a runway is to have at least three consecutive points inside the runway polygon. The procedure of checking for operational runway starts from the first point in arrival track and it stops as

soon as a runway is assigned to the flight. Figures 48 to 53 show the airport layout databases which are created for assigning different flights to different runways:

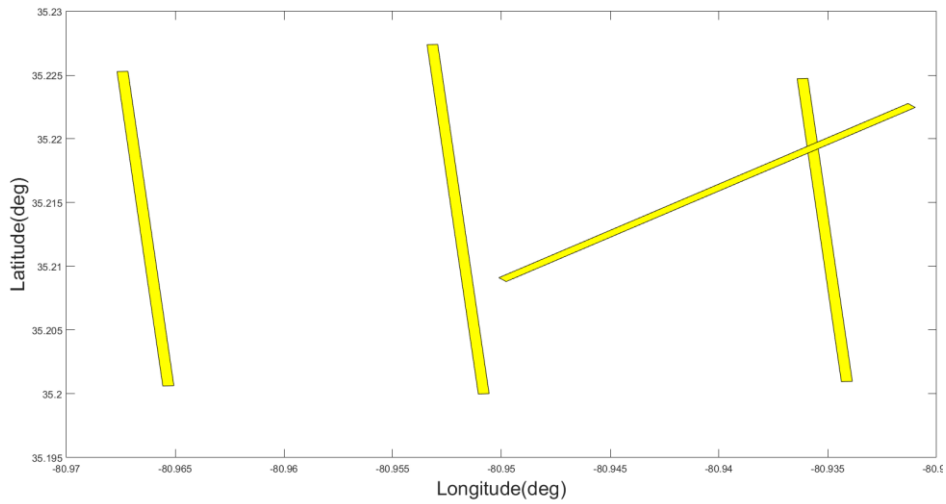


Figure 48. CLT Runway Layout.

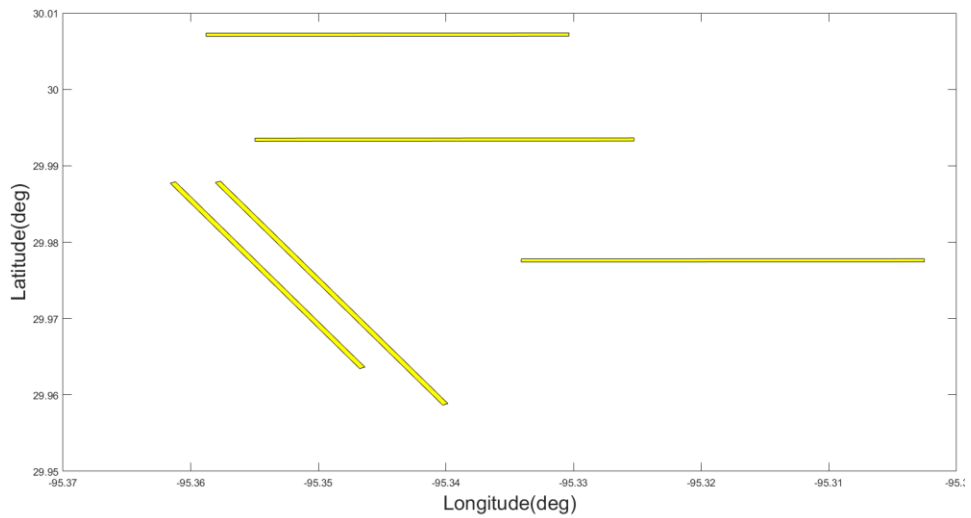


Figure 49. IAH Runway Layout.

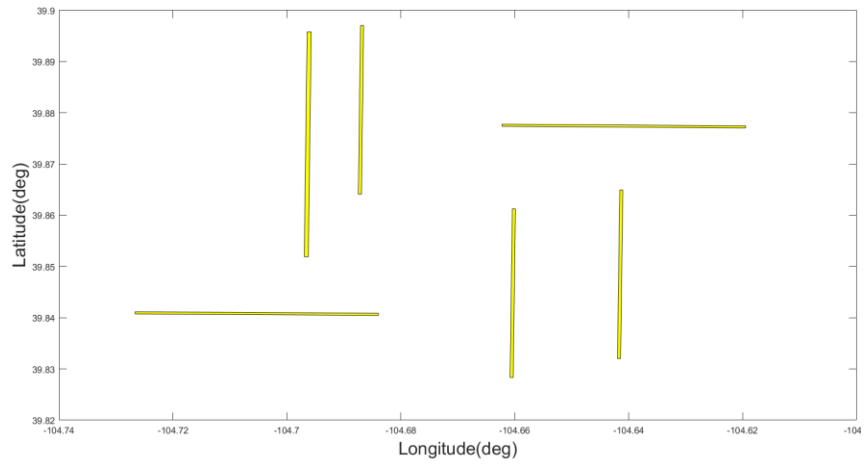


Figure 50. DEN Runway Layout.

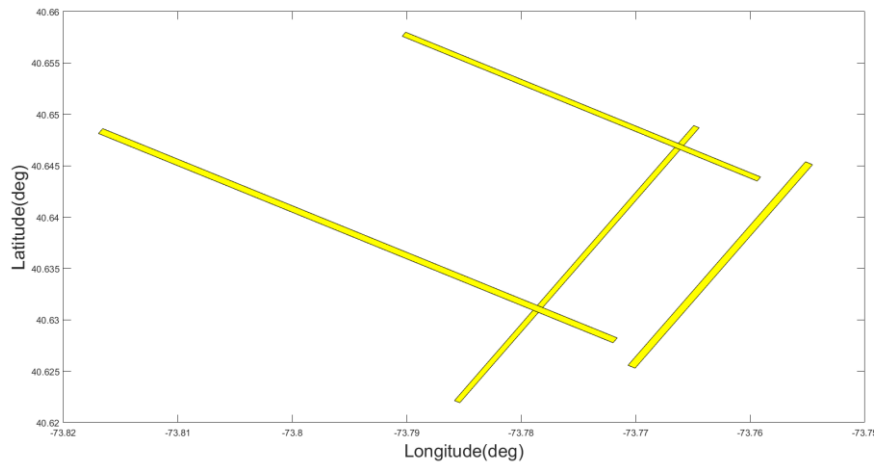


Figure 51. JFK Runway Layout.

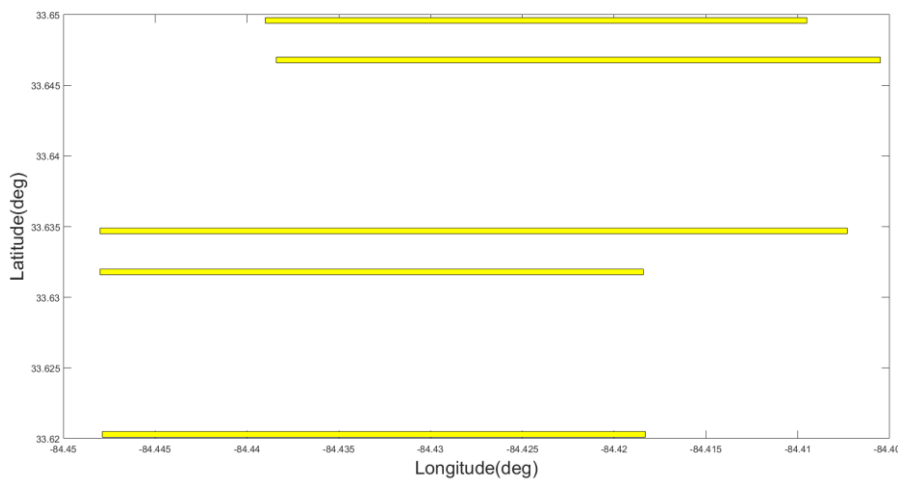


Figure 52. ATL Runway Layout.

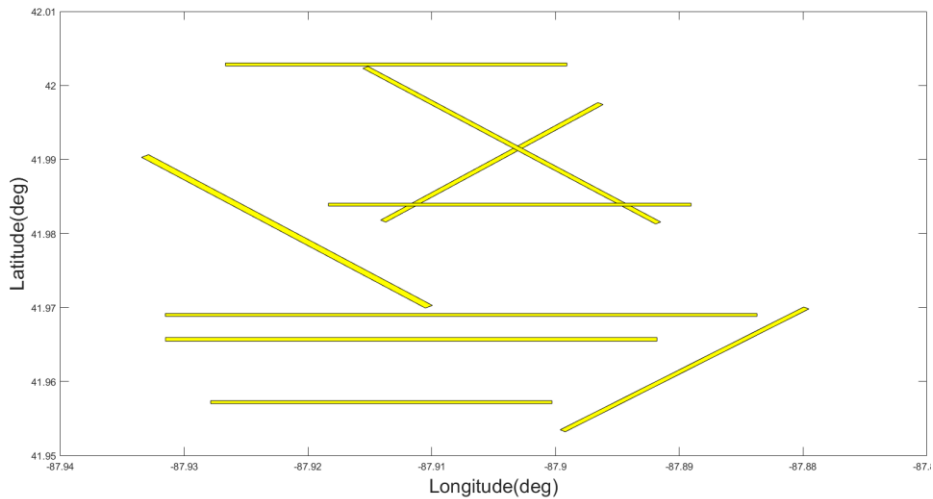


Figure 53. ORD Runway Layout.

- 2- Enter Runway: this point which is shown in Figure 47 with blue color and is labeled with number 1, is the first point of the arrival track which was recognized inside the runway polygon. Columns 8 and 9 of the final output table, show the latitude and longitude of this point. Column 7 shows the time of entering the runway, which in most of cases if it was possible to interpolate between the first point in runway polygon and the last point behind the runway threshold is the interpolated time between the first point inside the runway and the last point behind the runway. With the mentioned method we can get a better estimation of the threshold passing time by the arrival airplane. If the interpolation was not possible (due to strange location of flight tracks), runway enter time is just the converted time of the first point inside the runway polygon to the "year-month-day hour-minute-second" format.
- 3- Touchdown point: this point which is shown in Figure 47 with green color and is labeled with number 2, is the estimated touchdown point for the arrival flight. Because the altitude profiles which are reported in PDARS data are fuzzy, for the majority of the

arrival flights extracting the touchdown point using the altitude, does not lead to reasonable results.

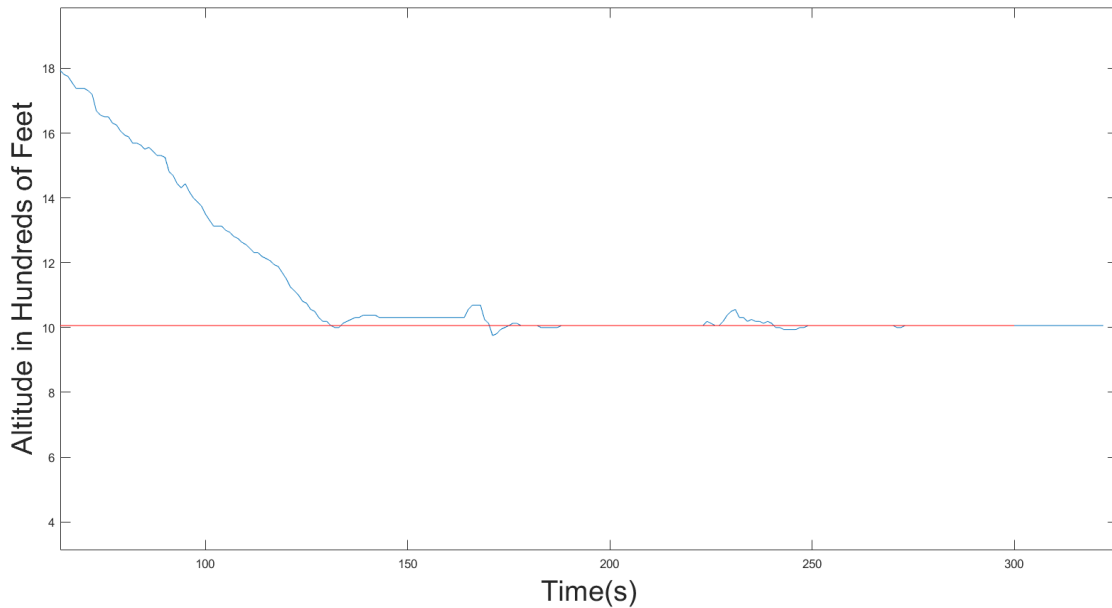


Figure 54. Sample of Fuzzy Altitude Profile. (Red Line Shows the Referenced Altitude of the Arrival Runway.)

As it is shown in Figure 54, based on the reported data, the airplane goes below the referenced altitude of the runway, which is not credible, and this noisy behavior repeats for most of the other operations and many worse situations were observed. Therefore, for extracting the touchdown point another approach was used:

- a) First, the instant speed of each track point was calculated. The reason for calculating the speed based on location and time tag was that the reported speed in data did not seem to be reliable:

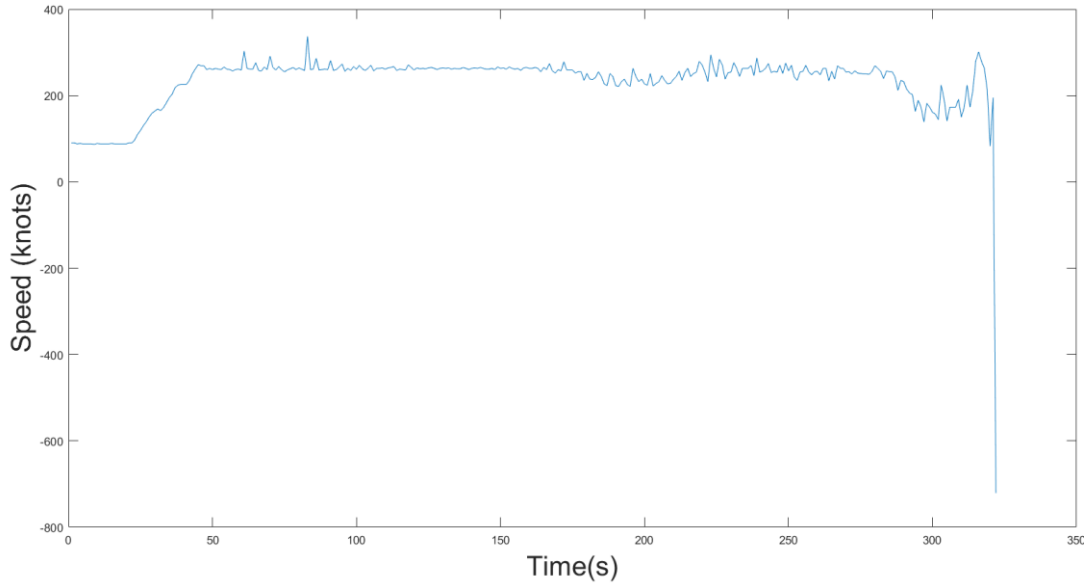


Figure 55. Sample of Reported Speed for an Arrival Flight in Data.

As Figure 55 shows, the reported speed does not even show a reasonable trend in speed change for different phases of arrival, therefore the speed was calculated based on location and time tag:

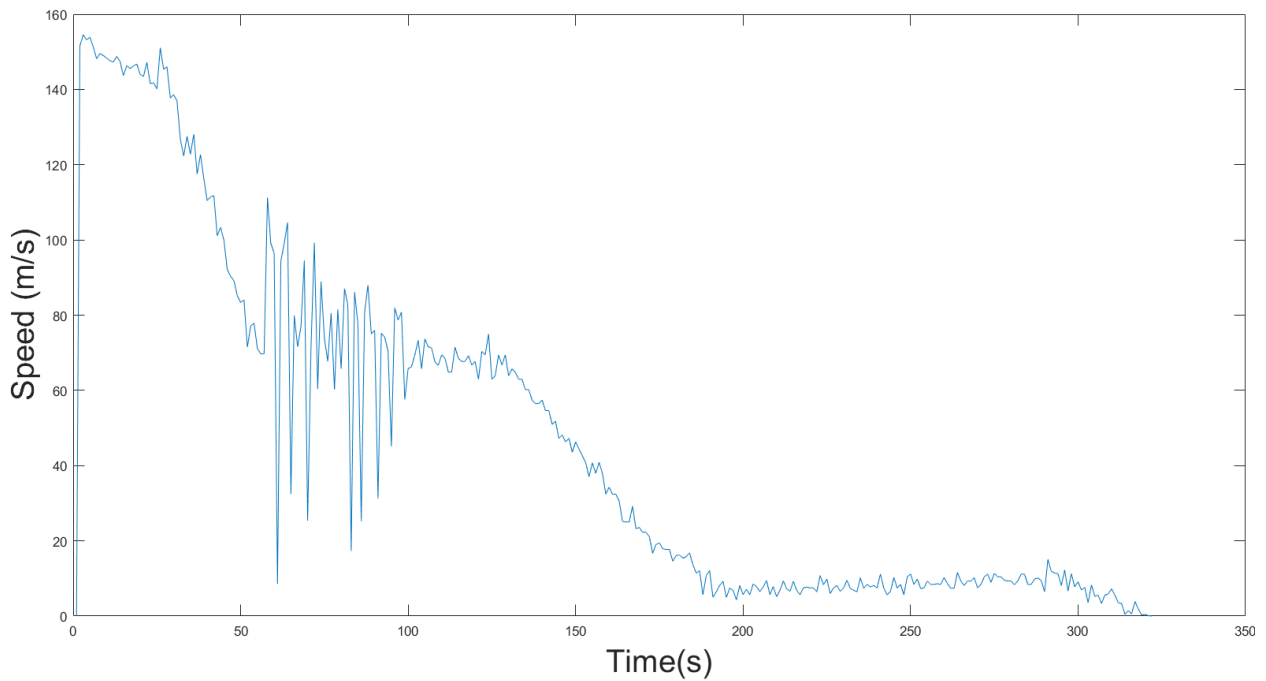


Figure 56. Calculated Speed Profile in m/s for the Flight Data Used in Figure 55.

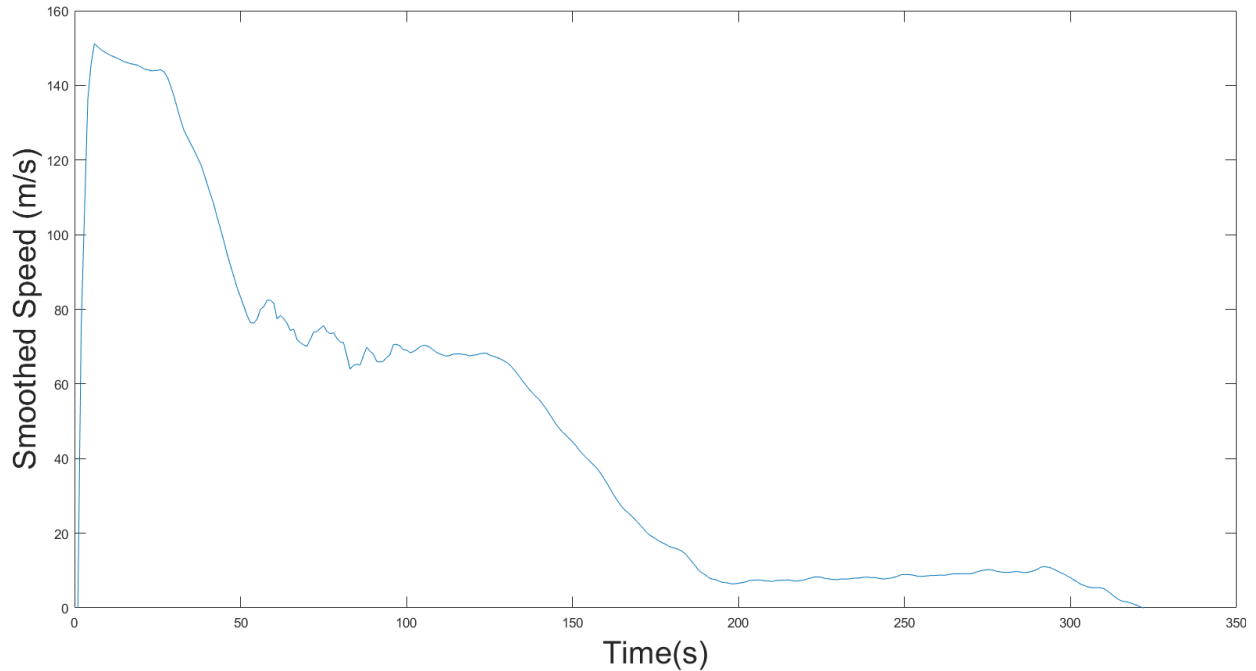


Figure 57. Smoothed Speed Profile in m/s for the Flight Data Used in Figure 55.

Although Figure 56 shows a reasonable trend in speed change for an arrival flight, it still has noise which might make the analysis uncertain. Therefore, the speed profiles were smoothed two times with moving average method and a sample of results can be seen in Figure 57.

- b) After smoothing the speed profile, the acceleration was calculated. It is obvious that when the airplane touches the ground, for having a successful landing the pilot applies all types of brakes in order to reduce the airplane speed, therefore in the acceleration profile of the landing move, there should be a point with minimum acceleration (maximum deceleration) which helps the plane reducing its speed and vacating the runway. That moment of highest deceleration happens after all the wheels are on the ground and then the brakes are applied.

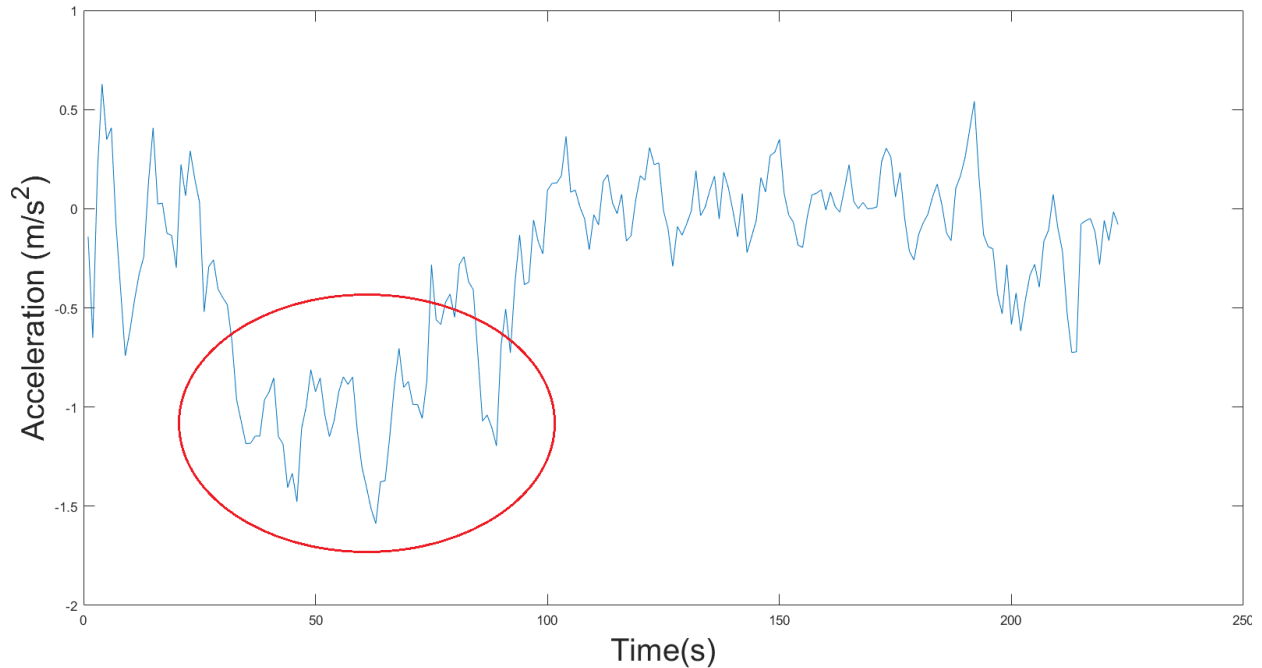


Figure 58. Sample of an Acceleration Profile of an Arrival Flight.

Figure 58 represents a sample of acceleration profile for an arrival flight. The area inside the red oval in Figure 58 shows the potential region for having the minimum acceleration which means that all the brakes were applied. In average it takes 10 seconds for the pilot to apply all the brakes and also the friction of tires helps the deceleration, therefore after finding that point on runway, 10 seconds are subtracted from the moment of minimum acceleration and that time is the touchdown moment. This 10 second is an average number which is extracted from analyzing landing videos taken by the author of this thesis at Chicago ORD airport in a runway exit study which is invested by Dr. Antonio Trani the principal investigator of Air Transportation Systems Lab at Virginia Tech.



- 4- Exit Runway point: this point is labeled with number 3 and is shown in Figure 47 with red dot. This shows the first point which was found outside of the runway polygon. In the final output table, columns 15, 16, and 17 shows exit point time, latitude, and longitude.
- 5- Near Gate point: this point is labeled with number 4 in Figure 47 and shows the last point of an arrival flight track. This point should be supposedly inside the apron area and near the gates, however the location of this point and the distance from apron area (gates) varies from flight to flight and from airport to airport.
- 6- Enter runway on/ off duration: the time difference between points 1 and 2 in Figure 47.
- 7- Enter runway on/ off distance: the distance between points 1 and 2 in Figure 47.
- 8- Enter runway exit runway duration: the time difference between points 1 and 3 in Figure 47.
- 9- Taxi in/ out duration: the time difference between points 3 and 4 in Figure 47.
- 10- Taxiing distance: the cumulative distance that airplane travels from the runway exit point to the near gate point. This distance is the travel distance from point 3 in Figure 47 to point 4 in Figure 47.
- 11- Average taxi speed: the smoothed taxiing speed from the runway exit point to the near gate point. This speed is the average of all the instant speeds from the point 3 in Figure 47 to point 4 in Figure 47.
- 12- Wait time: all the moments that the airplane was taxiing with a speed lower than 3m/s. This assumption was made to detect the places where airplanes were stuck in queues, however they had small changes in their instant location.

The unimpeded taxi time was calculated from following equation:

$$\text{Unimpeded Taxi-In Time} = \text{Taxi in duration} - \text{Wait time}$$

#### Equation 4. Unimpeded Taxi in Time

The precision of this method is to the seconds. There are some sources of radar data that report events with precision of fraction of seconds to the milliseconds.

A summary for all of the parsed flights from the six given samples are represented in Table 11. Although the event parser had a high success rate in parsing flights and assigning them to the operational runways, there are always a few flights which could not be analyzed easily due to data drop or non-precise data. Many times the track points show unusual behavior and exit the runway at strange points which makes the analysis harder. If the flight tracks would not meet the requirements of the event parser they're shown as "No Lat/ Long Found" in the final output table.

Note: Go around movements can be recognized by the event extraction model. The methodology for defining them is to check the average taxi speed. Because go around operations enter the runway polygon and spend several seconds inside and then leave, they have similar behavior to successful landings, however they vacate the runway and fly away instead of taking an exit like a normal arrival. Hence, if an arrival flight has an average taxi speed of more than 30m/s (~60 knots) it shows that it was a go around operation. Those flights are shown as "Go Around" in the final output table. Examples of a few go around movements at ORD are shown in Figure 59.

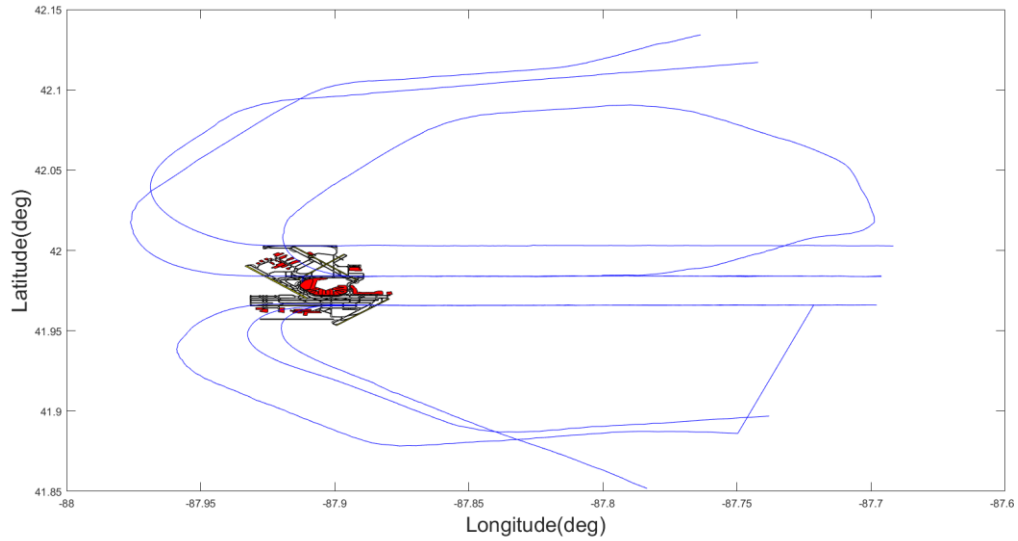


Figure 59. Example of Defined Go Around Operations at ORD.

### 3.4.2 Departures

All the fields extracted for arrivals and departures have a similar naming in the final output table. The criteria for finding an operational runway for departures is a little bit more complicated than arrivals, since the departure tracks pass more runways prior to the main operation. Figure 60 shows a sample of a departure flight.

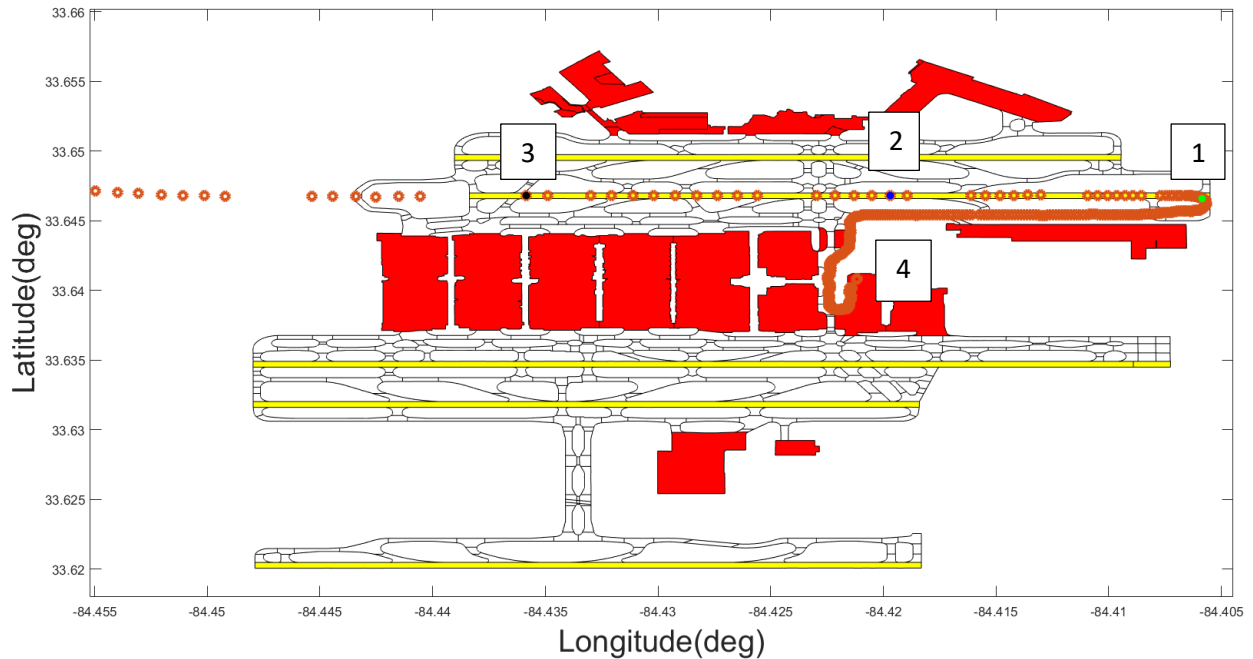


Figure 60. Sample of a Departure Flight and Important Events.

- 1- Operational runway: the same airport layout files are used for recognizing the departure runways as well. Those airport layout files are shown in Figures 48 to 53. The criteria for finding the departure runway are more complicated. To define a departure runway, the event parser searches for a track point in a departure flight which meets all of the following conditions:
  - a- Difference between the chosen point's altitude and the first point of the whole track's altitude should be equal or less than 150ft.
  - b- The chosen point should be inside one of the runway polygons in the airport.
  - c- The acceleration of the chosen point should be a local maximum among the other points of the departure track on the same runway.
  - d- There must be 10 or more points after the chosen point in the same runway polygon.
  - e- There must be 6 or more points prior to the chosen point in the same runway polygon.

f- The altitude difference between the chosen point and the 20<sup>th</sup> point ahead of that in the departure track should be equal or greater than 200ft.

If all of the above conditions are true for a departure track point, the runway which that point is located at, is the operational runway.

The most important aspect of the mentioned criteria is having a maximum acceleration on the operational runway, which is reasonable for a departure flight which wants to take-off from the ground.

Note: For departures, the criteria of having maximum acceleration was added to the procedure in order to prevent wrong runway assignment for the situations that the departure flight crosses other runways to get to its departure runway. Figure 61 represents a wrong runway assignment based on the number of track points inside the runway polygon, while Figure 62 represents the same flight which is assigned to the correct runway polygon after applying the acceleration profile criteria to the runway defining procedure.

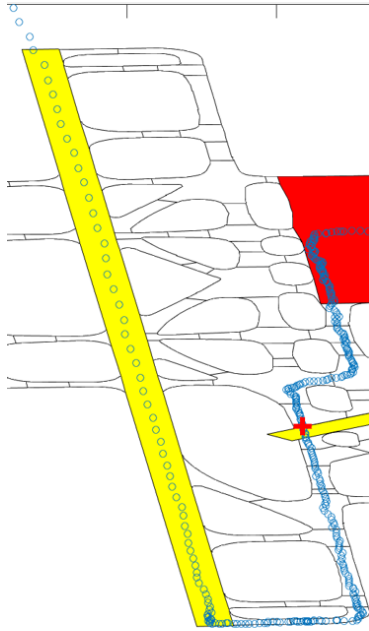


Figure 61. Sample of Wrong Runway Assignment with the Criteria of Just Having Few Points on Runway.

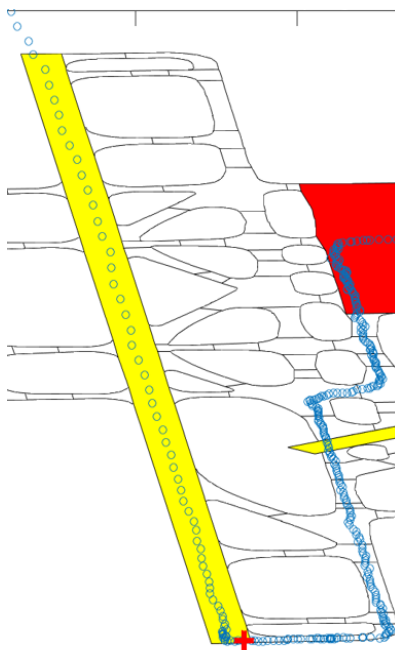


Figure 62. Correct Runway Assignment after Using the Maximum Acceleration Algorithm.

- 2- Enter runway point: this point is the green point labeled with number 1 in Figure 60. This is the first point which entered the operational runway that is found in step one. The time tag for this point is converted to the format of “yyyy-mm-dd HH:MM:SS”.
- 3- Wheels off point: this point is the red point labeled with number 2 in Figure 60. This point is found based on the criteria of finding the operational runway. After the point with the highest acceleration and other altitude criteria is found on the runway, a few more seconds are added to that moment to estimate the wheels off point location and time.
- 4- Exit runway point: this point is the black point labeled with 3 in Figure 60. This shows the first point which is touching the boundaries of the runway polygon or entirely outside the runway. This point is not always at the other end of the runway since some flights diverge from runway heading after taking off.
- 5- Near gate point: this point is labeled with number 4 in Figure 60. This represents the first point in the departure track which is supposedly inside the apron area or near the gate. Many of the departures started their taxiing travel outside of the apron area of the airports. The event parser extracts the first point in the track as the near gate point.
- 6- Enter runway on/ off duration: the time difference between points 1 and 2 in Figure 60.
- 7- Enter runway on/ off distance: the distance between points 1 and 2 in Figure 60.
- 8- Enter runway exit runway duration: the time difference between points 1 and 3 in Figure 60.
- 9- Taxi in/ out duration: the time difference between points 1 and 4 in Figure 60.
- 10- Taxiing distance: the cumulative distance that airplane travels from the near gate point to the runway enter point. This distance is the travel distance from point 4 in Figure 60 to point 1 in Figure 60.

11- Average taxi speed: the smoothed taxiing speed from the near gate point to the enter runway point. This speed is the average of all the instant speeds from the point 4 in Figure 60 to point 1 in Figure 60.

12- Wait time: all the moments that the airplane was taxiing with a speed lower than 3m/s. This assumption was made to detect the places where airplanes were stuck in queues, however they had small changes in their instant location.

The unimpeded taxi time for departures will be calculated from the equation below:

$$\text{Unimpeded Taxi-Out Time} = \text{Taxi out duration} - \text{Wait time}$$

Equation 5. Unimpeded Taxi Out Time.

After extracting all the required fields for the final output, many parameters were extracted to evaluate the taxiing parameters. These values are represented in Table 12.



### 3.5. Summary Tables

Table 11. Summary of all Six PDARS Samples of Airports and the Number of Operations.

Airport Name	Total Movements in the Sample File	Number of Parsed Flights	Number of Arrival Flights	Number of Departure Flights	Runways Used for Arrivals	Runways Used for Departures	Number of Arrivals Which the Event Parser Assigned to Runways	Number of Departures Which the Event Parser Assigned to Runways	Ratio of Assigned Flights to Runways over Non-assigned Flights to Runways
CLT	2455	1566	780	786	05 36C,36L,36R	05,18L 36C,36R	771	772	98.5%
IAH	2116	1514	749	762	15L,15R,26L 26R,33L,33R	08L,08R,15L 15R,26L,26R,27	747	762	99.9%
DEN	2410	1652	823	828	08,17R 25,34L	16L,16R 17R,26,34R,35L	829	825	99.7%
JFK	5969	1388	692	696	04R,13L 22L,31L,31R	13R,31L	682	680	98.13%
ATL	3886	2630	1308	1320	08L,08R 09L,09R,10 26L,26R,27L	08R,09L 26L,27L 27R	1297	1311	99.2%
ORD	5426	2693	1343	1345	27L,27R 28C,28R	10C,10L 22L,28C,28R 32L	1342	1345	99.97%

Table 12. Summary of Taxiing Variables for Six Airports.

Airport Name	Average Taxi-in Time (minute)	Average Taxi-out Time (minute)	Average Waiting Time for Arrivals (minute)	Average Waiting Time for Departures (minute)	Average Taxiing Distance for Arrivals (km)	Average Taxiing Distance for Departures (km)	Average Taxiing Speed for Arrivals (m/s)	Average Taxiing Speed for Departures (m/s)
CLT	8.37	14.40	3.30	7.76	2.34	2.87	7.29	6.27
IAH	5.86	8.74	1.74	3.71	2.2	2.28	8.53	6.56
DEN	5.53	8.31	0.82	2.84	2.91	2.85	10.62	8.02
JFK	6.29	20.76	1.42	12.48	2.23	3.3	7.72	5.81
ATL	6.80	10.10	1.01	5.37	3.24	1.89	9.14	5.20
ORD	11.22	20.92	3.46	14.50	3.87	2.74	7.74	5.10

Table 12 contains many summarizing parameters for describing the taxiing behavior of airplanes at different facilities. Those reported numbers are summarizing the taxiing parameters for six airports and one day of PDARS data, however it seems that after reviewing the numbers precisely we can interpret valuable information from those numbers. Among the six airports ORD had the highest average taxi-in time for arrival flights. This airport also had the longest average taxiing distance and the highest waiting time for arrivals. These numbers show us that many flight at Chicago O'HARE Airport have considerable long taxiing paths and times which might be because of insufficient number of gates. Notice that these taxiing parameters are still missing the real gate-in time which can only be extracted from Aviation System Performance Metrics (ASPM). For the current studies this data set was not available to be used for the author.

ORD did not have the lowest average taxi-in speed among the six airports, where CLT had the lowest with an average taxi-in speed of 7.29 m/s. This average makes sense after we notice that CLT was the second airport in terms of waiting time for arrivals with an average of 3.3 minutes. The average taxiing distance of arrivals at CLT was around 1.5 km lower than the same amount for ORD, therefore we can figure out that why CLT had the lowest taxi-in speed.

DEN had the lowest average taxi-in time with an average of 5.53 minutes. This airport had the lowest waiting time for arrivals as well with an average of 0.82 minutes. Therefore, the highest average taxi-in speed of 10.62 m/s would not be surprise then.

ORD and JFK are the top two airports with the highest values of average taxi-out time. Since ORD had the highest average taxi-in time as well, ones can quickly conclude that JFK has an issue with the departure taxiing paths, as this facility did not have a high average taxi time for arrivals.

ORD has the highest waiting time for departures as well. The average waiting time for departures at this airport was 14.50 minutes which is almost 2 minutes more than the same value for JFK. Therefore, again it is not surprising to see that the average taxi-out speed at ORD was the lowest among all other five airports with a speed of 5.1 m/s. Although this analysis is done on the operations of one day at each of those airports, the values can be helpful for understating the taxiing patterns at those facilities. Many airports run almost the same fleet mix and flight schedule every day, so ones can refer to these numbers as relatively reliable taxiing information. ORD had the worst performance in terms of taxiing phases for both arrivals and departures. This mean that this facility may not have enough gates to accommodate to the flights, or may not have an efficient flight assignment to runways to reduce the waiting time in arrival or departure queues. JFK had the longest average taxi-out distance with an average of 3.3 kilometers. CLT stands at the third ranking of highest taxi-out times.

Generally, at all of the airports the taxi-out phases took a longer time than taxi-in phases. Moreover, the waiting times in taxi-out movements were higher than the waiting times in taxi-in movements. However, the taxiing distance is not following the same trend. DEN, ATL, and ORD had longer taxi-in distances than taxi-out distance. This might due to the runway configurations at airports, which need some procedures to let the departures fly while the arrivals are taxiing.

All of these parameters draw very precise information about the taxiing behaviors at each facility. The reliable functionality of Taxi Event Extraction Model is that each of those parameters are available for every flight. This reiterates how robust this approach is when studying taxiing behavior.

### 3.6. GUI

The source code of the Taxi Event Extraction Model was developed in MATLAB, however for more practical usage and upon request of the FAA operation office, a standalone application was developed based on the source code to meet the preferences of the users of this model.

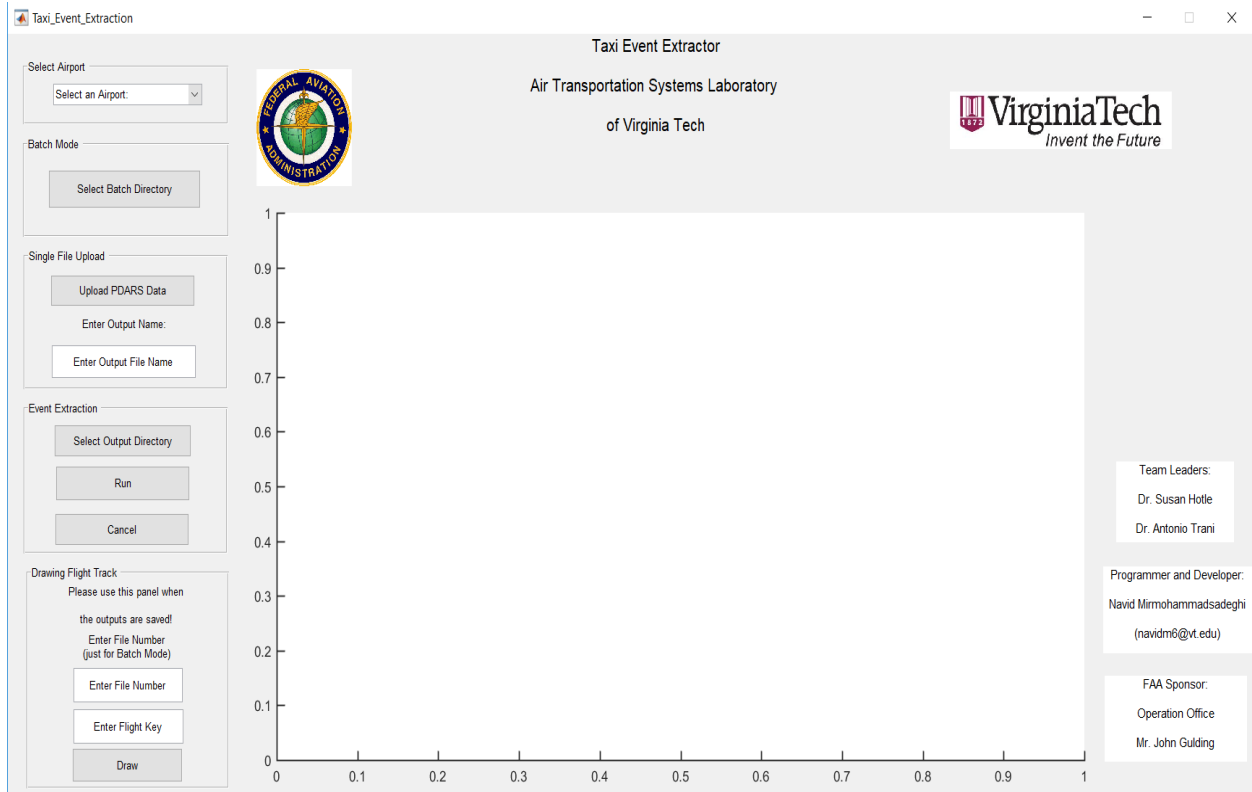


Figure 63. User Interface of Taxi Event Extraction Model.

Figure 63 represents the user interface of the event extractor. The user interface has 5 panels which can be used for different airports and different running conditions.

Since the sample inputs were provided for six airports, in the airport pop up menu there are 6 airports which are available for the user to choose and run the desired csv files for the selected facility.

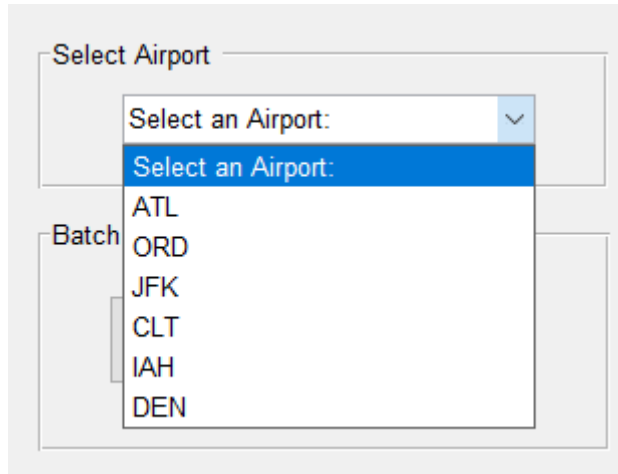


Figure 64. Six Airports Which the Event Extraction Model Supports.

Each airport can be run with two different methods:

- 1- Individual File Upload
- 2- Batch mode (multiple days for a single airport)

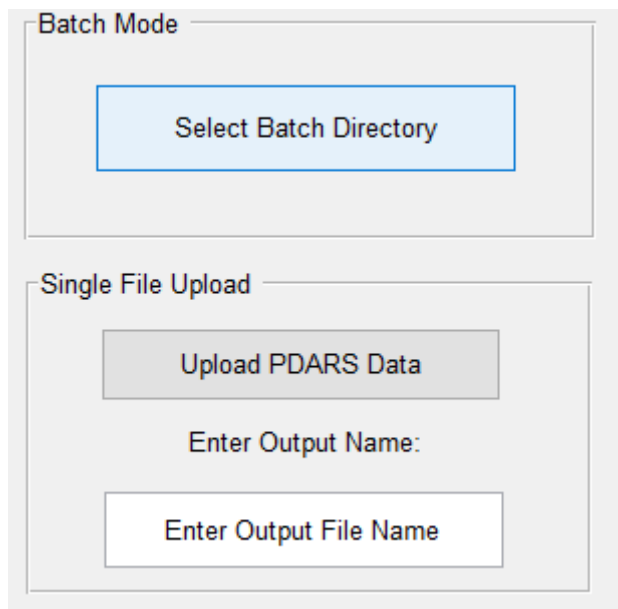


Figure 65. Selecting Input Files in Two Possible Ways.

The batch directory should contain only the PDARS sample for the defined airport. For example, if the user wants to run many PDARS samples for CLT, after selecting CLT from the pop up menu, the selected directory for the batch mode should only contain the PDARS IFF samples of CLT airport.

For single file upload, the user will be navigated to a file browser in its computer and it can choose an IFF PDARS sample to analyze. The single file upload gives the ability of saving the output files with the user's desired name, however in the batch mode the name of the input files will be used with a prefix of results.

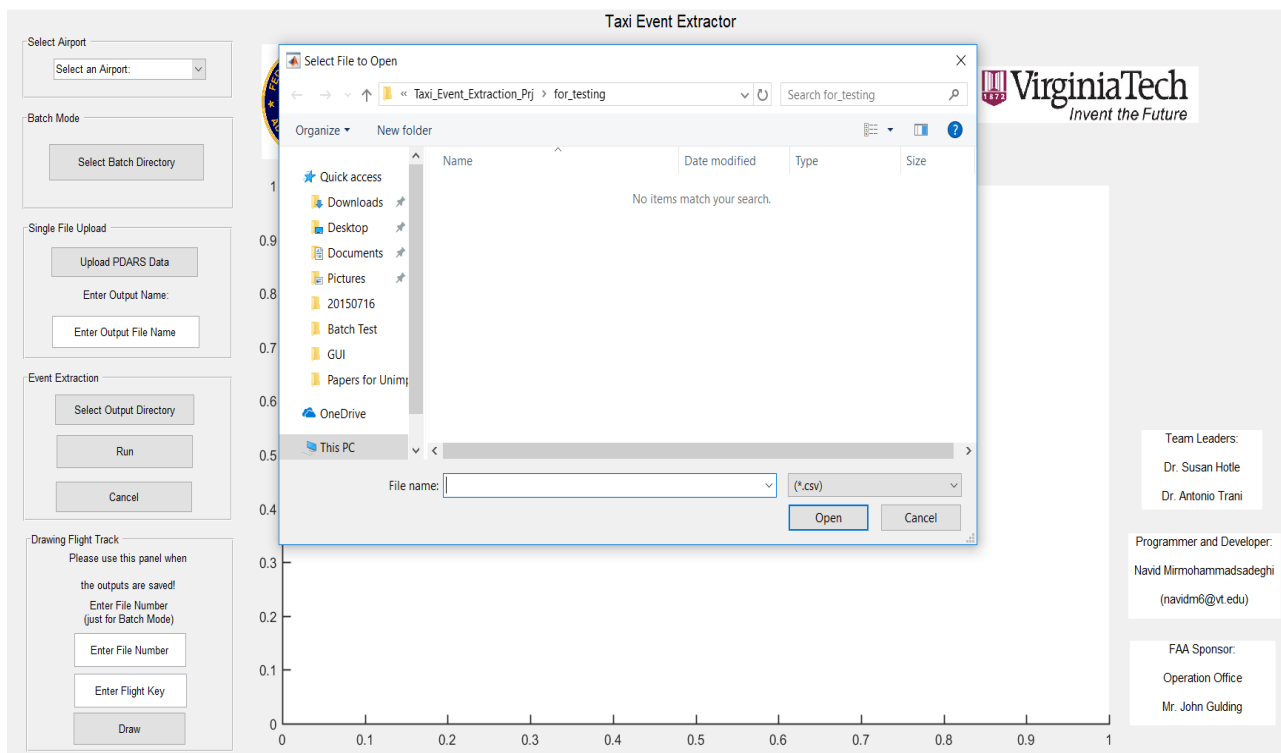


Figure 66. Folder Browser for Uploading the Input File.

The event extraction panel has two important keys. The user can choose an output directory for the final output tables to be saved. The tables will be in (.csv) format and they can be opened in

Excel. The second important key is run button which after activating will show the number of parsed movements from the input files. This will give the user an idea of how many movements were parsed from the input file. In batch mode, this number refresh for every new file that the model starts analyzing.

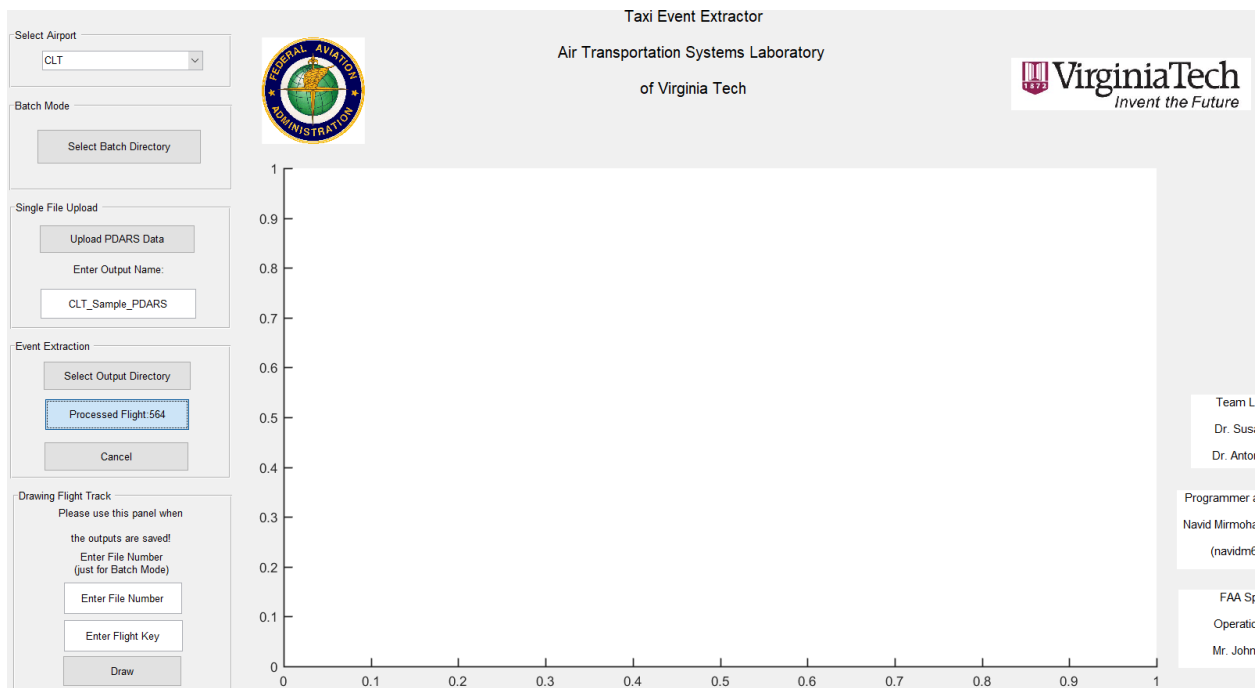


Figure 67. The Number of Processed Flights is Shown to the User.

After finishing the initial parsing and reading all the movements from the input files, the model starts extracting critical taxi events at the airport. A waiting bar shows the process to the user. By the end of the analysis the user will be notified that the extraction is complete and the output files are saved in the output directory.



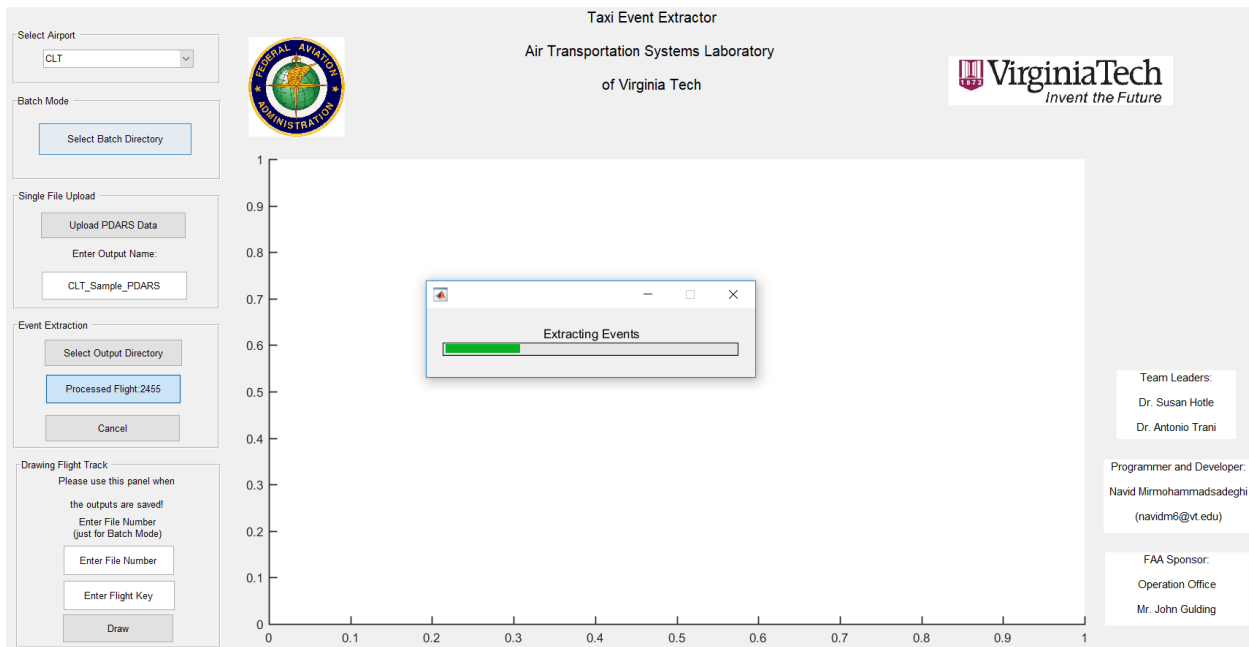


Figure 68. A Waiting Bar Shows the Process of Event Extraction to the User.

As it is mentioned earlier the output for each airport sample file is a table with 25 fields. The table summarizes each operation in terms of entering or leaving the airport and important events while taxiing in airport. Each even is reported with a start and end time tag, plus the location of each of those moments.

Another feature provided for the user in this tool is that after the analysis is done and output files are saved, the user can draw any specific flight’s track point to have an idea of how the operation happened at the airport. The visualization feature can be helpful for further validations as well, because it represents the critical extracted moments as well. A big challenge for such studies and even companies which analyze the ASDE-X data at airports is the ability of tool to assign the operation to the correct runway end which was used in the real operation. The visualization

option of the tool can help the user to validate the process which was done for assigning the flights to the runways. Visualization of different flights are shown in Figures 69 and 70.

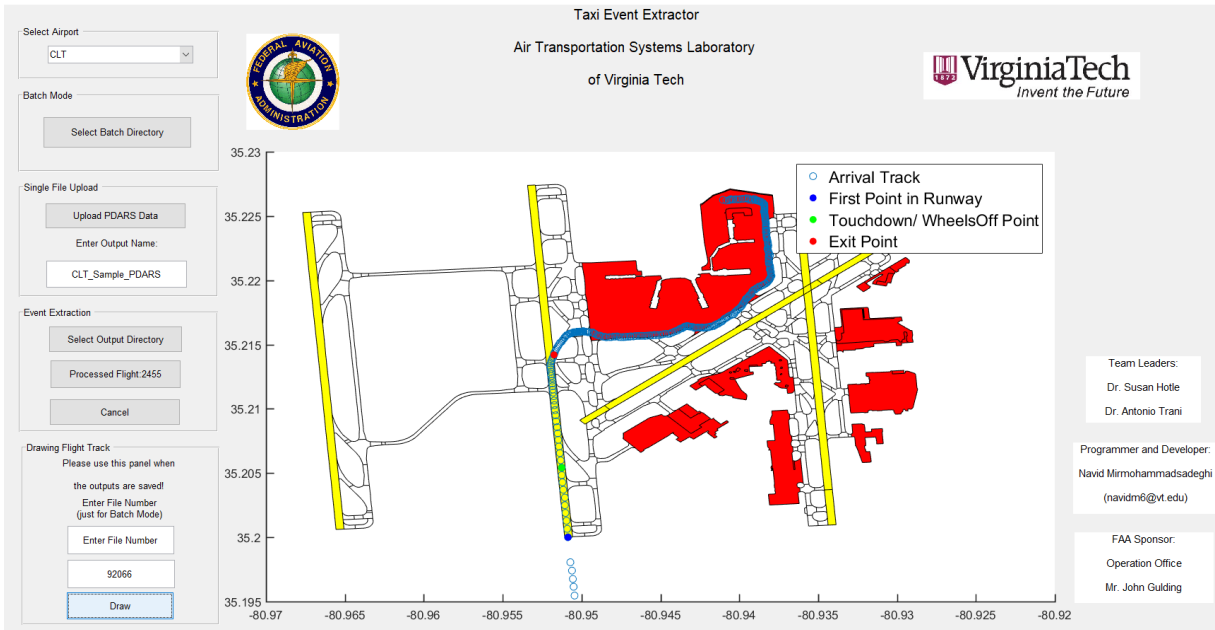


Figure 69. Visualization Tool of Event Extraction Model Showing an Arrival at CLT with Critical Moments.

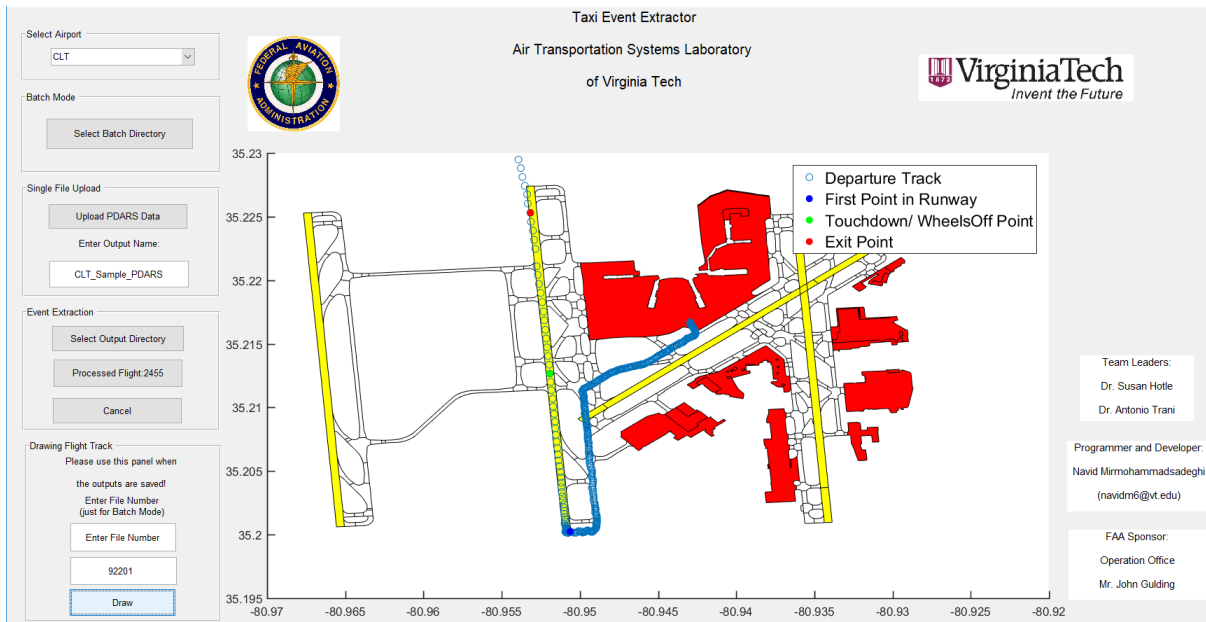


Figure 70. Visualization Tool of Event Extraction Model Showing a Departure at CLT with Critical Moments.

### 3.7. Validation Plots

## Charlotte Douglas International Airport (CLT)

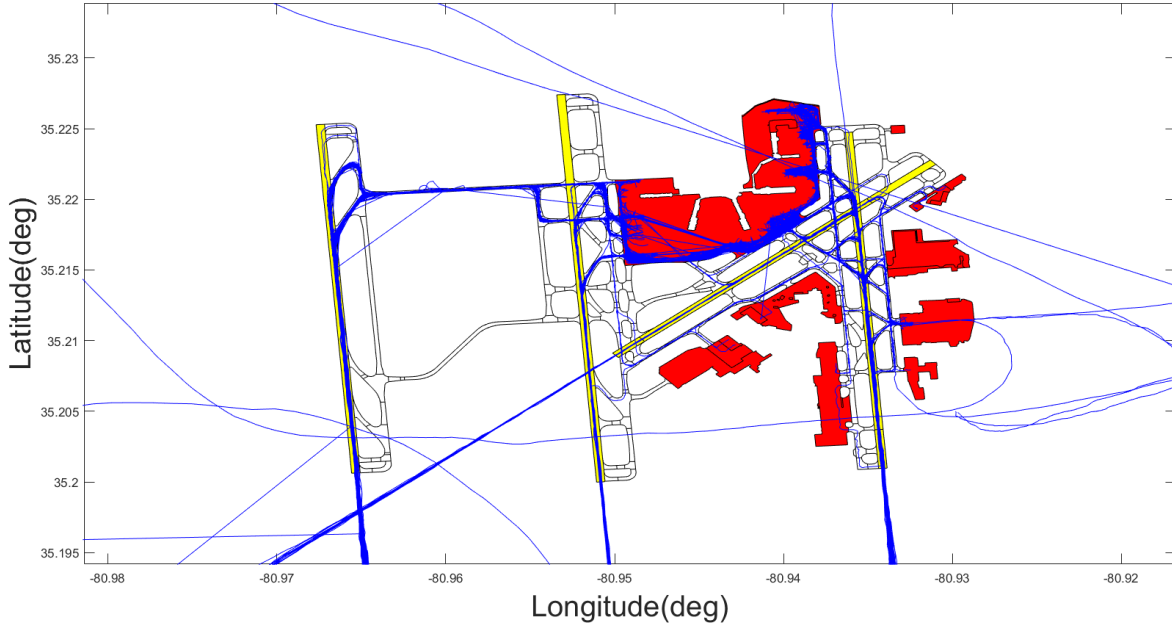


Figure 71. CLT, all of the Arrivals on 2015-07-16 and a few on 2015-07-17.

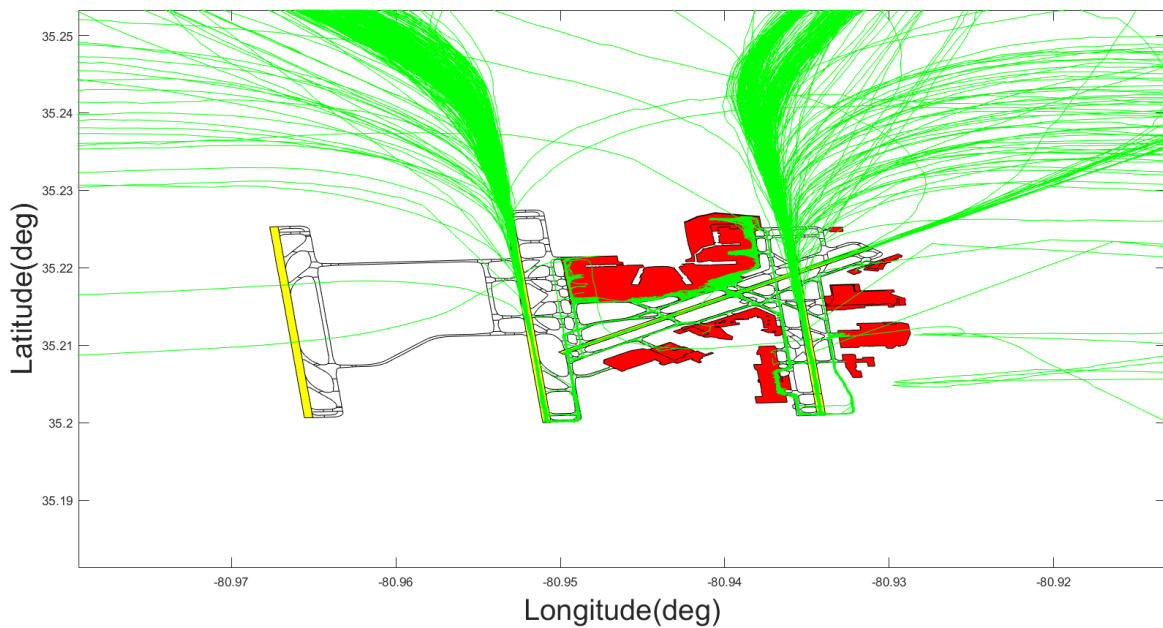


Figure 72. CLT, all of the Departures on 2015-07-16 and a few on 2015-07-17.

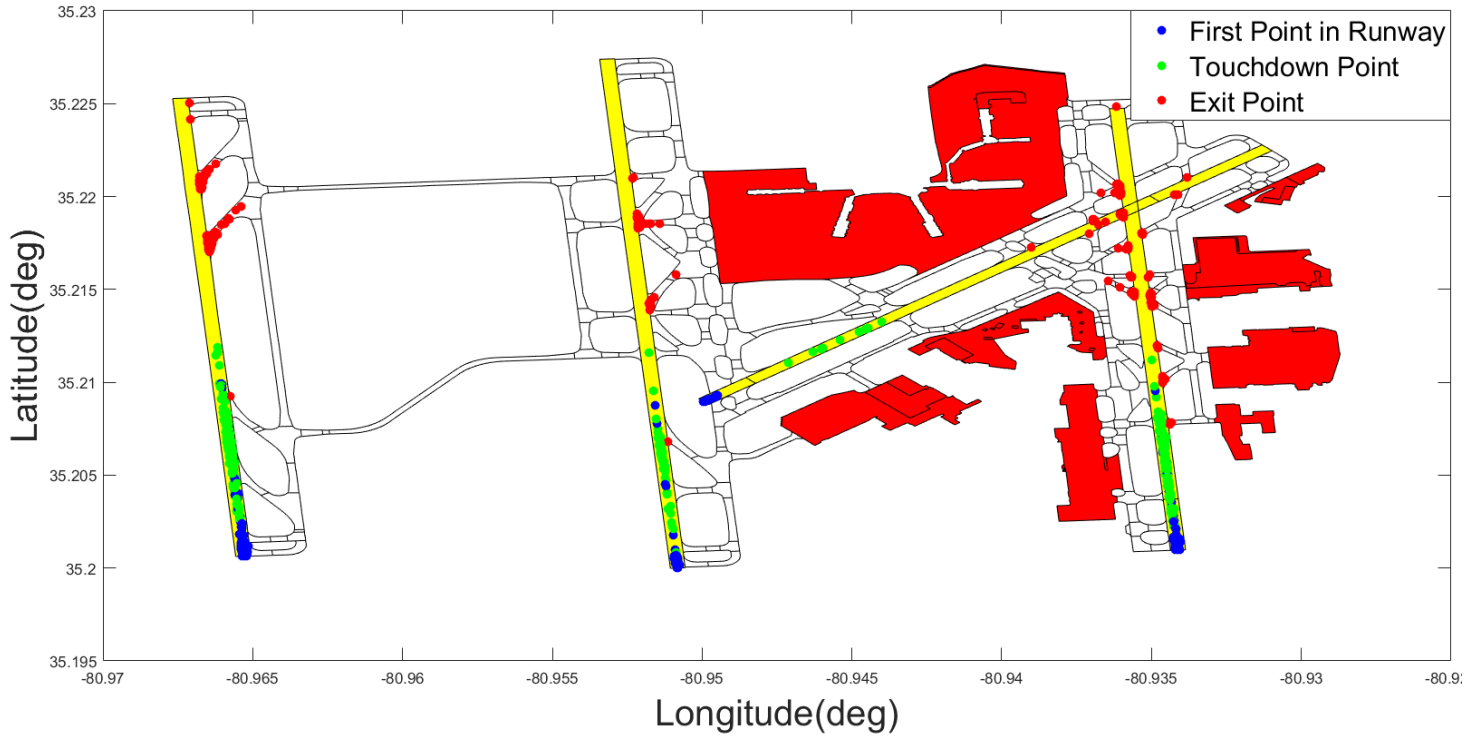


Figure 73. Event Extraction Parser Critical Points for Arrivals, Locations of the First Point in Runway Polygon, Touchdown Point, and Exit Points.

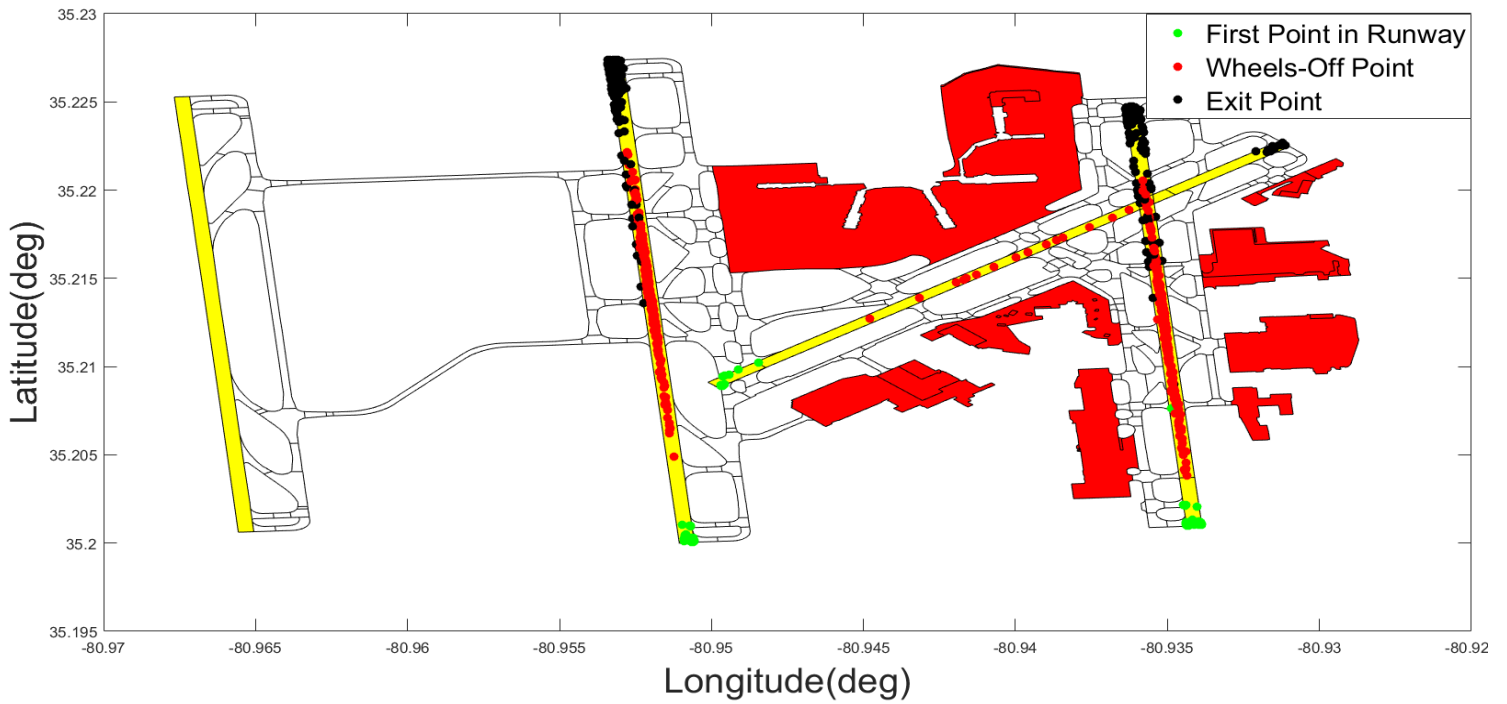


Figure 74. Event Extraction Parser Critical Points for Departures, Locations of the First Point in Runway Polygon, Wheels Off Point, and Exit Points.

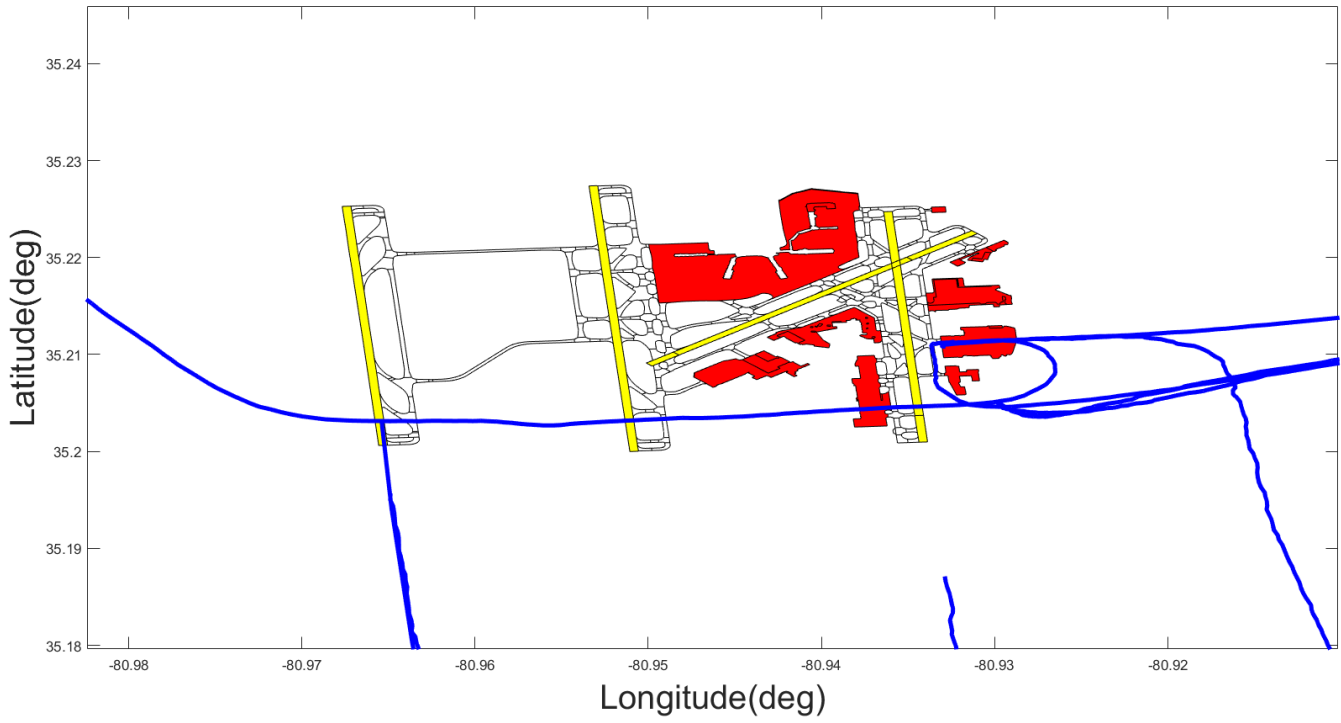


Figure 75. Arrival Flights Which are not Assigned to any Runways.

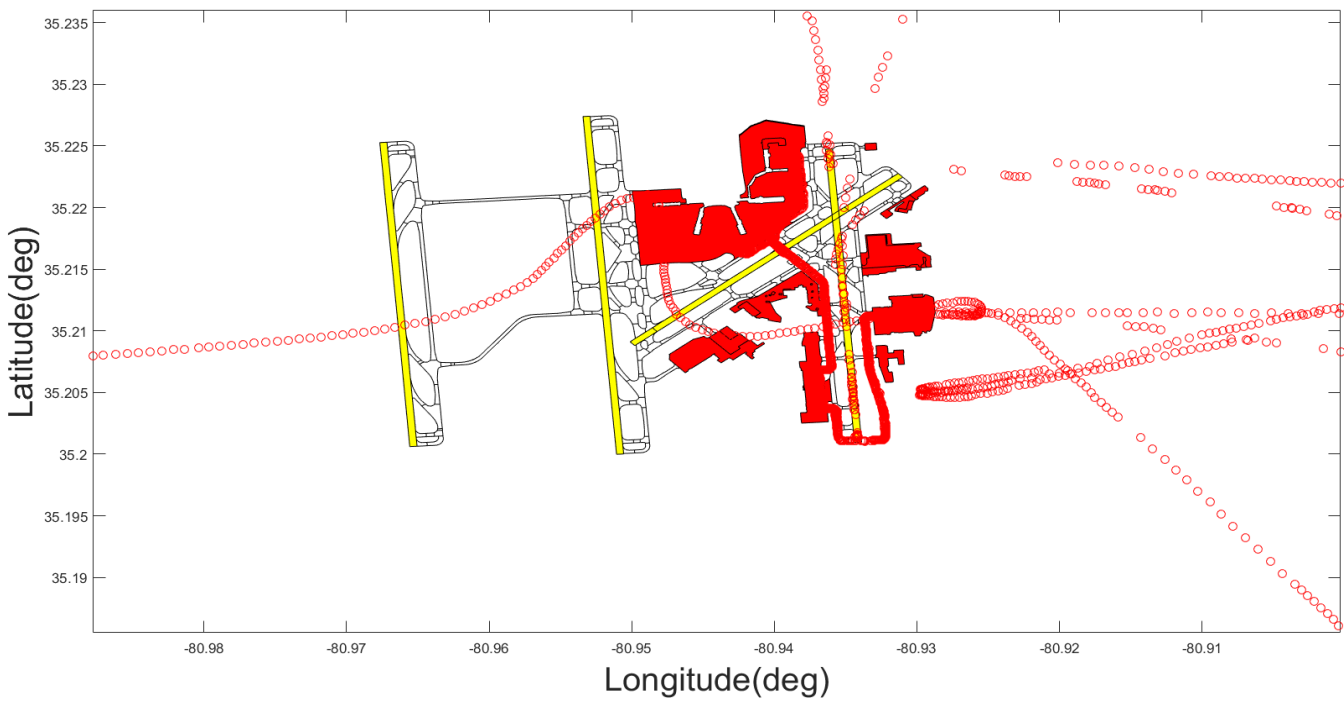


Figure 76. Departure Flights Which are not Assigned to any Runways.

Note: Incomplete track lines or strange tracks can be seen in Figure 6.

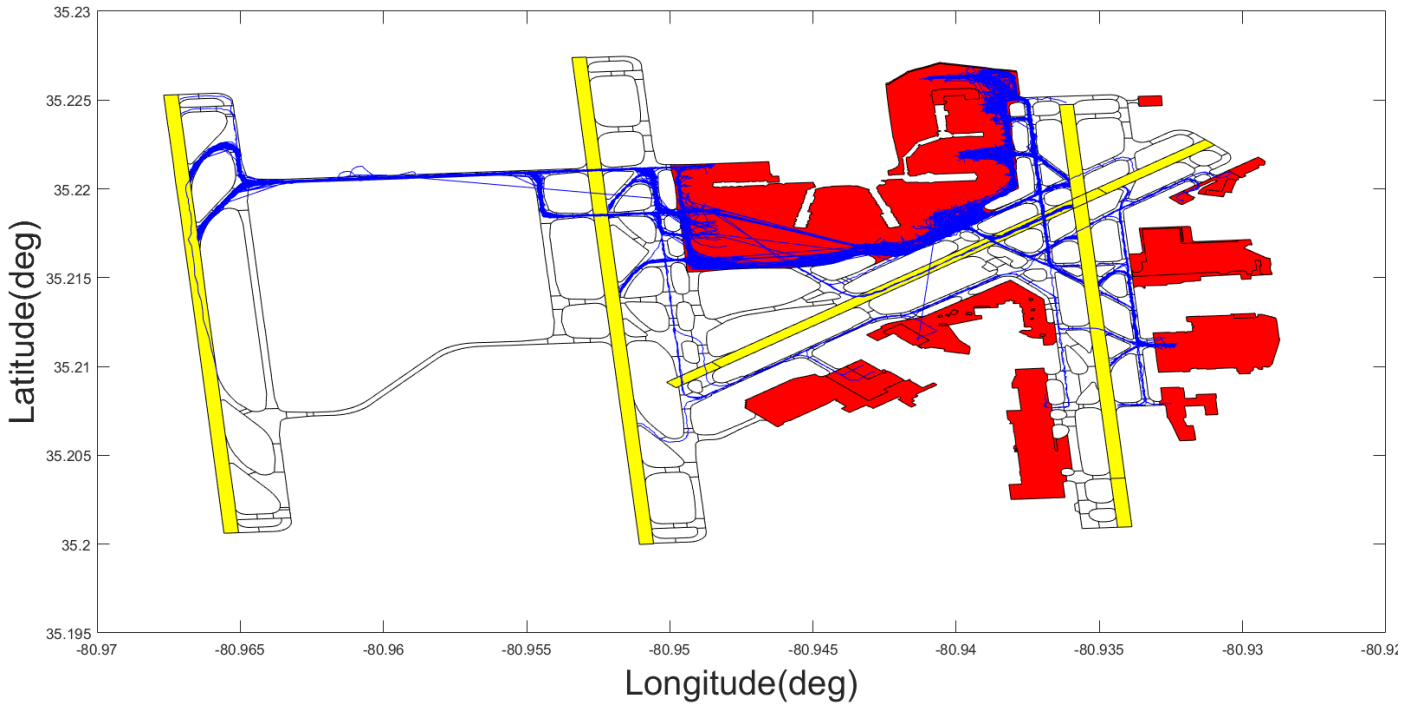


Figure 77. Arrivals Taxiing Tracks from the Runway Exit to the Final Track Point.

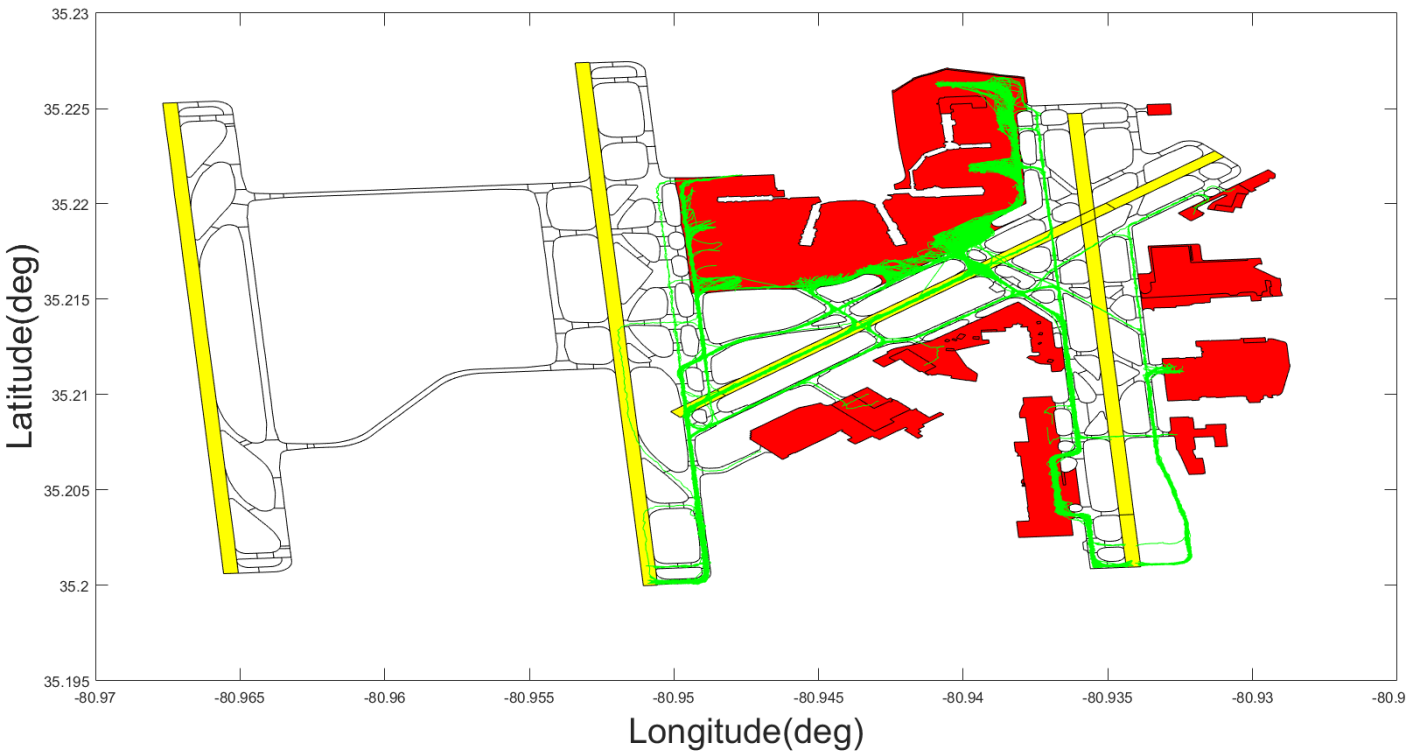


Figure 78. Departures Taxiing Tracks from the First Track Point to the Enter Runway Point.

Note: Few tracks on the runways show that airplanes use part of runway for taxiing.



# George Bush Intercontinental Airport (IAH)

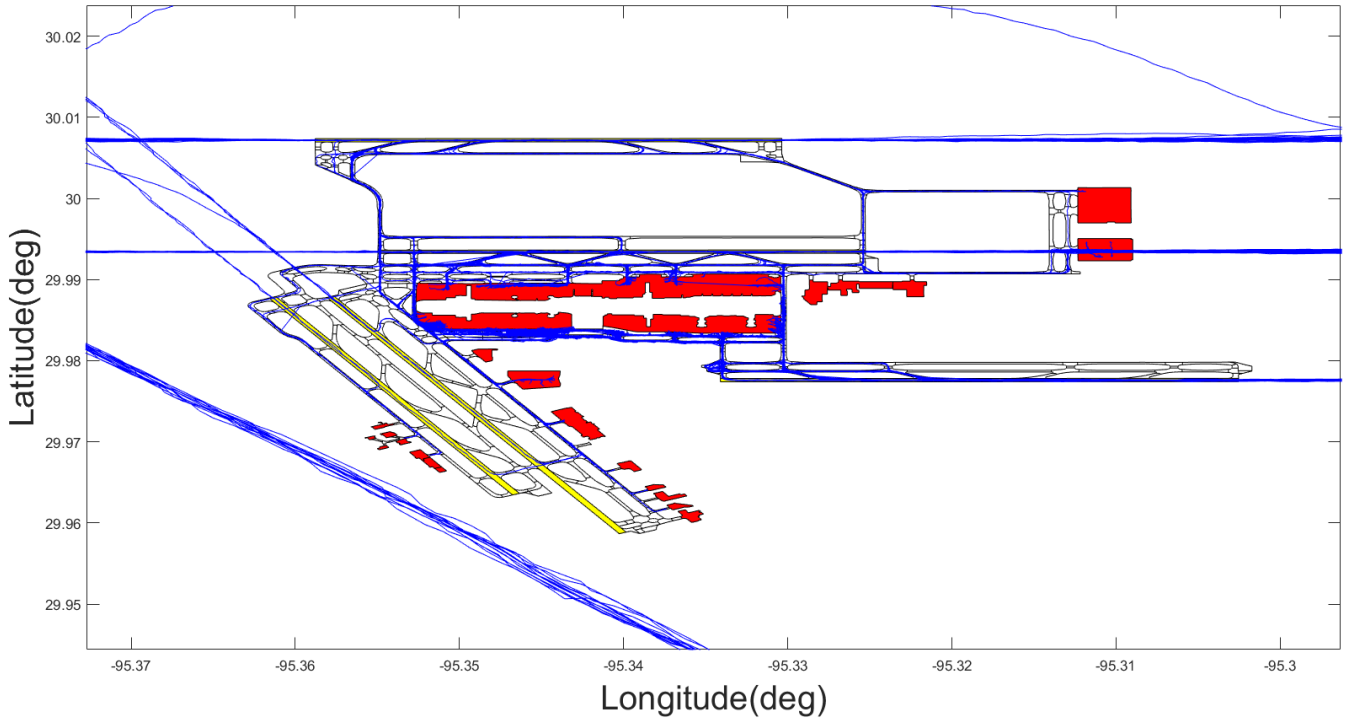


Figure 79. IAH, all of the Arrivals on 2015-07-16 and a few on 2015-07-17.

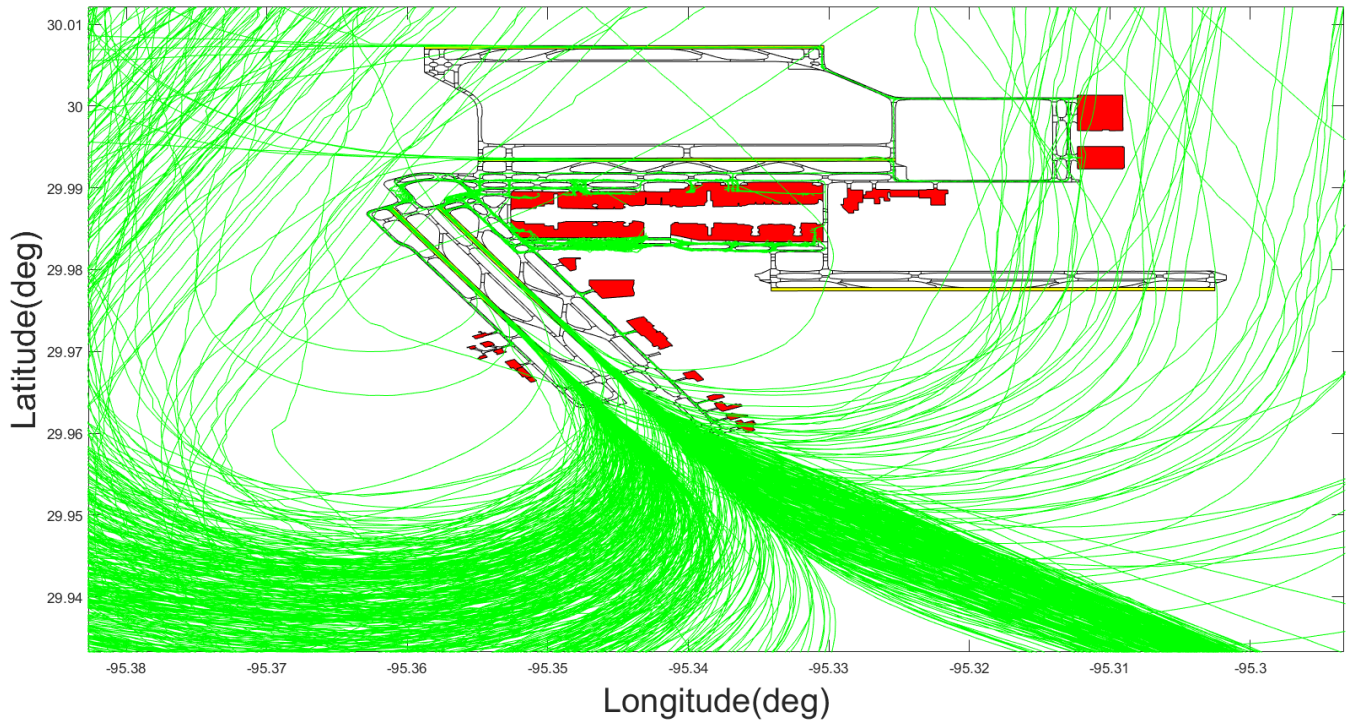


Figure 80. IAH, all of the Departures on 2015-07-16 and a few on 2015-07-17.

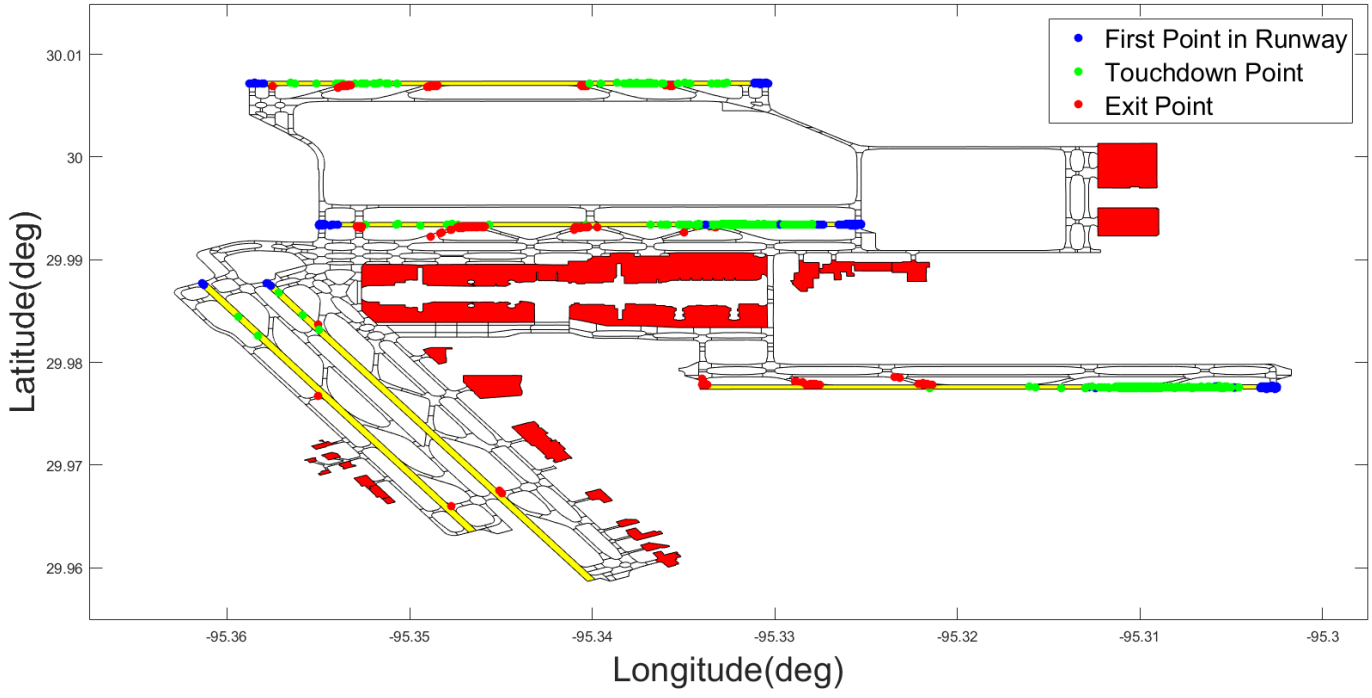


Figure 81. Event Extraction Parser Critical Points for Arrivals, Locations of the First Point in Runway Polygon, Touchdown Point, and Exit Points.

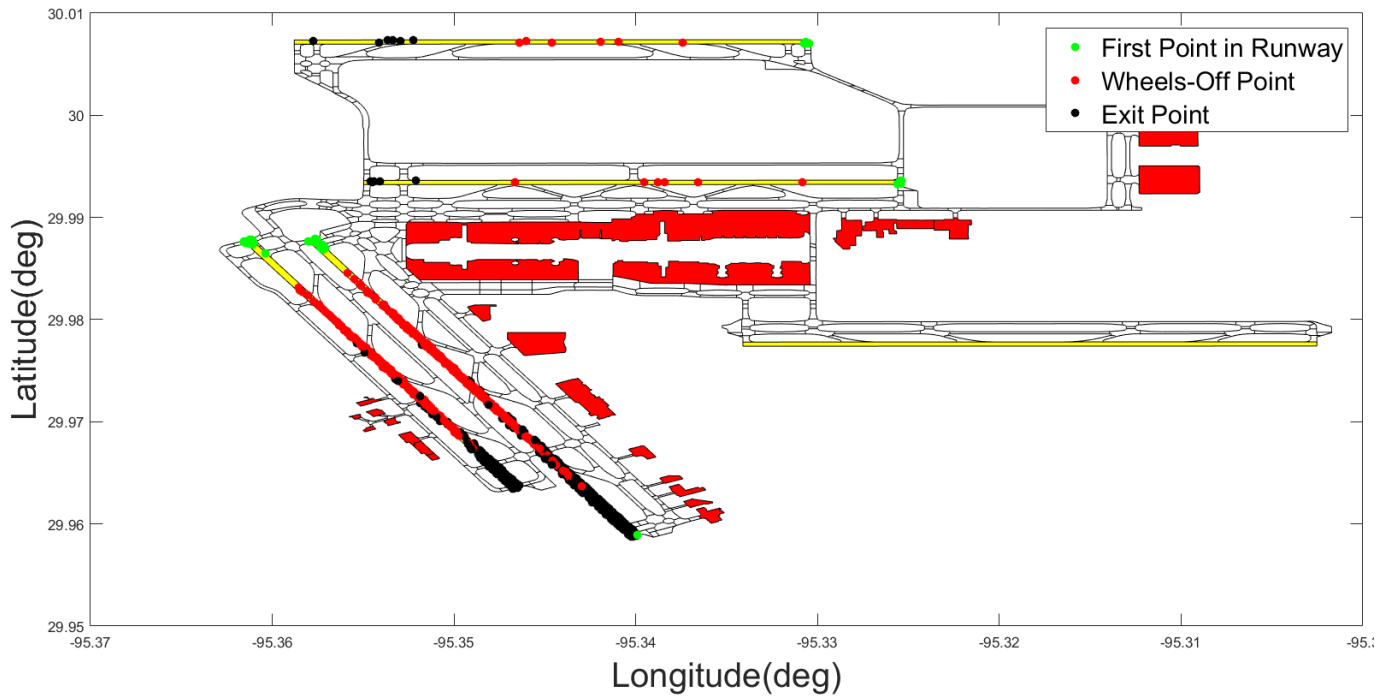


Figure 82. Event Extraction Parser Critical Points for Departures, Locations of the First Point in Runway Polygon, Wheels Off Point, and Exit Points.



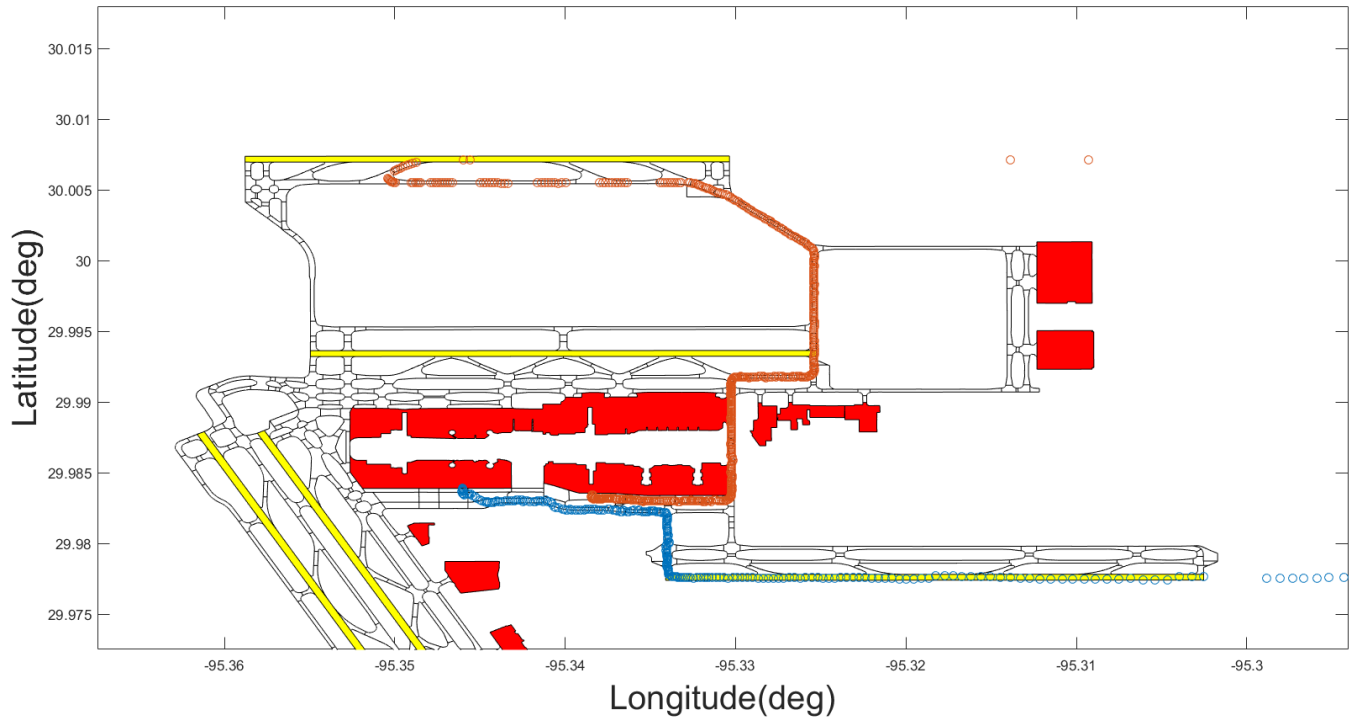


Figure 83. Arrival Flights Which are not Assigned to any Runways.

Note: Incomplete arrival track, and inaccurate track points were extracted from the runway group in order to have more reliable calculated variables.

Note: This airport did not have any departure flights which the event model could not be able to assign to any runways.

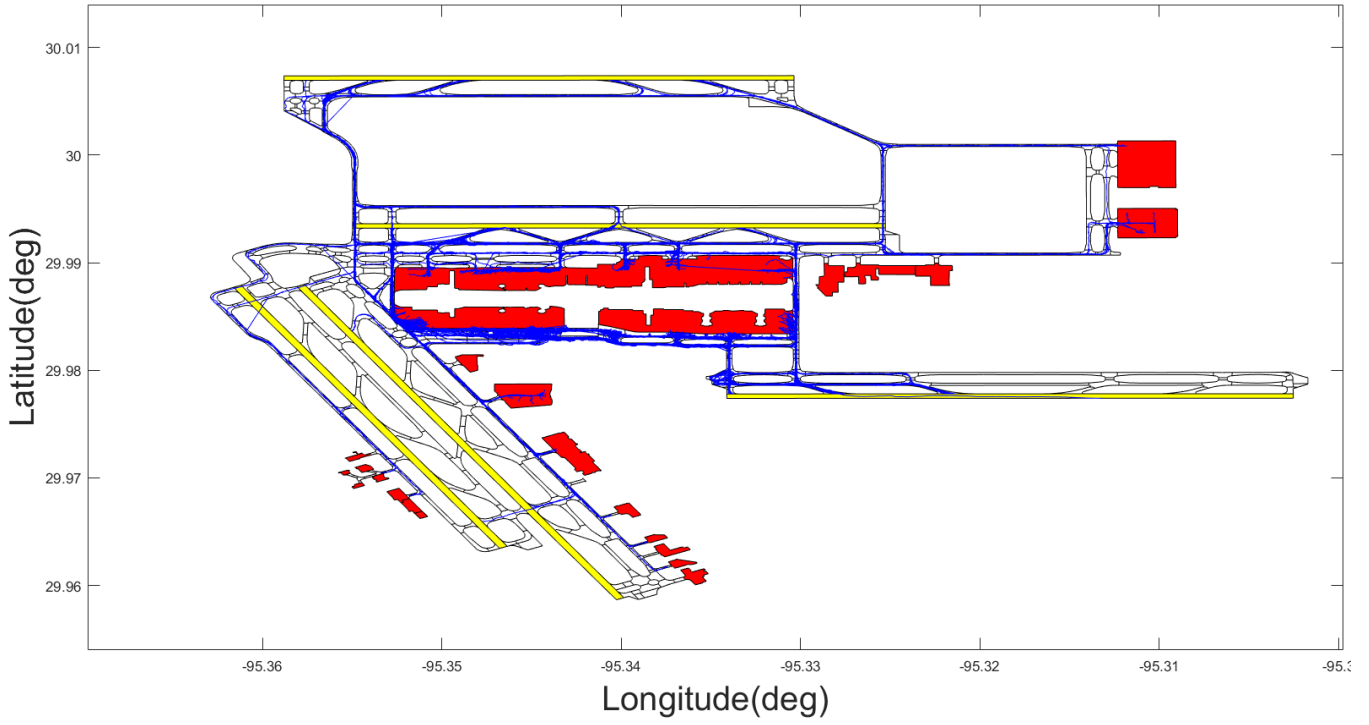


Figure 84. Arrivals Taxiing Tracks from the Runway Exit to the Final Track Point.

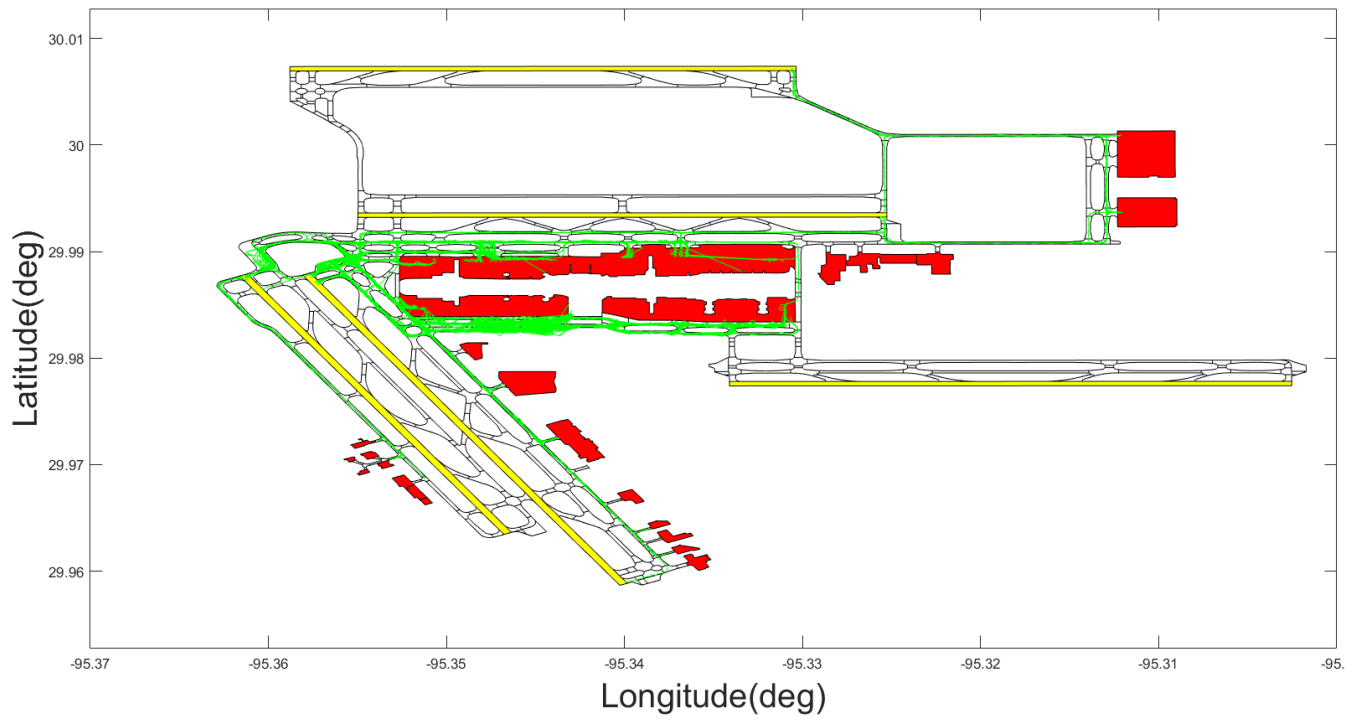


Figure 85. Departures Taxiing Tracks from the First Track Point to the Enter Runway Point.

# Denver International Airport (DEN)

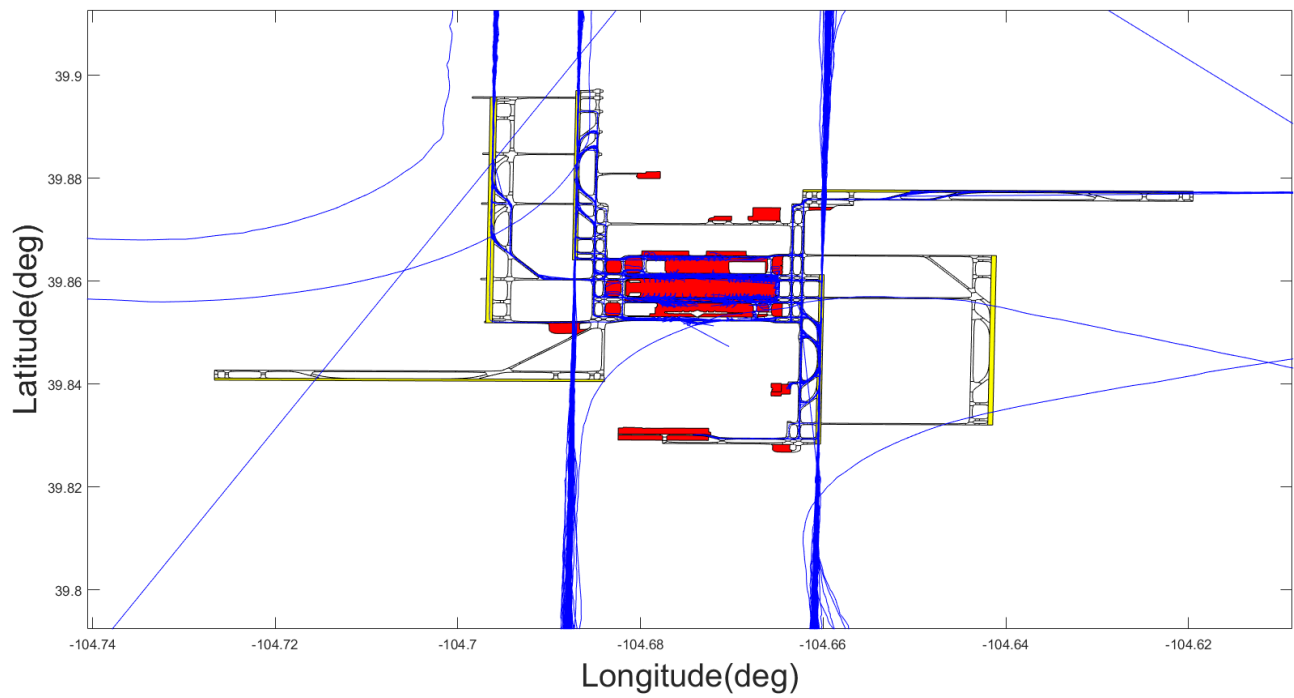


Figure 86. DEN, all of the Arrivals on 2015-07-16 and a few on 2015-07-17.

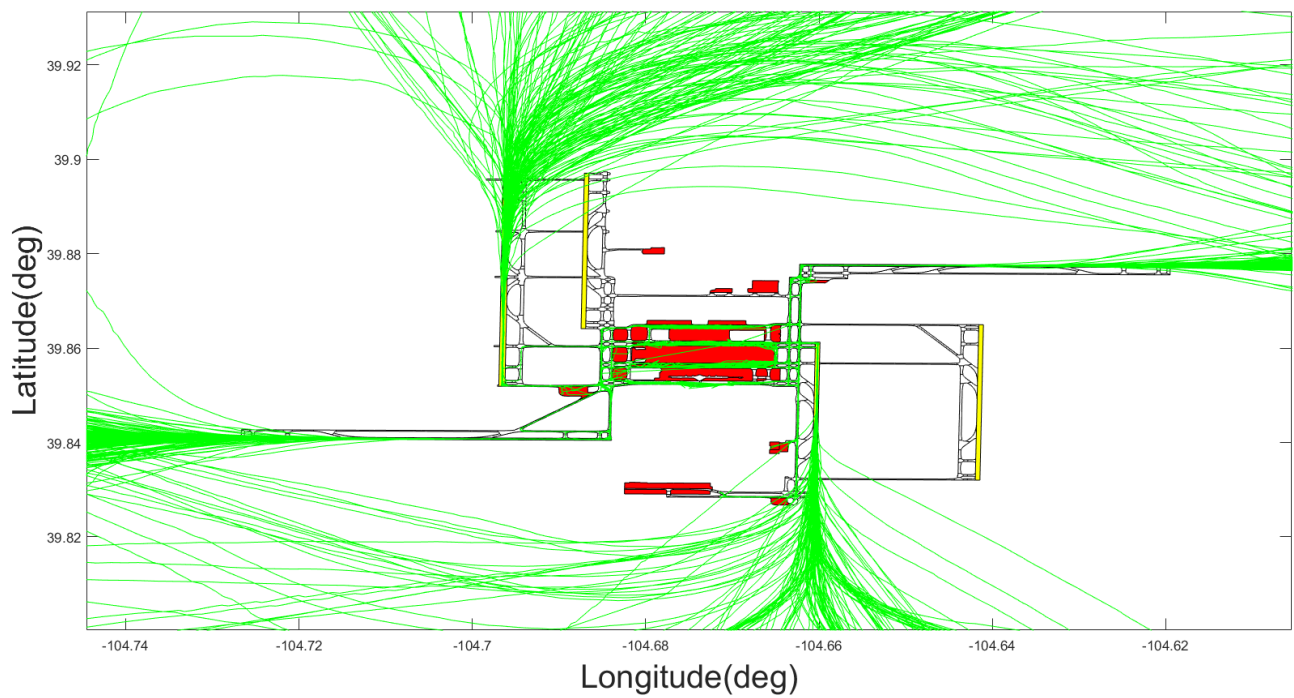


Figure 87. DEN, all of the Departures on 2015-07-16 and a few on 2015-07-17.

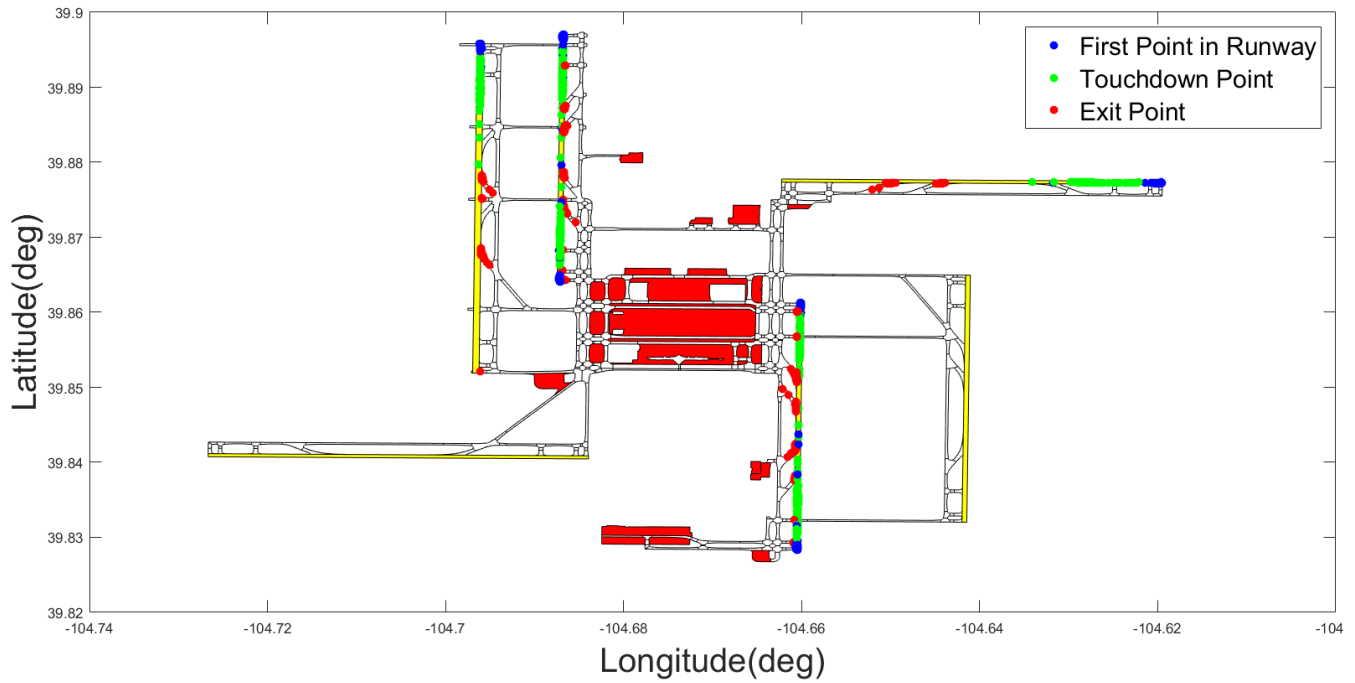


Figure 88. Event Extraction Parser Critical Points for Arrivals, Locations of the First Point in Runway Polygon, Touchdown Point, and Exit Points.

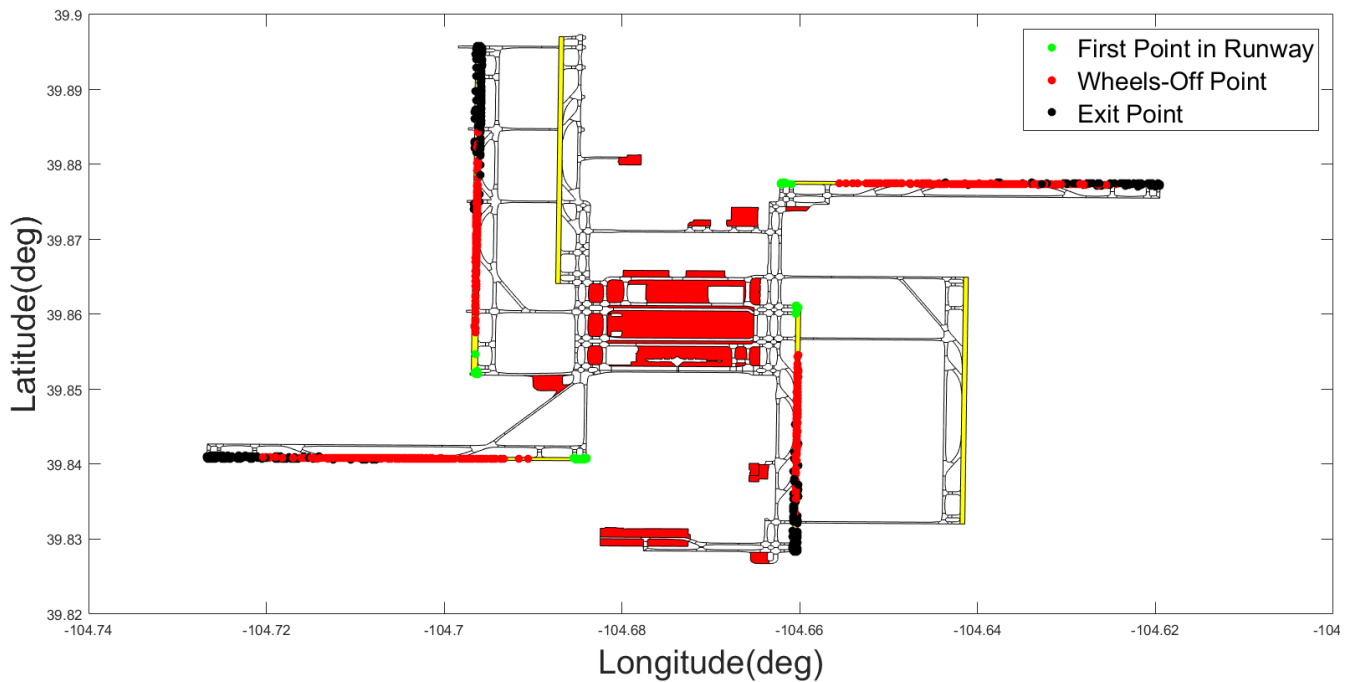


Figure 89. Event Extraction Parser Critical Points for Departures, Locations of the First Point in Runway Polygon, Wheels Off Point, and Exit Points.

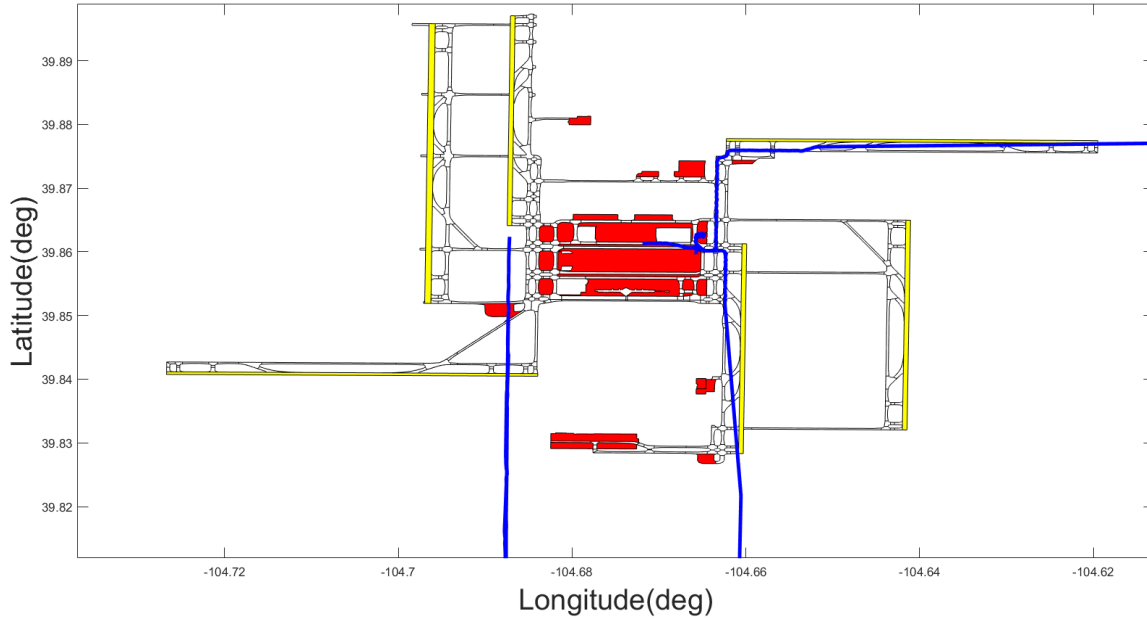


Figure 90. Arrival Flights Which are not Assigned to any Runways.

Note: Flight tracks are not reaching runway polygons, or they do not even touch the boundaries of runway polygons.

There were three departure flights that were not assign to any runway due to not satisfying of departures altitude requirements.

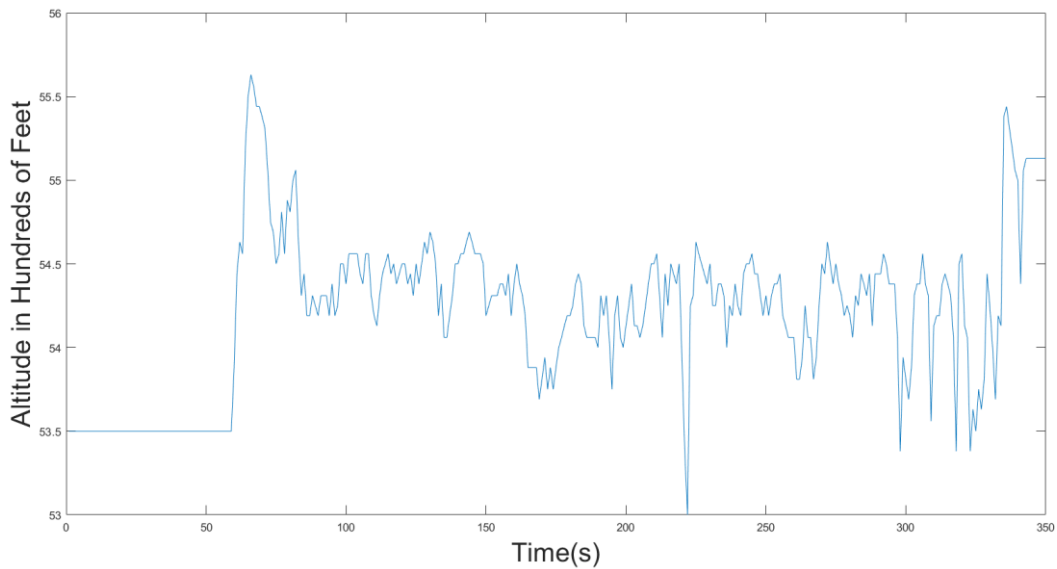


Figure 91. Noisy Altitude Profile of One of the Departure Flights, which is not Assigned to any Runway.

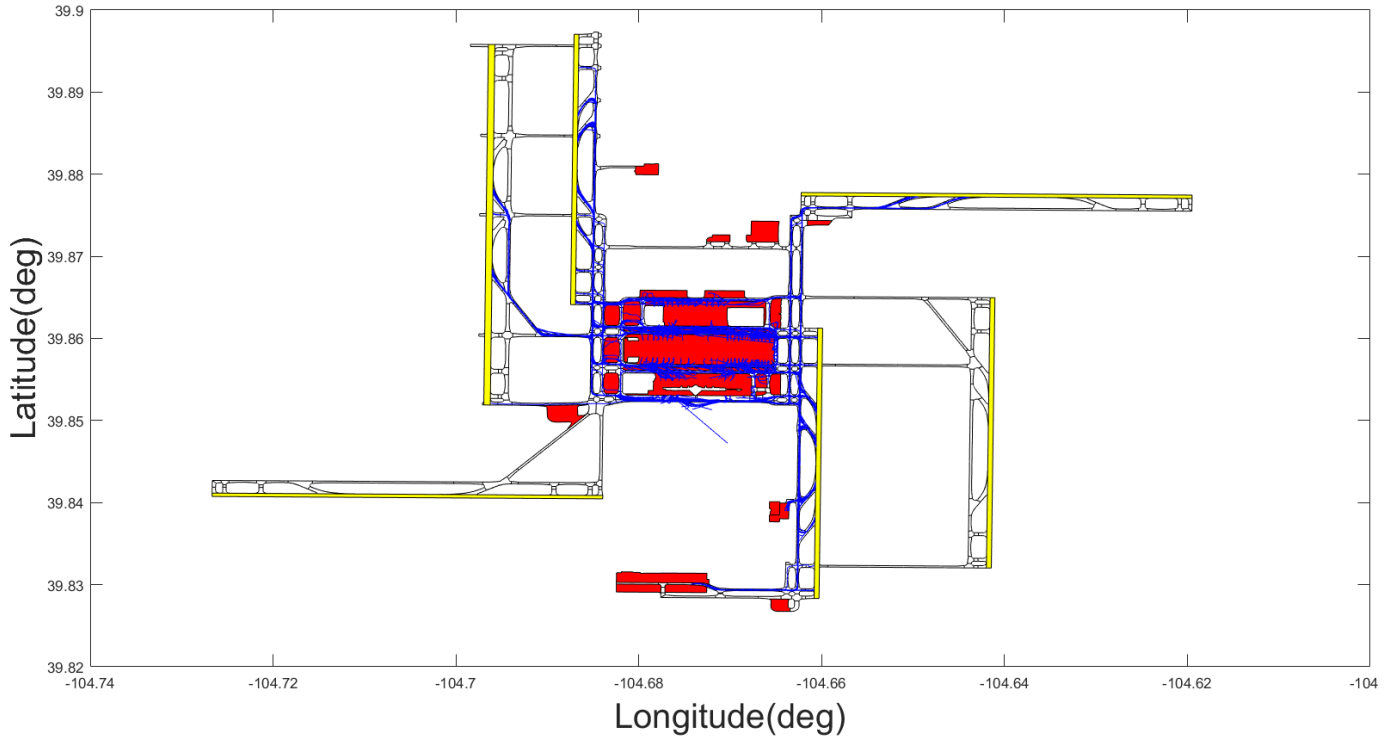


Figure 92. Arrivals Taxiing Tracks from the Runway Exit to the Final Track Point.

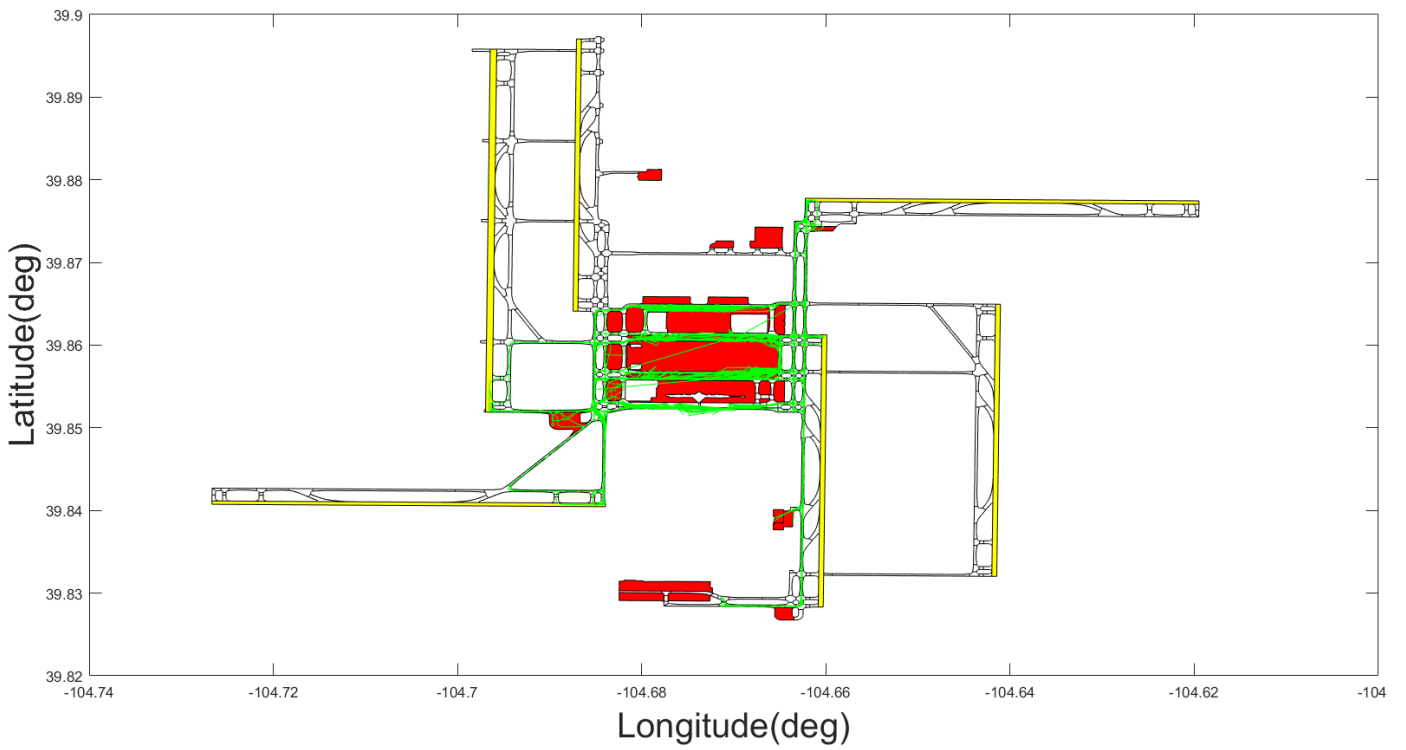


Figure 93. Departures Taxiing Tracks from the First Track Point to the Enter Runway Point.

# John F. Kennedy International Airport (JFK)

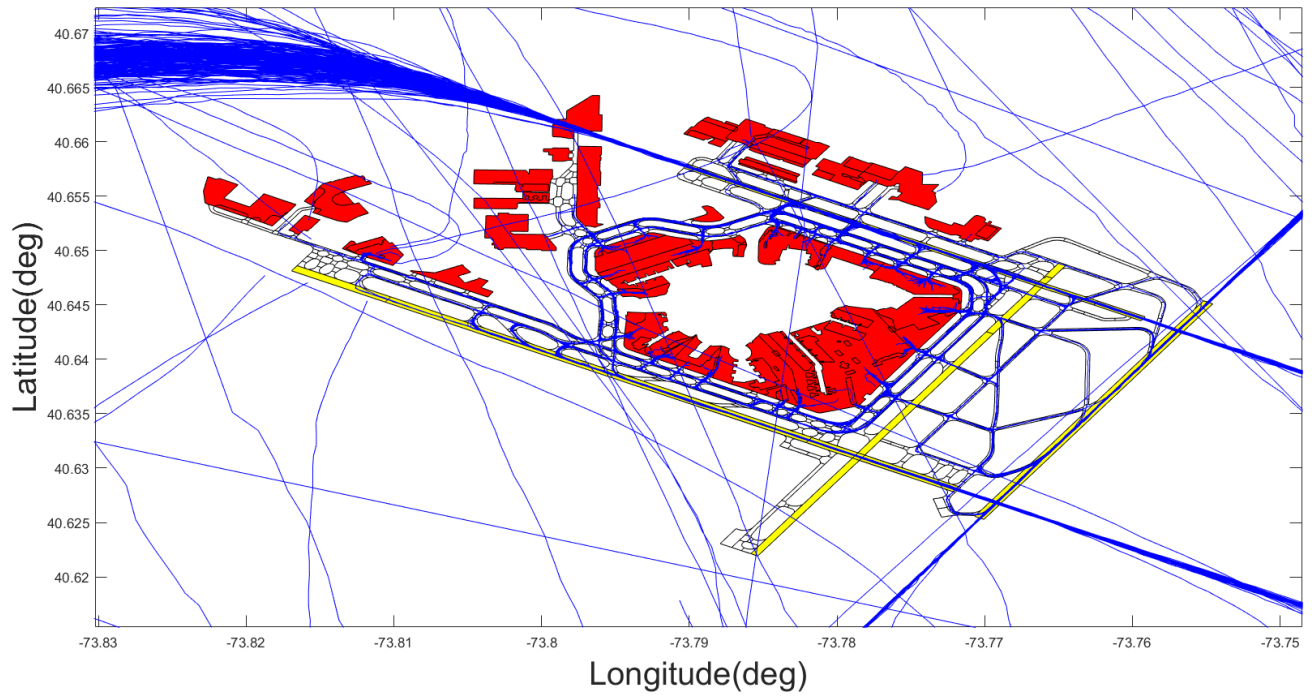


Figure 94. JFK, all of the Arrivals on 2015-07-16 and a few on 2015-07-17.

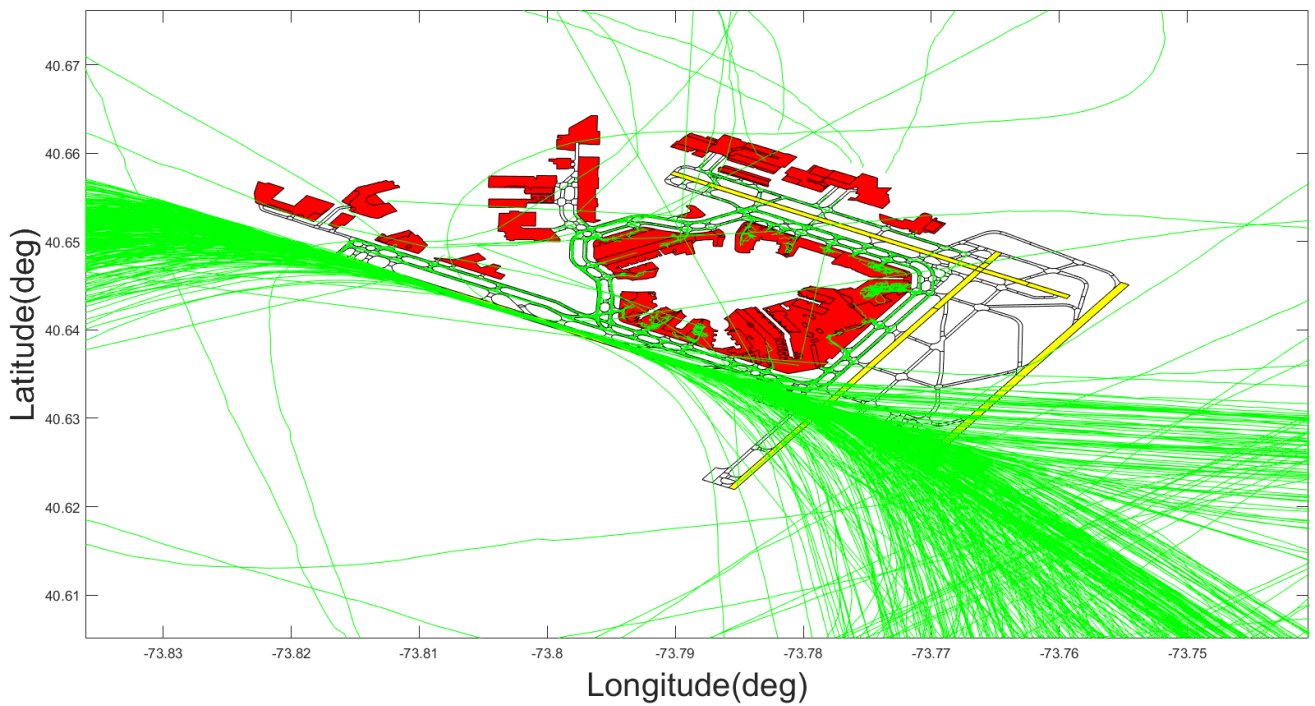


Figure 95. JFK, all of the Departures on 2015-07-16 and a few on 2015-07-17.



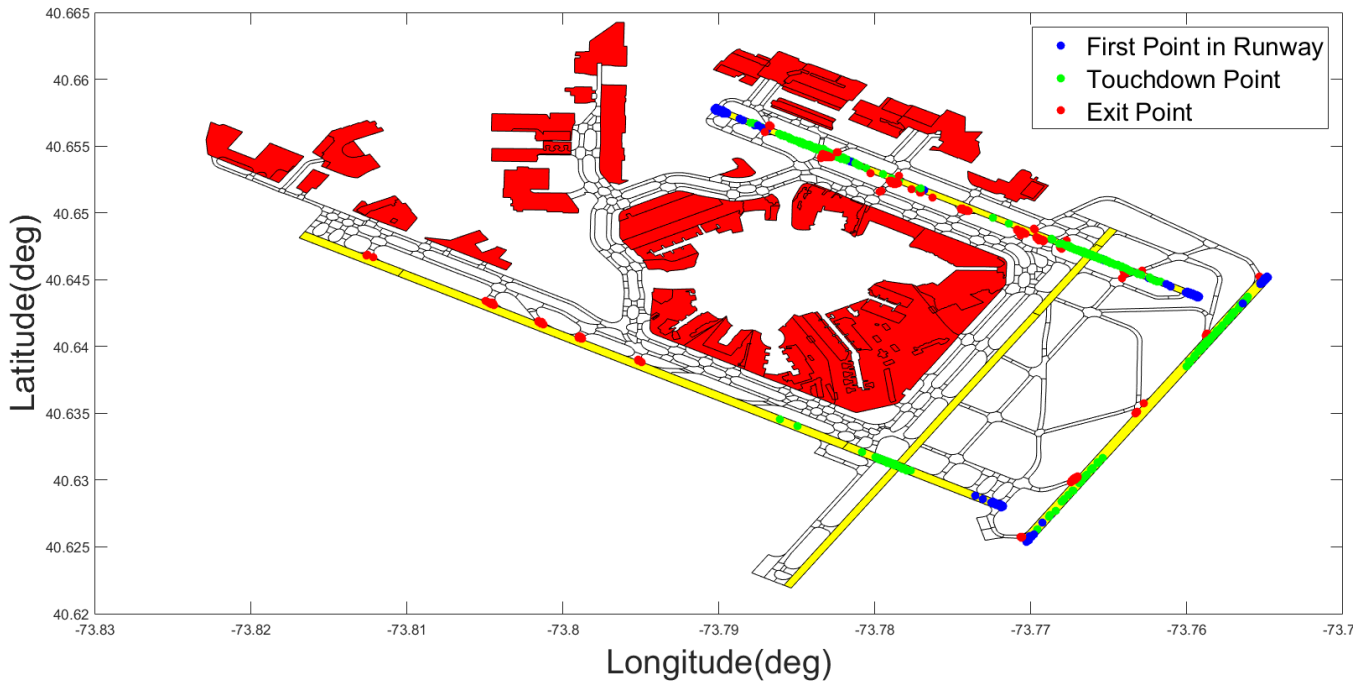


Figure 96. Event Extraction Parser Critical Points for Arrivals, Locations of the First Point in Runway Polygon, Touchdown Point, and Exit Points.

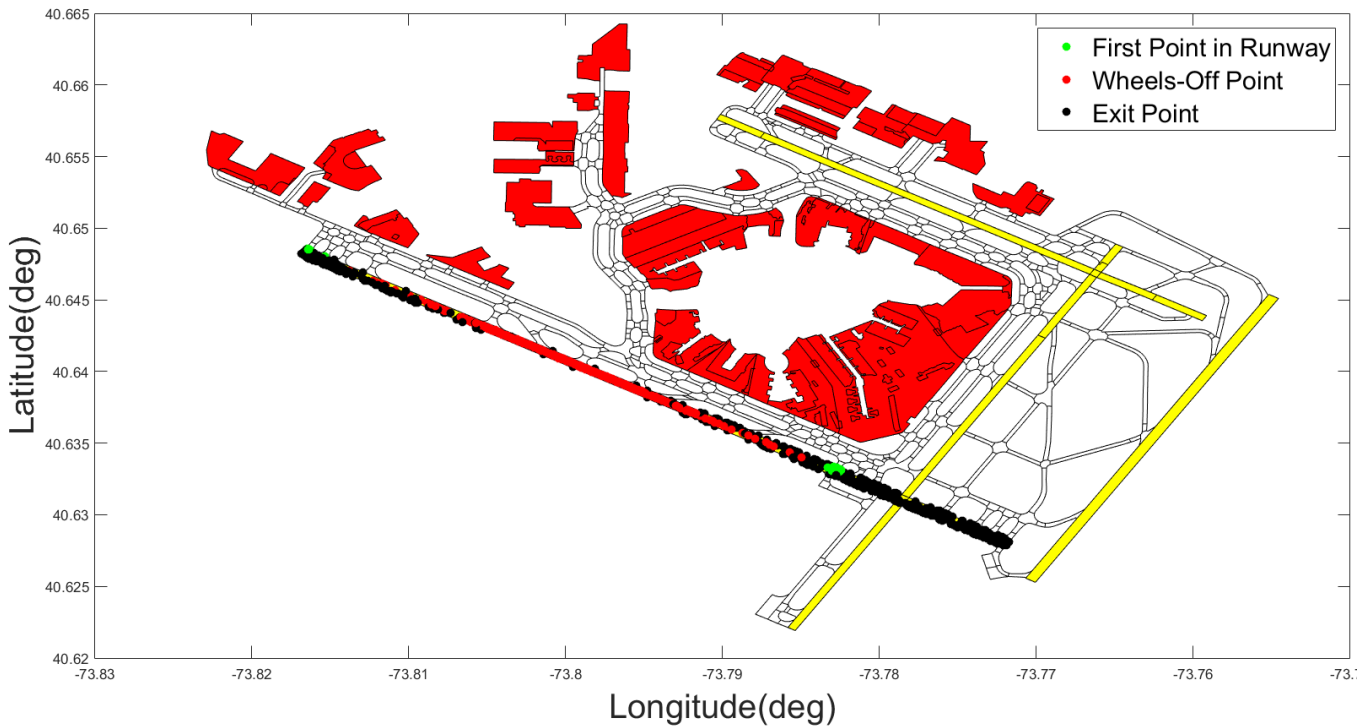


Figure 97. Event Extraction Parser Critical Points for Departures, Locations of the First Point in Runway Polygon, Wheels Off Point, and Exit Points.



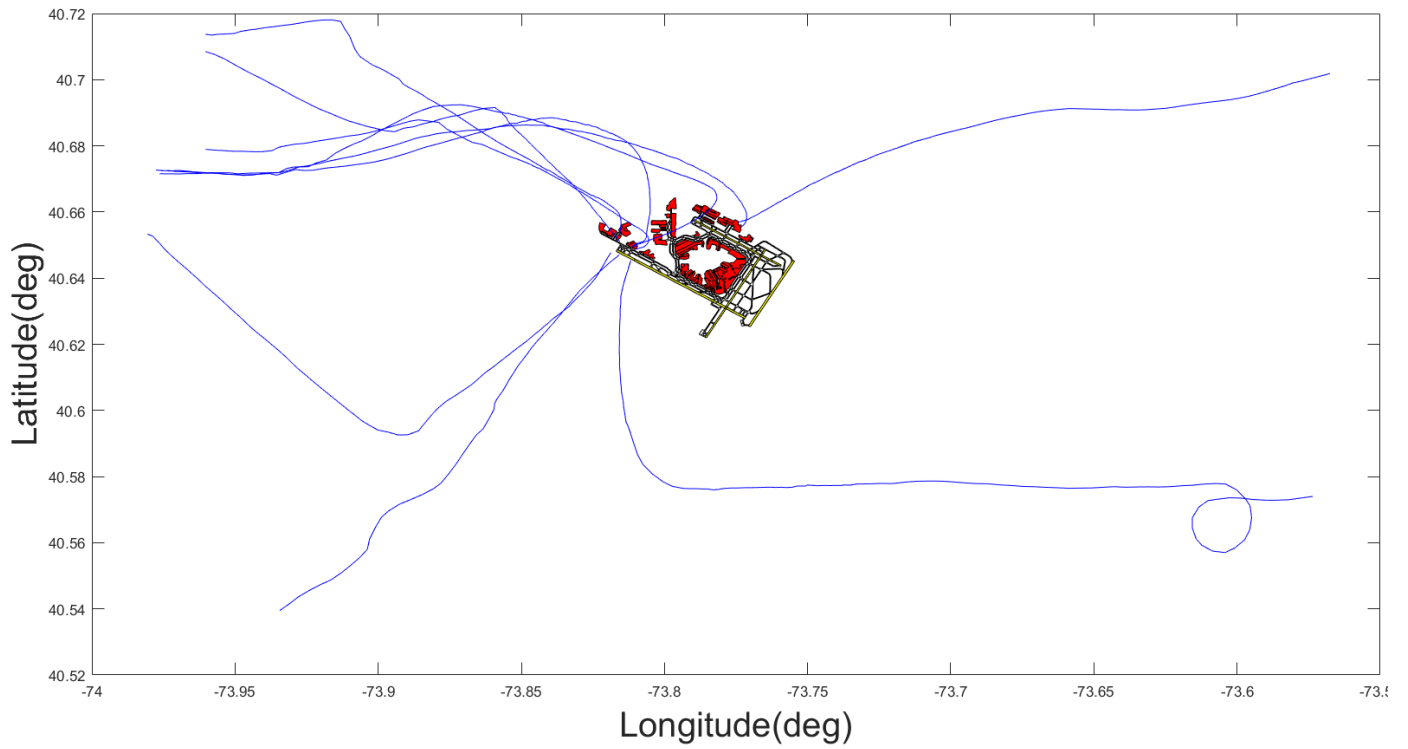


Figure 98. Arrival Flights Which are not Assigned to any Runways.

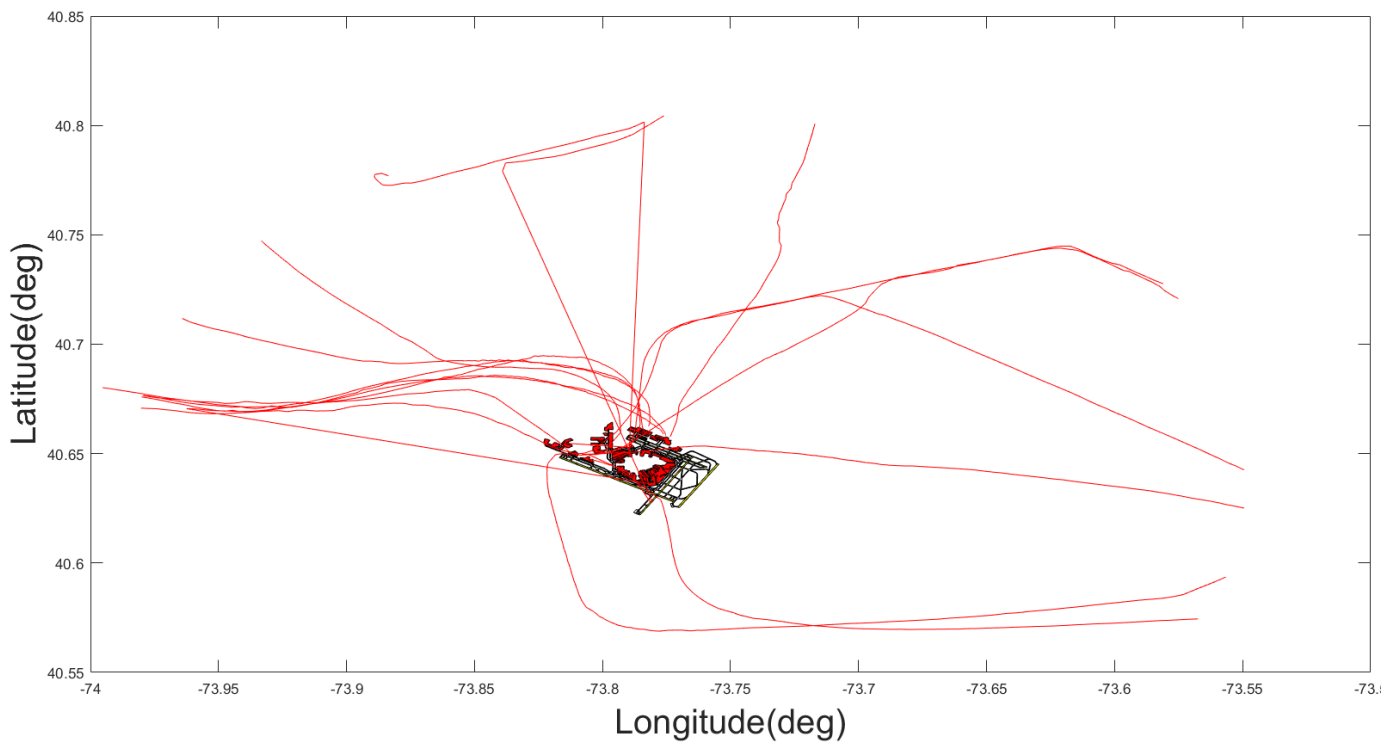


Figure 99. Departure Flights Which are not Assigned to any Runways.

Note: Departure tracks are not over any runways.

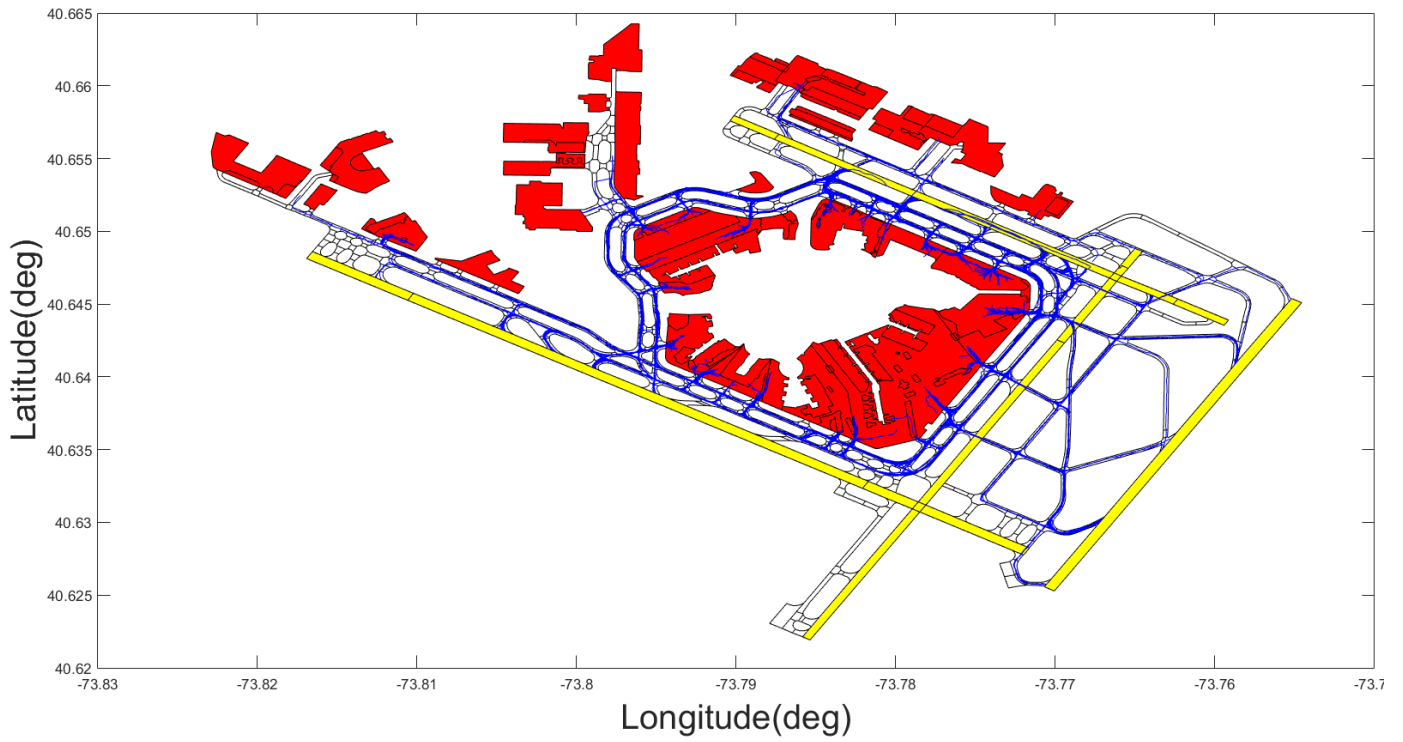


Figure 100. Arrivals Taxiing Tracks from the Runway Exit to the Final Track Point.

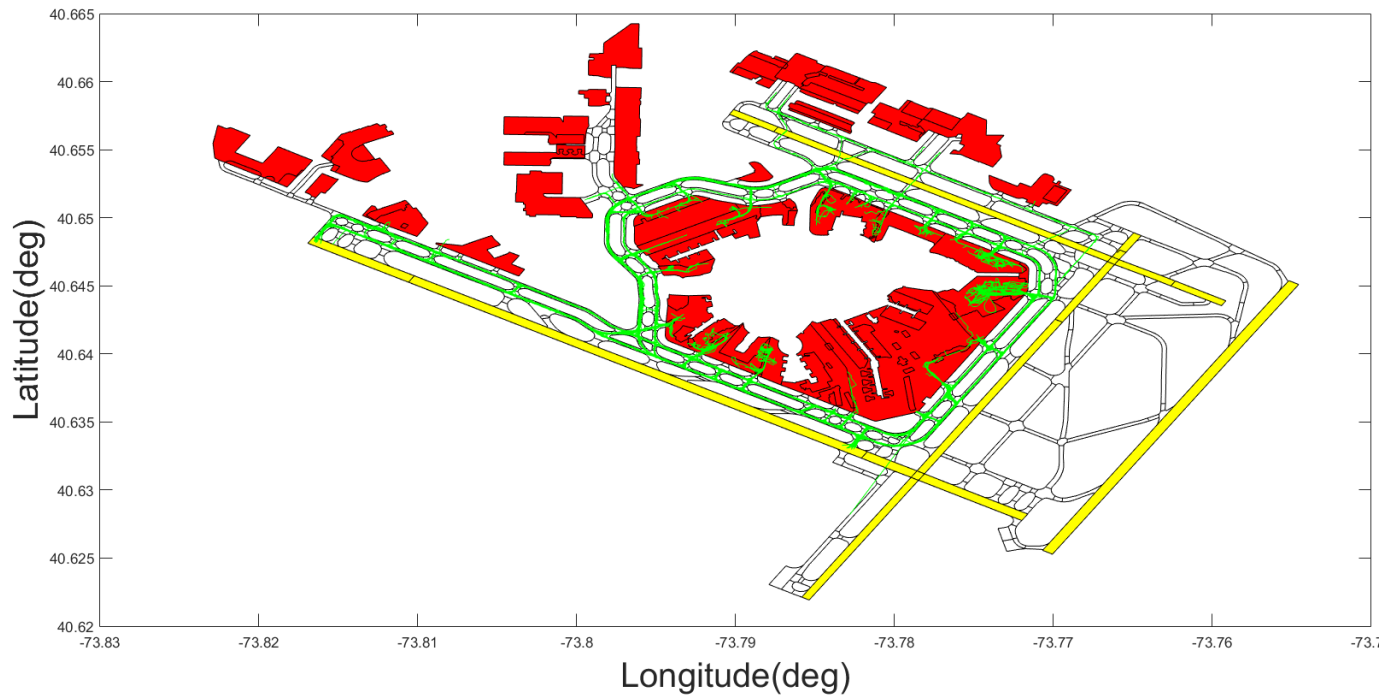


Figure 101. Departures Taxiing Tracks from the First Track Point to the Enter Runway Point.

# Hartsfield–Jackson Atlanta International Airport (ATL)

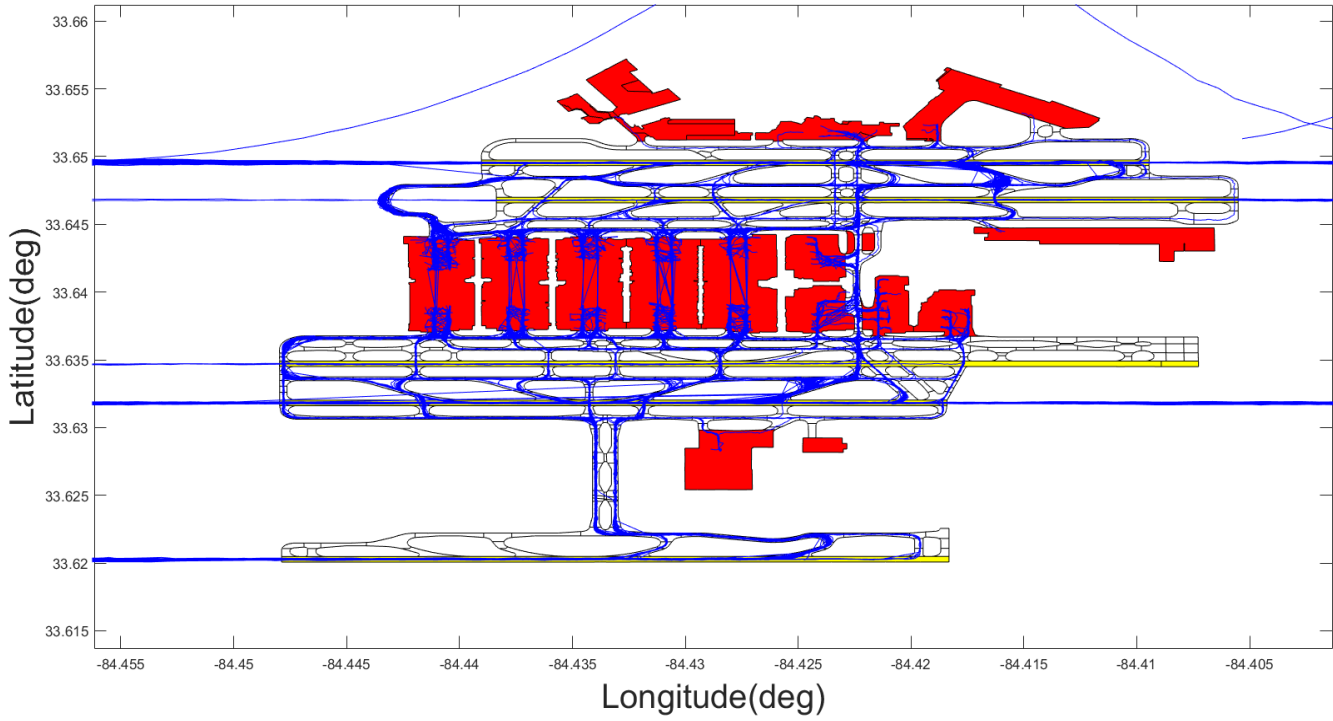


Figure 102. ATL, all of the Arrivals on 2015-07-16 and a few on 2015-07-17.

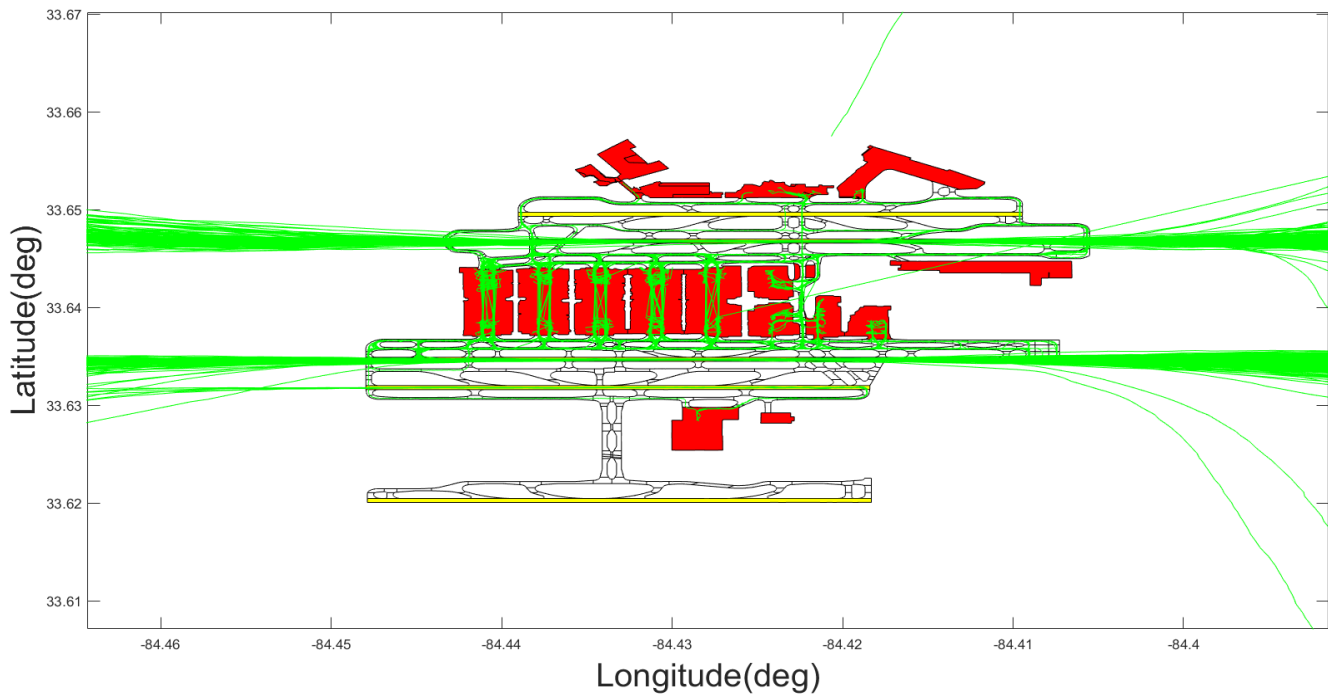


Figure 103. ATL, all of the Departures on 2015-07-16 and a few on 2015-07-17.

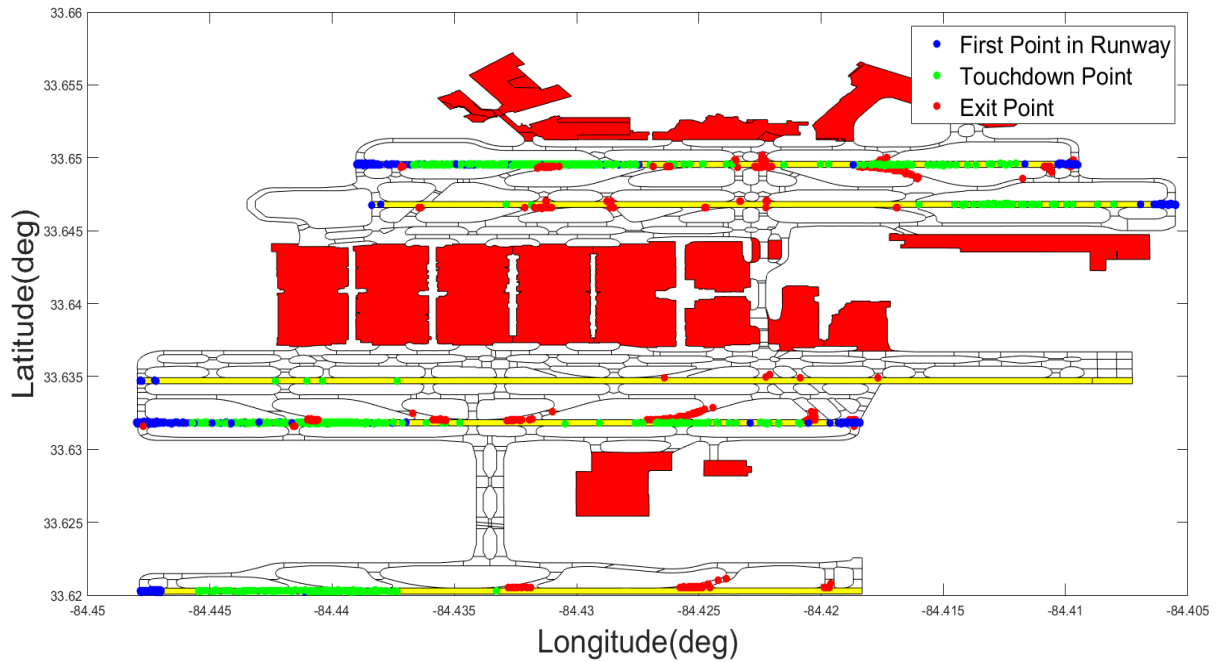


Figure 104. Event Extraction Parser Critical Points for Arrivals, Locations of the First Point in Runway Polygon, Touchdown Point, and Exit Points.

Note: Many arrival tracks at ATL had too much data drop, that is why there are blue points in runways far from the runway thresholds.

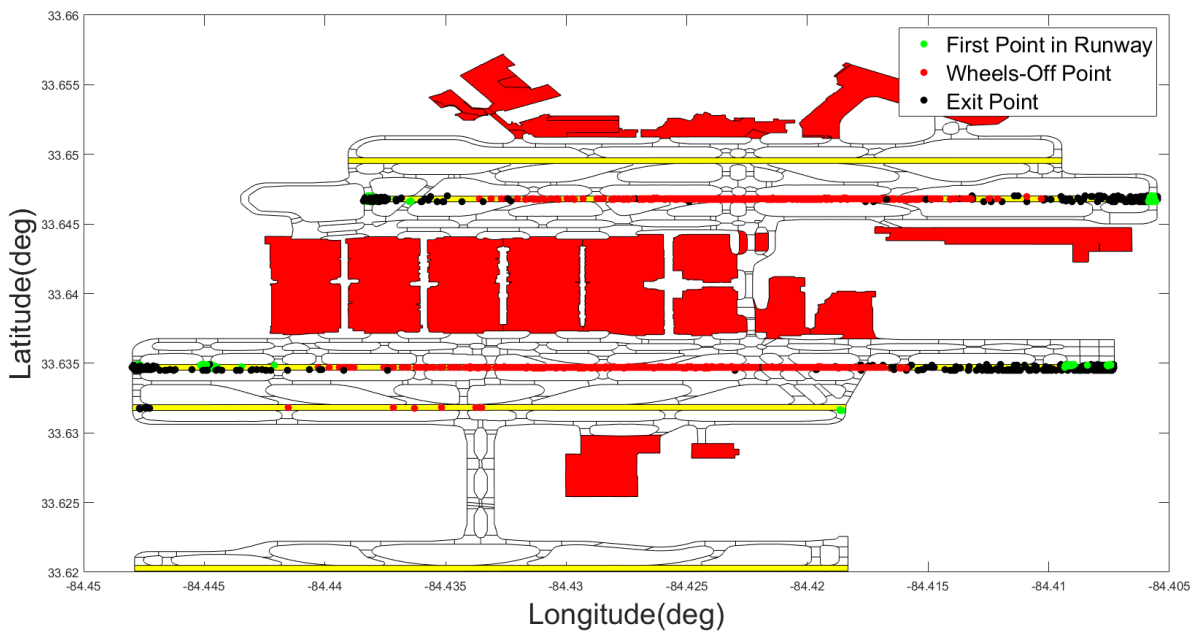


Figure 105. Event Extraction Parser Critical Points for Departures, Locations of the First Point in Runway Polygon, Wheels Off Point, and Exit Points.

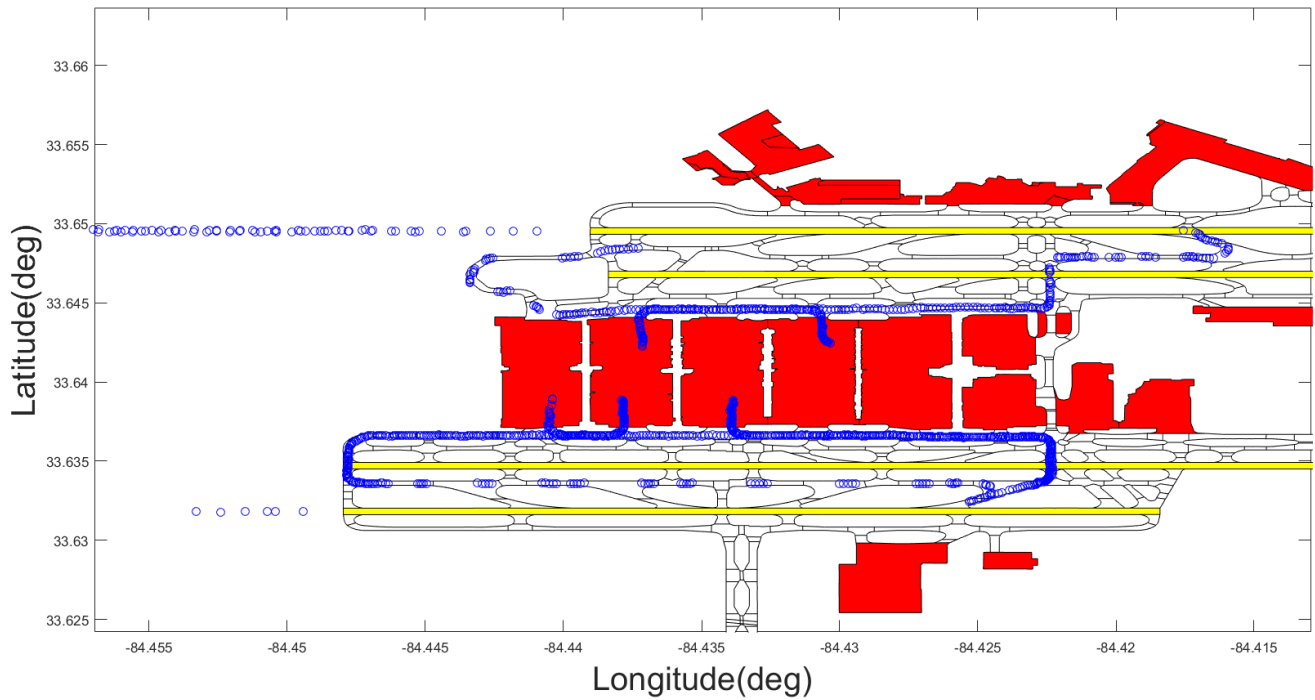


Figure 106. Arrival Flights Which are not Assigned to any Runways.

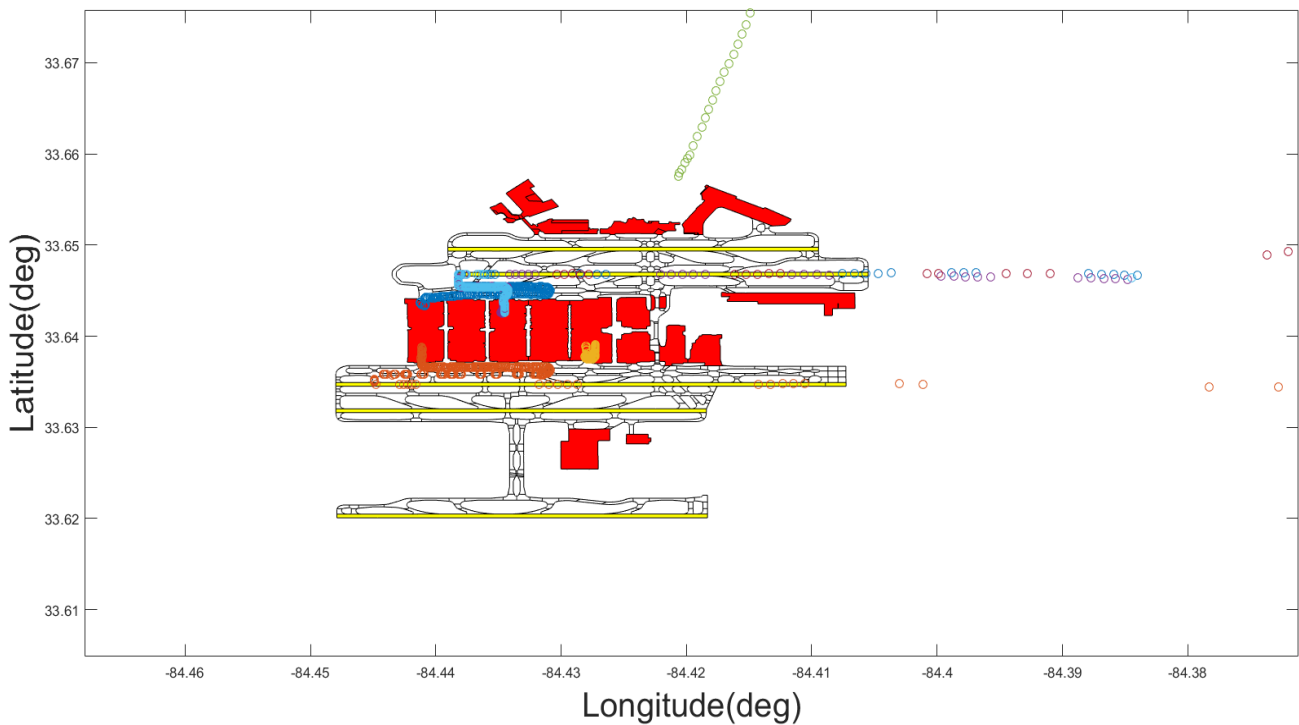


Figure 107. Departure Flights Which are not Assigned to any Runways.

Note: Incomplete departure tracks can be seen in different colors.

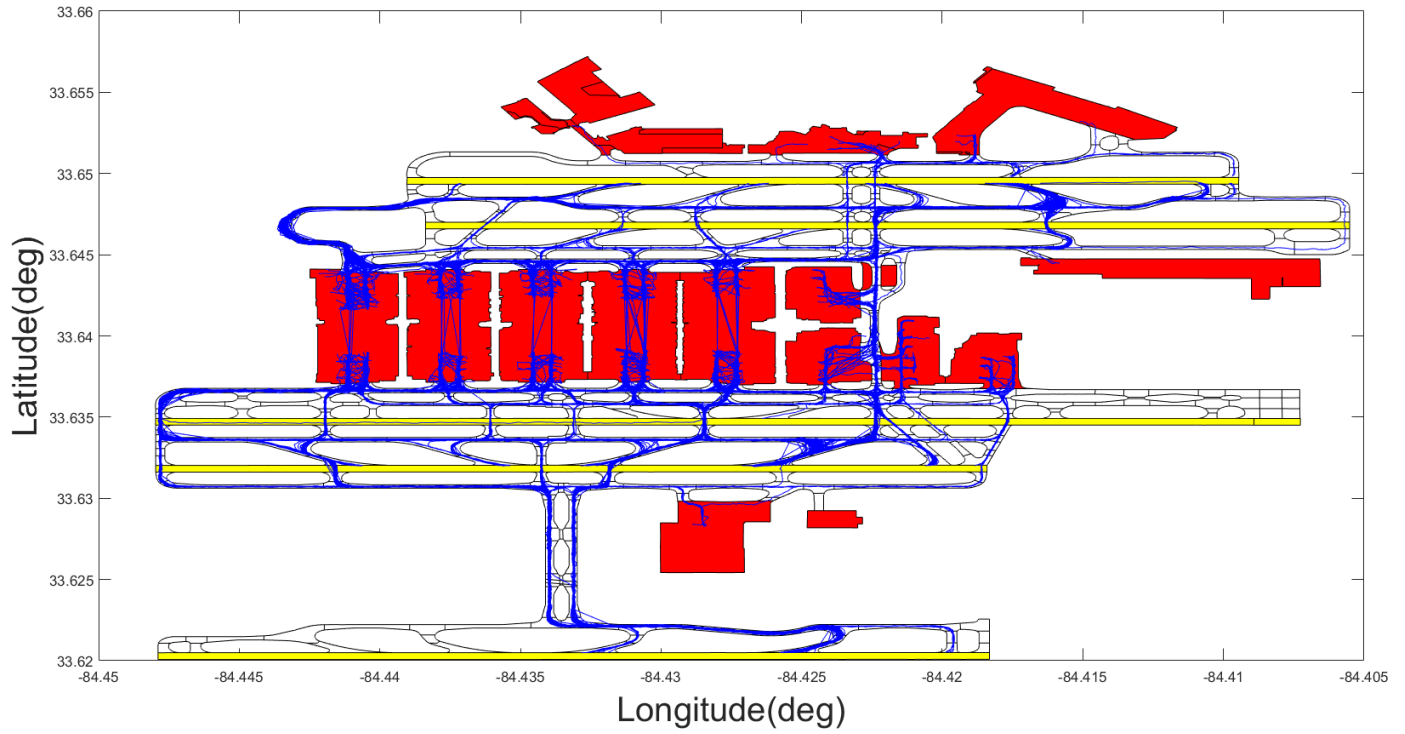


Figure 108. Arrivals Taxiing Tracks from the Runway Exit to the Final Track Point.

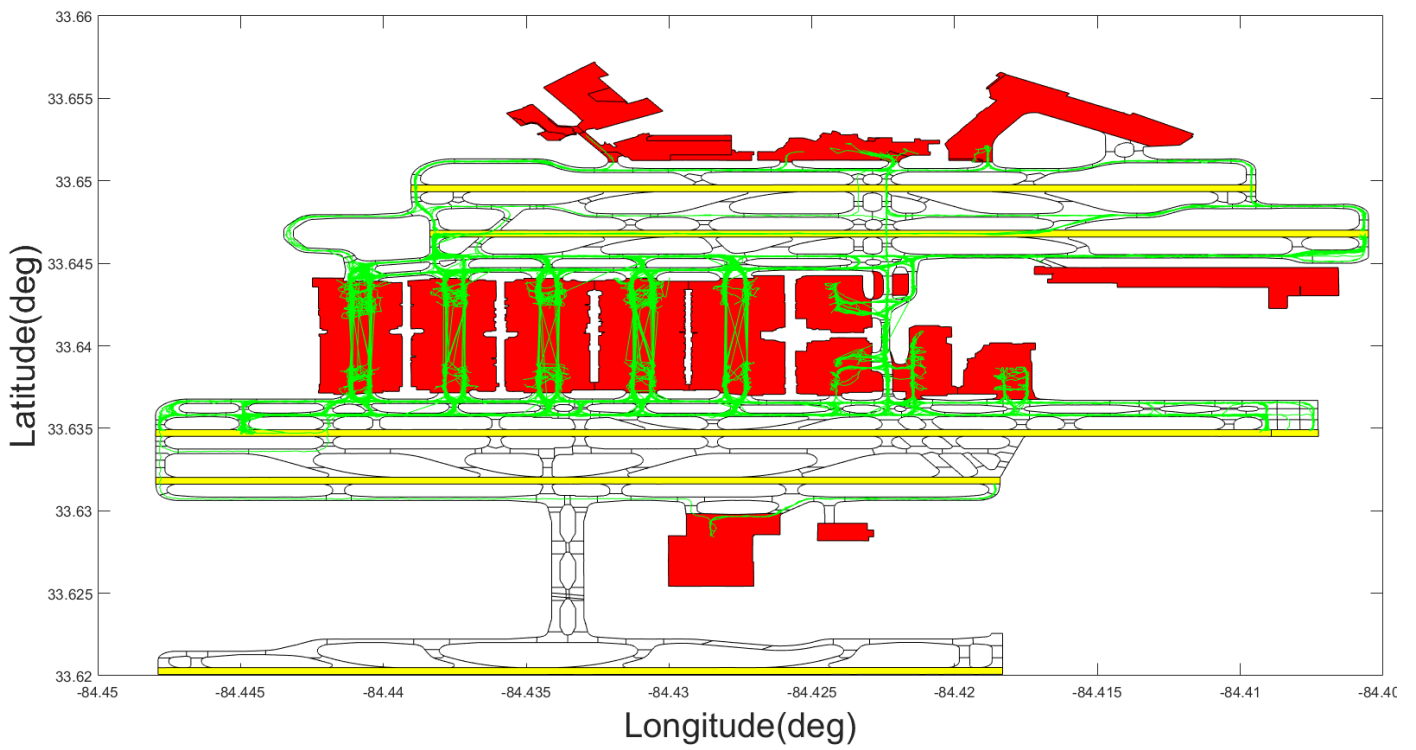


Figure 109. Departures Taxiing Tracks from the First Track Point to the Enter Runway Point.



# O'Hare International Airport (ORD)

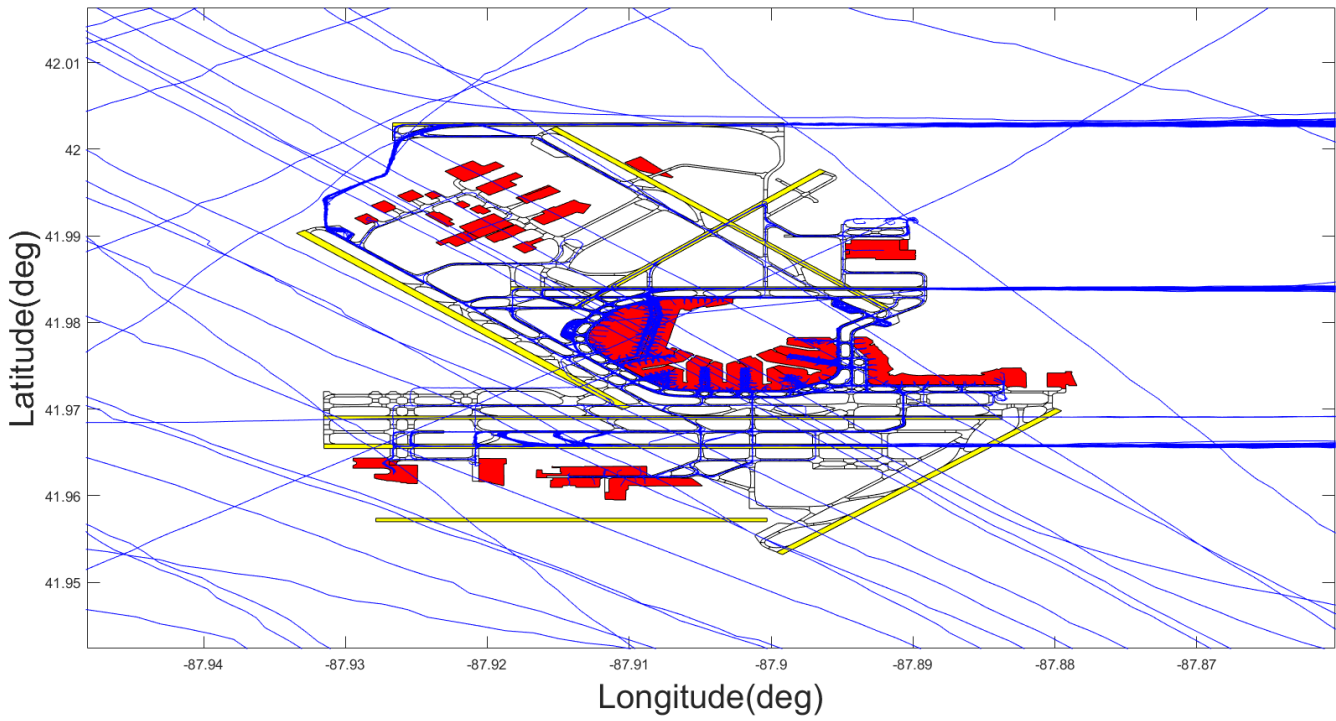


Figure 110. ORD, all of the Arrivals on 2015-07-16 and a few on 2015-07-17.

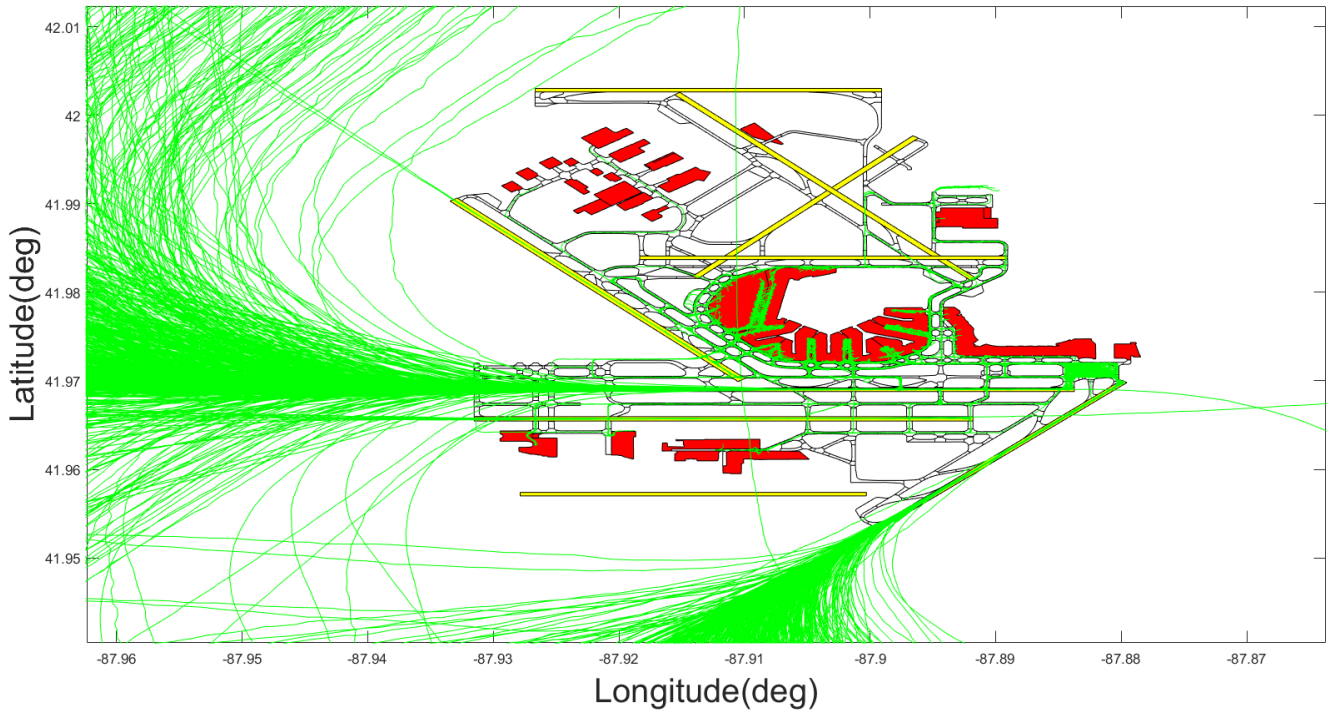


Figure 111. ORD, all of the Departures on 2015-07-16 and a few on 2015-07-17.

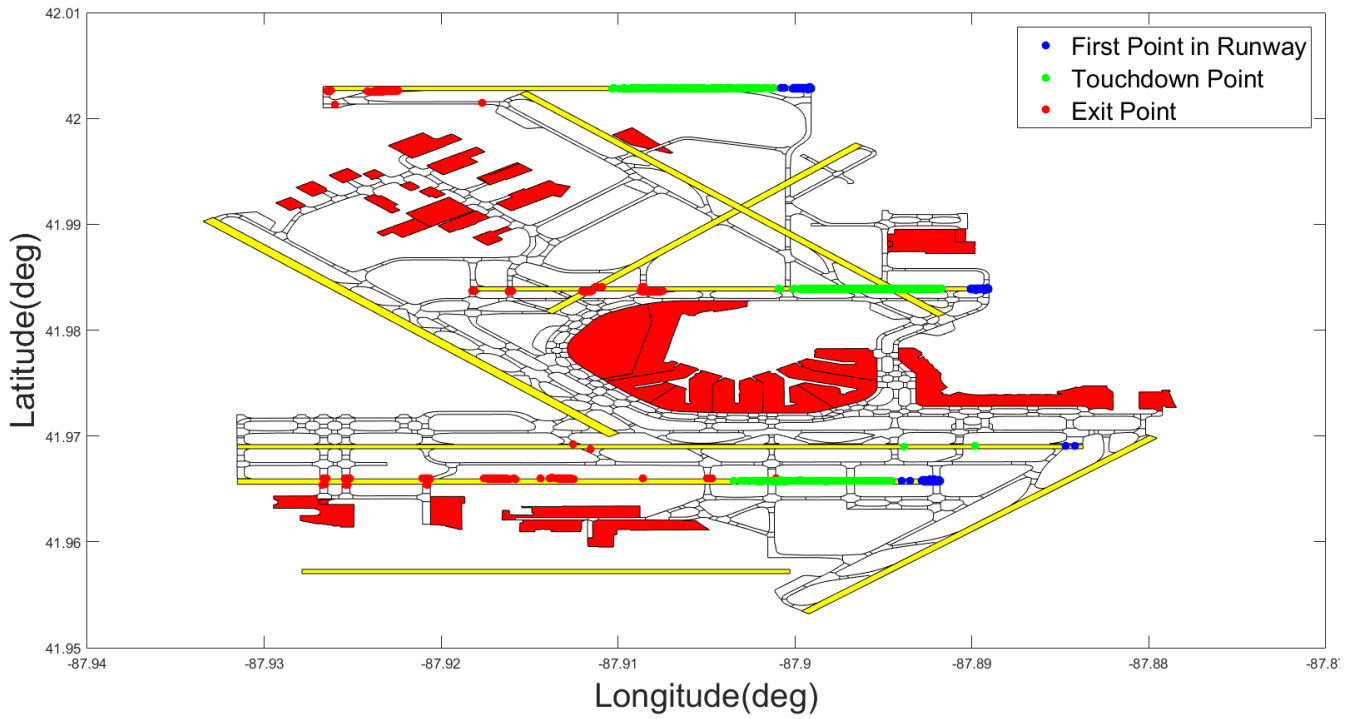


Figure 112. Event Extraction Parser Critical Points for Arrivals, Locations of the First Point in Runway Polygon, Touchdown Point, and Exit Points.

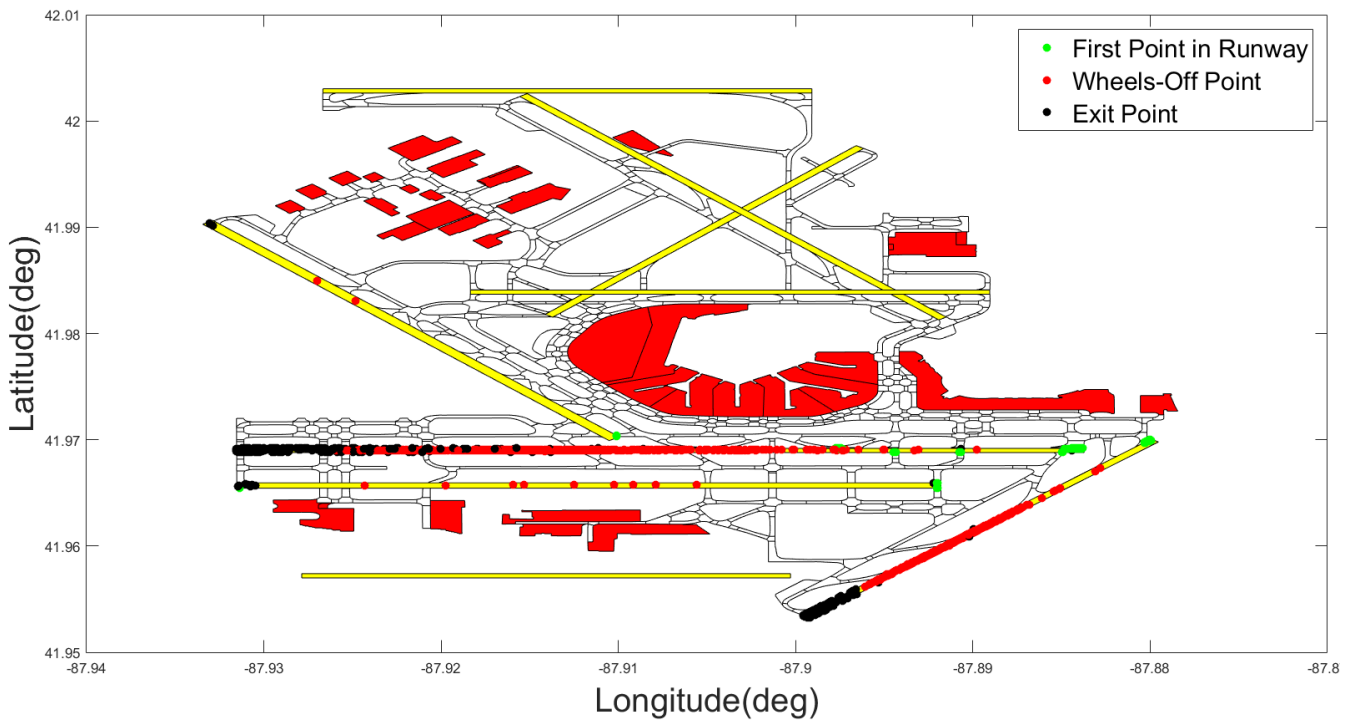


Figure 113. Event Extraction Parser Critical Points for Departures, Locations of the First Point in Runway Polygon, Wheels Off Point, and Exit Points.



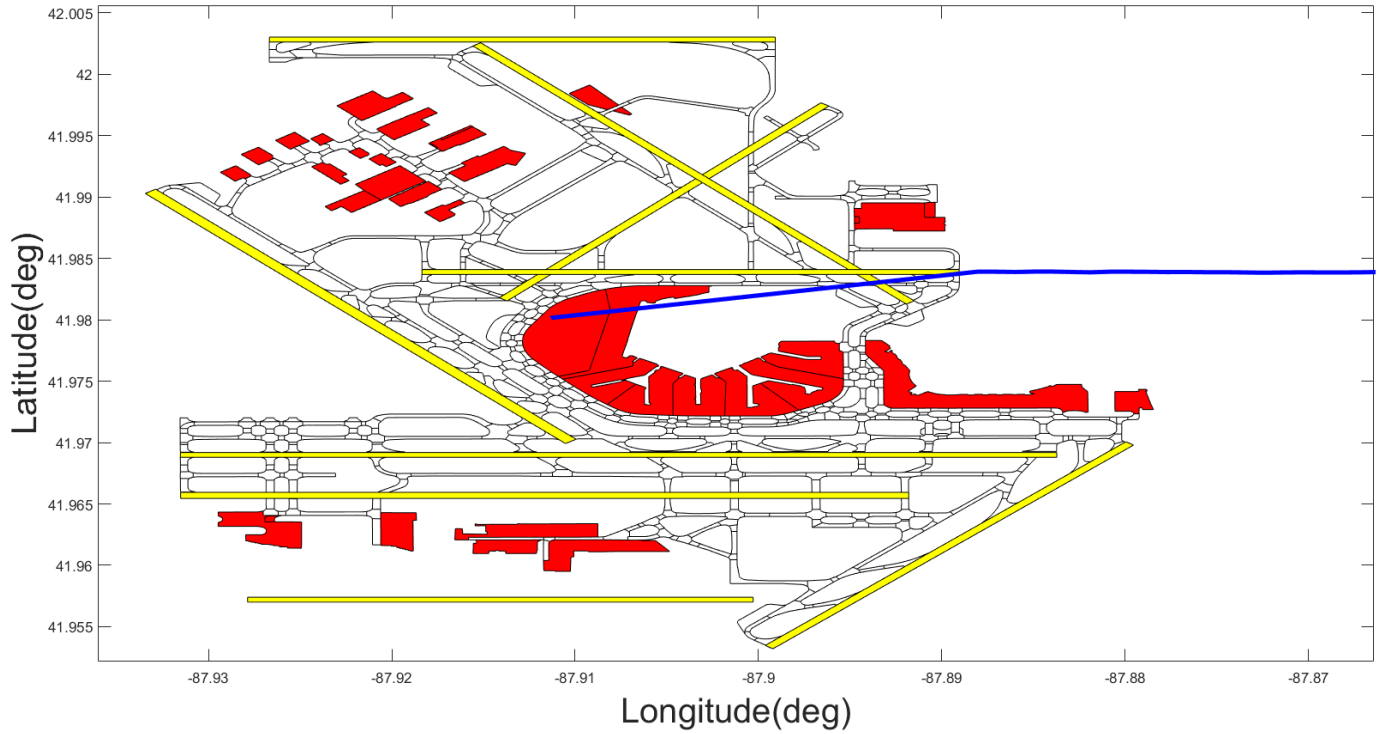


Figure 114. Arrival Flights Which are not Assigned to any Runways.

Note: This airport did not have any departure flights which the event model could not be able to assign to any runways.

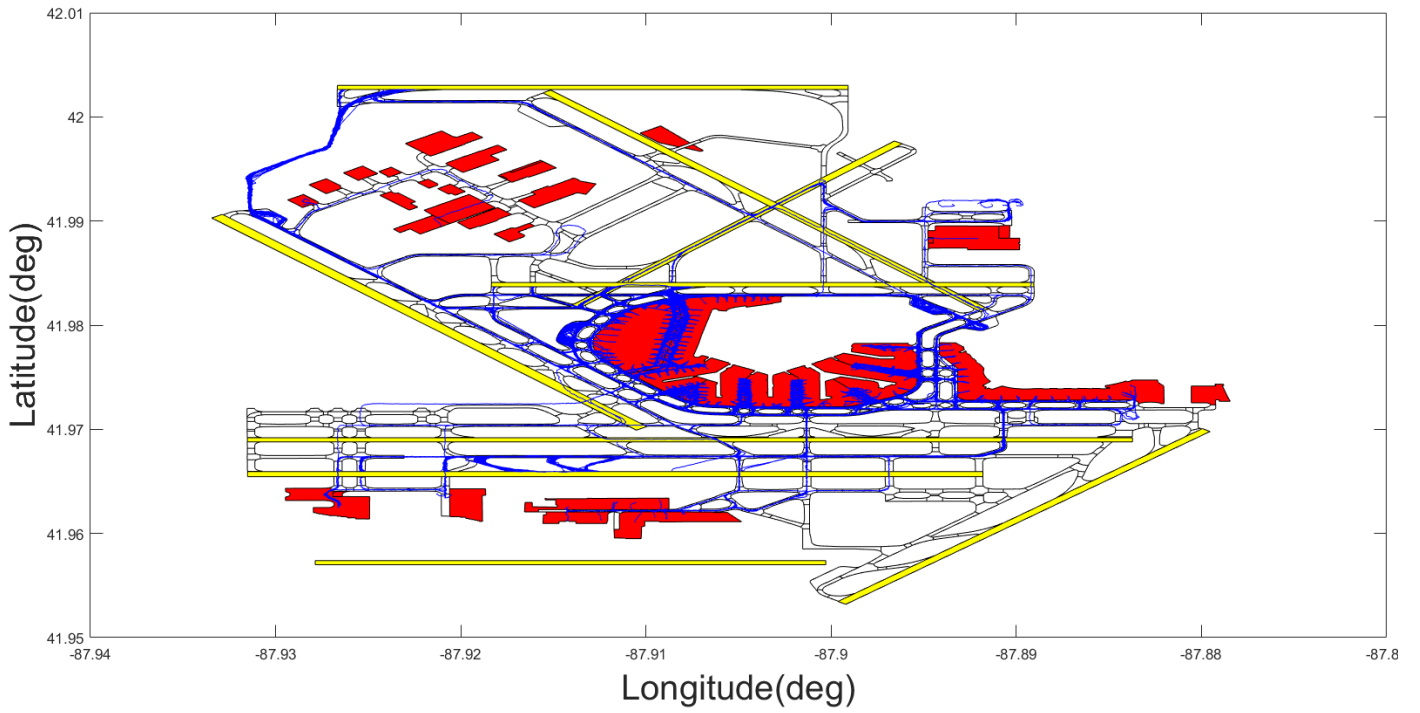


Figure 115. Arrivals Taxiing Tracks from the Runway Exit to the Final Track Point.

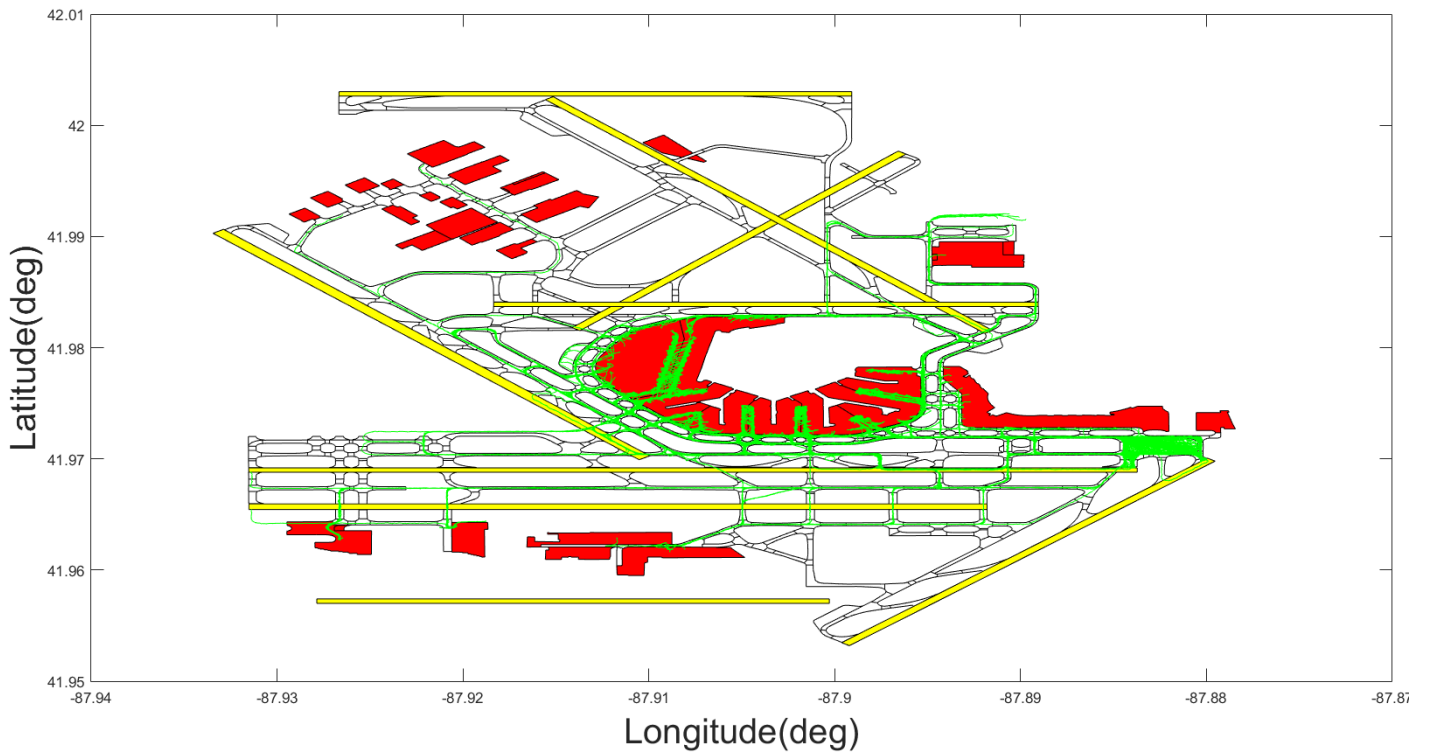


Figure 116. Departures Taxiing Tracks from the First Track Point to the Enter Runway Point.

### 3.8. Summary and Conclusion

Having a precise picture of ground operations at airports will help the decision makers to evaluate each facility with all the problems that they have on having smoother operation procedures. Calculating the unimpeded taxi time is just a small detail which can be extracted from real radar data using tools like Taxi Event Extraction model. This tool can be used for extracting many technical parameters of airplanes like runway occupancy times for departures and arrivals, average touchdown or wheels off distance and time, average deceleration rate for arrivals or acceleration rate for departures, the percentage of usage of specific runway exits, the percentage of usage of different runway ends at the facility, clustering the flights which were assigned to similar runways and used similar gates, estimation of very accurate taxiing time and distance, and many more practical functionalities which can be used for future planning or current analysis. The powerful visualization tools provided in tools like Taxi Event Extraction model can help the authorities to extract strange flight behaviors on specific days. The bottlenecks at airports can be identified, and the locations which airplanes were waiting in queues can be recognized. These visualization features can also help the decision makers to design new operating paths for taxiing airplanes.

The precision level of all of the extracted variables from Taxi Event Extraction model can be a motivation to extract many distributions for various airplanes' behaviors. Those distributions can be broadly used by simulation models to draw more realistic pictures from airports' potential capacities to designers or planners.

Moreover, since every phase of taxiing journey at each airport is extracted precisely by this tool, the reliability of the final output is way more than biased statistical analysis, when no detail is available for the further sanity checks.

## 4. Conclusion

The results of the RUNSIM v.2.00 showed that with changes in separation systems, different airports can be benefited in different ways. Since the capacity issues of airports are very important these days, using such simulation models can help the planners to improve the functionality of the airports' operations. This model is a very useful tool for airport authorities to estimate the maximum arrival and departure capacity of airport under various input parameters.

The feature of modelling individual aircraft type is a very unique option among runway simulation models, and this feature can be used in order to create big separation matrices and evaluate the airport capacity under each of them. The capability of simulating environmental conditions in the model can show the users the amount of lost operations due to tough weather conditions. This tool can be used in practical ways in terms of testing the possibility of applying new separation and air traffic regulations for improving the airports' capacities.

The results of the taxi time study were considerably logical and can be referenced for future studies. The used method of reviewing taxiing behavior based on the real radar data and visualizing each flight to evaluate the quality of estimated parameters can be used to identify facilities with considerable reported delay time. The techniques used in this study for estimating the airplanes' normal and unimpeded taxi times can be utilized for analyzing airports' taxiing performance. All of the taxing parameters in this study were extracted from real radar data at

airports, therefore the reported taxing parameters can be used for analyzing the airplanes' taxing behavior. Therefore, the users of this extraction tool can improve the inefficiencies by running many days of radar data at big airports. The extractor designed for analyzing the airports' taxing parameters is able to run multiple radar data for each facility. The visualization feature of the extractor can help the potential users to validate the reported taxing parameters and have a better understanding of airplanes' taxing behavior at airports.

## 5. Recommendation

Applying safe dynamic separation rules which can be simulated over time with variable environmental features is the main recommended field for the runway capacity model.

Since there are ongoing wake studies which believe that with different environmental conditions minimum separations between airplanes can vary through time, it is valuable to apply those conditions in the computer model to estimate the new capacities under different environmental conditions.

For the second study it is recommended to match the PDARS data with ASPM data and complete the taxi time profile for the flights all the way to the gates.

The studied radar data showed that many departure flights don't end up their journey at gates, and it means that the pilots turn off the radar and they stop sending signals. Therefore, the gap between the time that pilots turned off the signals and the time that they really stopped by gates is missing from PDARS data. For estimating a very realistic taxi time one can match those data sets together and report the most accurate taxi time.

Moreover, the second study was done for six airports with one operation day for each of them. Many times the taxiing pattern changes from day to day, or season to season. Therefore, it is recommended to study more days (preferably months) of multiple airports and then trying to extract the taxiing parameters from those studies.

## Appendix A

### Data Dictionary for Event Extraction Model

Number of Column	Field Name	Description
1	Flight_ID	Flights Call Sign
2	Flight_Key	A Unique Integer Representing Each Flight
3	Operation	Type of Operations: A: Arrival D: Departure
4	Aircraft_Type	Model of the Airplane Ex: B777
5	Airport	Airport which the operations happened at. Ex: ORD
6	Operational_Runway	Defines the threshold name of the runway which the operation happened at. Ex: 27R
7	Enter_Rwy_Time	Time which airplanes entered the operational runway For arrivals: time when they first passed the threshold For departures: time when they entered the departing runway Format:yyyy-mm-dd HH:MM:SS (UTC)
8	Enter_Rwy_Lat	Latitude of first point inside operational runway
9	Enter_Rwy_Long	Longitude of first point inside operational runway
10	EnterRwy_On_Off_Dur	Time the plane took to touchdown (arrival) or wheels-off (departure) from Enter_Rwy_Time in seconds
11	On_Off_Lat	Latitude of Touchdown (arrivals) or Wheels-off (departures)
12	On_Off_Long	Longitude of Touchdown (arrivals) or Wheels-off (departures)

13	EnterRwy_On_Off_Dist	Distance from Operational_Runway threshold to touchdown (arrivals) or wheels-off (departures) location in meters
14	EnterRwy_ExitRwy_Dur	Runway occupancy time in seconds
15	Exit_Rwy_Time	Time which airplane vacates the runway For arrivals: taking exits For departures: passing the opposite threshold or the first point outside of the departing runway Format: yyyy-mm-dd HH:MM:SS (UTC)
16	Exit_Rwy_Lat	Latitude of the exiting point
17	Exit_Rwy_Long	Longitude of the exiting point
18	Near_Gate_Lat	Latitude of the nearest track point to the gates: For arrivals: the last track point in the data For departures: the first track point in the data
19	Near_Gate_Long	Longitude of the nearest track point to the gates: For arrivals: the last track point in the data For departures: the first track point in the data
20	Gate_Label	Label of gate (apron) area from FAA airports layout files
21	Taxi_In_Out_Dur	Taxi in (arrivals) or Taxi out (departures) time in second Arrivals: time from Exit_Rwy point to the Near_Gate point Departures: time from the Near_Gate point to the Enter_Rwy point
22	Avg_Taxi_Speed	Taxiing speed (m/s) Smoothed average taxiing speed
23	Taxi_Dist	Taxiing distance (meters)
24	Wait_Time	Times that airplanes had taxiing speed lower than 3m/s during taxiing
25	Taxi_Time_Minus_Wait	Taxi in (arrivals) or Taxi out (departures) time minus Wait_Time_Under_3



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