Spring 2014

Investigating Surface Performance Trade-offs of Unimpeded Taxiways

Tiffany T. Le
Purdue University

Graduate School ETD Form 9
(Revised 01/14)

PURDUE UNIVERSITY
GRADUATE SCHOOL
Thesis/Dissertation Acceptance

This is to certify that the thesis/dissertation prepared

By Tiffany T. Le

Entitled
Investigating Surface Performance Trade-offs of Unimpeded Taxiways

For the degree of Master of Science in Aeronautics and Astronautics

Is approved by the final examining committee:

Karen Marais

Steven Landry

Dengfeng Sun

To the best of my knowledge and as understood by the student in the *Thesis/Dissertation Agreement. Publication Delay, and Certification/Disclaimer (Graduate School Form 32)*, this thesis/dissertation adheres to the provisions of Purdue University's "Policy on Integrity in Research" and the use of copyrighted material.

Approved by Major Professor(s): Karen Marais

Approved by: Tom Shih 03/28/2014

Head of the Department Graduate Program Date

INVESTIGATING SURFACE PERFORMANCE TRADE-OFFS OF UNIMPEDED TAXIWAYS

A Thesis

Submitted to the Faculty

of

Purdue University

by

Tiffany T. Le

In Partial Fulfillment of the

Requirements for the Degree

of

Master of Science in Aeronautics and Astronautics

May 2014

Purdue University

West Lafayette, Indiana

To my Dad and Mom for their strength, perseverance, and sacrifice to give me an opportunity to further my education. I admire your courage to escape during the Vietnam War and established a new life in America. To my sister and brother for their support, advice, and wisdom whenever I needed to talk. To both my roommates who has been on this crazy adventure with me moving from San Diego to Indiana. We got to experience snowstorms, Wabash River flooding, tornados, mouse and insects, sleepless nights, laughter, tears, feasts, and so much more together. To my second family, Graduate Intervaristy Christian Fellowship and Clear River Church, for showing me how to love like Jesus. This community has been my home away from home.

ACKNOWLEDGEMENTS

I would first like to thank God, my Savior, who has provided everything for me and for being with me in all that I do. Next I want to thank Dr. Karen Marais for giving me this opportunity and guiding me throughout this research. I am very grateful for your mentorship. Thank you for challenging me, but also supporting me in my research these past two years. It has been a blessing to have you as my adviser and it has truly impacted my life and career. Thank you to Dr. Steven Landry and Dr. Dengfeng Sun for being on my committee and for your advice and support. Thank you to Pat Moran from the FAA for managing this project. This work was partially funded by the Federal Aviation Administration under Award Nos. 06-C-NE-MIT, Amendment No. 017 and 07-C-NE-PU, Amendment No. 024. The balance of the funding was provided by the Purdue Doctoral Fellowship. I also thank Tom Reynolds and Melanie Sandberg from MIT Lincoln Laboratory for their help in acquiring ASDE-X data for my research.

TABLE OF CONTENTS

Page

Page

Page

Page

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

Figure Page

Appendix Figure Page

LIST OF ABBREVIATIONS

AOSC	Airport Obstructions Standards Committee
ASDE-X	Airport Surface Detection Equipment Model-X
ASPM	Airport System Performance Metric
ATC	Air Traffic Control
ATL	Atlanta Hartsfield-Jackson International Airport
DFW	Dallas/Fort Worth International Airport
DOT	Department of Transportation
DTW	Detroit Metropolitan Wayne County Airport
EAT	End-Around Taxiway
FAA	Federal Aviation Administration
ICAO	International Civil Aviation Organization
MIA	Miami International Airport

ABSTRACT

Le, Tiffany T. M.S.A.A., Purdue University, May 2014. Investigating Surface Performance of Unimpeded Taxiways. Major Professor: Dr. Karen Marais.

Optimizing usage of unimpeded taxiways is a near-term operational change to mitigate emission impact on aviation and increase efficiency at airports. An unimpeded taxiway is a path for an aircraft to taxi around an active runway. Unimpeded taxiways provide benefits such as increased departure throughput, increased safety, reduced surface congestion, more efficient taxi-in procedures, and thereby also yield environmental benefits. The goals of this work are to investigate the use of current taxiways, examine surface performance and fuel burn trade-offs, and to develop a decision-support model based on potential fuel savings of unimpeded taxiways. This study analyzes unimpeded taxiway use at Hartsfield-Jackson International Airport (ATL), Dallas/Fort-Worth International Airport (DFW), and Detroit Metro Airport (DTW) using ASDE-X data from 10 September 2012 to 28 February 2013. The trends and patterns of aircraft taxi routes show the unimpeded taxiway is used the most during peak arrival and peak departure hours. This study provides decision-makers at the operations level a practical guidance tool with the necessary information to effectively use unimpeded taxiways and conventional taxiways from an environmental perspective. Decision rules were developed to maximize fuel savings. The decision scenario analysis concluded that the most promising decision rule at ATL, DFW, and DTW to yield the most environmental benefit is based on multiple factors. The multi-factor decision rule based on terminal destination, arrival time, and aircraft type resulted in an average aircraft fuel savings of 8.1% to 20.4%.

CHAPTER 1. INTRODUCTION

1.1 Background and Motivation

As air traffic continues to grow, there are concerns that aviation's impact on the environment is incompatible with mobility needs. Aviation's contribution to global warming and environmental effects, coupled with rising fuel costs, motivates the need for solutions that increase fuel efficiency. There are several strategies being pursued to mitigate the environmental impacts of aviation, including developing advanced aircraft technologies, researching sustainable alternative jet fuels, and improving operational procedures. Developing new technologies and sustainable jet fuel research can significantly reduce environmental impact, but require mid to long timeframes. This motivates an assessment of improving operational changes that have smaller overall mitigation potential but can be implemented in much shorter timeframes with existing aircraft types [Marais et al., 2010]. There is also the additional need to improve surface operations because airports are reaching capacity, which causes surface congestion and delays. The two main ways to increase airport capacity are by adding runways or by increasing efficiency. Potential barriers to adding runways are high costs, limited land, and long time duration to complete construction. An operational change to potentially increase airport capacity is to use unimpeded taxiways. Unimpeded taxiways are paths for aircraft to taxi around active runways without runway crossings. An example of an unimpeded taxiway is an end-around taxiway (EAT), which is a constructed taxiway designated to only unimpeded taxi-in operations.

Most work on unimpeded taxiing has focused on EATs. Previous research focused on the safety assessment and impact of end-around taxiways on taxiway system

[Engelland, 2010; Satyamurti, 2007; Massidda, 2013]. In addition to the assessment of current taxiway systems, there is a need to provide a decision-support tool in the near-term that can manage surface operations to reduce fuel burn, increase safety, and increase efficiency. Previous work in our group analyzed a 4-week period (15 November to 13 December 2010) of end-around taxiway use at DFW airport [Uday et al., 2011]. The analysis showed that taxi-in fuel burn was affected by several factors including traffic conditions on adjacent runways, traffic flow direction, arrival time of aircraft, and aircraft type. Simple decision rules based on these factors and observations showed the potential for significant taxi-in fuel burn reduction. The present study expands the time period analyzed and investigated fuel burn and performance trade-offs for all taxi routes at multiple airports in order to refine decision rules to yield maximum fuel savings.

The intention of this research is to improve the operations of unimpeded taxiways by investigating EATs to maximize environmental benefits. The majority of our data is for end-around taxiways, so that was used for taxi analysis. However, in the case of ATL a general unimpeded taxiway is also considered. The methods and findings from this research are applicable to all unimpeded taxiways. Our goal is to provide a data driven practical guidance tool for airports, air traffic controllers, and other stakeholders to compare and select the best taxi procedure from an environmental perspective. The guidance tool leverages ASDE-X data to calculate average potential fuel savings of an aircraft based on various decision rules. A combination of decision rules based on traffic trends, airport configuration, and other factors such as terminal gate location were used to develop several simulation scenarios. Implementation of the unimpeded taxiway decision-support tool is feasible since real-time ASDE-X feeds are already available at most major airports within the US.

1.2 End-Around Taxiways

1.2.1 Development of EATs

To increase operational capacity, airports have constructed dual or even triple parallel runways. Usually the in-board runway (closest to the terminal) is used for departures and the out-board runway is used for arrivals. Arriving aircraft must therefore cross the in-board runway to reach the terminal gate. To increase operational capacity and reduce the risk of runway incursions, airports have constructed taxiways that go around a runway, commonly called an end-around taxiway (EAT). Figure 1 shows the EAT as a path for an aircraft to taxi around an active runway compared to a conventional taxiway requires aircraft to cross the in-board runway to reach the terminal. Currently there are four operational end-around taxiways in the United States: Hartsfield-Jackson International Airport (ATL), Dallas/Fort-Worth International Airport (DFW), Detroit Metro Airport (DTW), and Miami International Airport (MIA).

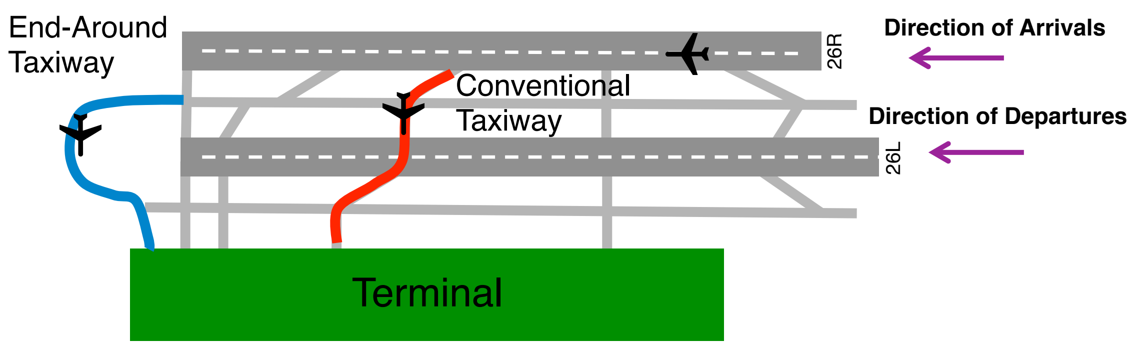


Figure 1. End-Around Taxiway airport diagram

1.2.2 Potential Barriers and Safety of EATs

There are several potential barriers to EATs. Besides limited land at airports and construction cost, there are safety and human factor concerns. MITRE/CAASD conducted simulations at airline training centers and NASA Ames to assess the impact of human factors on EAT safety operations. One study found 25% of the pilots incorrectly identified an aircraft as crossing the departure runway or taxing on the departure-end of the EAT [Hoover, 2007]. As a result, there were rejected takeoffs from misinterpreting a taxing aircraft on the EAT as on the departure runway and failure to abort takeoffs with runways incursion aircraft. To mitigate human error, two strategies were implemented in the final simulation. The first strategy was to put up a visual screen to partition the departing runway from the end around taxiway. The second strategy was to build the end around taxiway at a depression so the aircraft on the EAT can be noticeably lower than the departing aircrafts. As a result, the EAT at ATL was built at a 30 feet lower than the end of the runway.

The FAA Airport Obstructions Standards Committee (AOSC) Executive Steering Group directed that a visual screen type device be designed and installed to assist pilots on a takeoff roll to better discern when a aircraft is crossing the active runway versus the aircraft operating on the EAT [Patterson, 2007]. For further safety precautions, the use of the perimeter taxiway is constrained by flow direction and aircraft tail height. An aircraft with a maximum tail height of 65 feet would not be permitted to use the EAT like an Airbus A380 due to departure takeoff slope requirements [FAA AOSC, 2004]. Also, current FAA policy established by the AOSC [FAA AOSC, 2004, 2005, 2006] permits only departing aircraft to overfly an operational perimeter taxiway. There have been extensive studies addressing safety issues of EATs resulting in the above requirements for construction and operations of EATs. End-around taxiways meet the safety requirements of the FAA and provide safety at airports by providing a taxi path that does not require runway crossings thus reducing risk of runway incursions.

1.2.3 Benefits of EATs

End-around taxiways provide several benefits such as increase departure throughput, increase safety, reduced surface congestion, increase efficient taxi-in procedures, and yield environmental benefits. Safety is increased because using the EAT minimizing the number of runway crossings which reduces risk of runway incursions. EAT usage also reduces the load of air traffic controllers because ATC would not need to coordinate arrivals crossing the departure runway. At a busy airport using the EAT increases departure throughput by providing a path for arrivals to taxi around the active departure runway. An unimpeded taxi route reduces surface congestion by allowing aircraft to continuously taxi without stopping and waiting for clearance to cross a runway. More efficient taxi procedures have the potential to reduce fuel burn and environmental impact. The EAT is a longer taxi distance, but it could have a lower taxi time and fuel burn due to less stops and accelerations, therefore it is beneficial to understand under what conditions does using the EAT save fuel.

1.3 Other Unimpeded Taxiways

At Chicago O'Hare International Airport, a large construction project is underway to transform the outdated system of intersecting runways into a modern parallel runway configuration to reduce flight delays and increase capacity [City of Chicago, 2011]. One goal of the O'Hare Modernization Program (OMP) is to improve taxi flows to improve efficiency and reduce fuel burn. Figure 2 is an example of an unimpeded taxiway when the runways are in east-flow configuration [Markwell, 2012]. Aircraft arriving on runway 10C taxi around departure runway 10L. This taxi flow operation allows arrivals to have an unimpeded taxi path to the gate and provides departures to operate independently from arrivals.

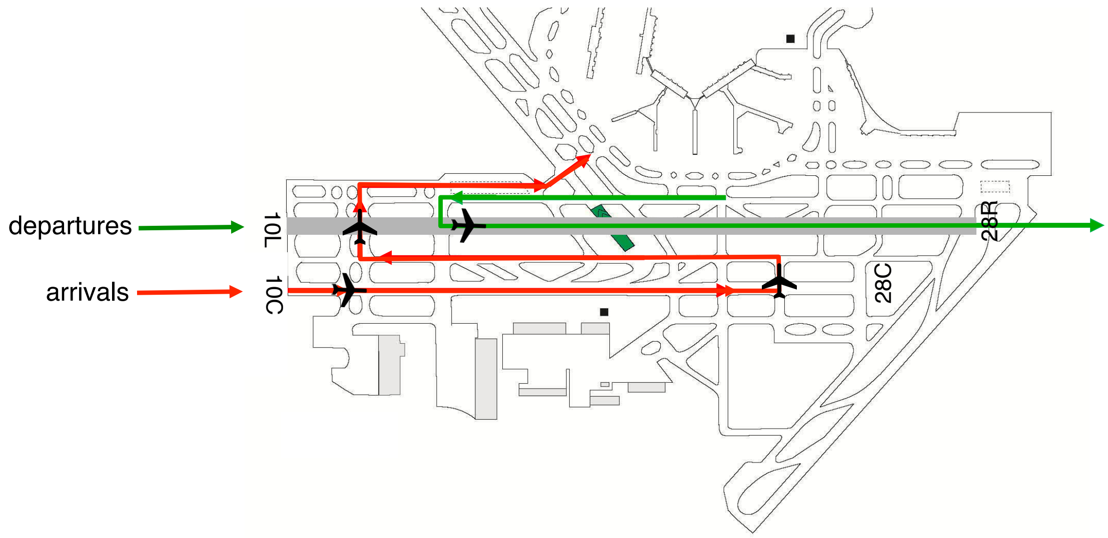


Figure 2. Unimpeded Taxiway at Chicago O'hare airport.

1.4 Research Objectives

The aim of this research is to investigate surface performance trade-offs of unimpeded taxiways and to develop a decision model to improve taxi operations. As mentioned earlier, the majority of our data is for end-around taxiways, so that was used for taxi analysis. However, in the case of ATL a general unimpeded taxiway is also considered. The methods and findings from this research are applicable to all unimpeded taxiways. This thesis' objectives are to:

1. Evaluate unimpeded taxiway usage trends and patterns
2. Assess environmental benefits by quantifying taxi time and fuel burn for unimpeded taxiways
3. Develop decision rules to maximize fuel savings
4. Draft implementation strategies for the most feasible and environmentally beneficial decision rule

Decision tools can reduce fuel burn and improve efficiency of unimpeded taxiway usage, but in practice, the tool must have the capability to be easily integrated into air traffic controllers' operation procedures. Therefore there is a need to better understand the potential benefits of operation procedures of unimpeded taxiways and barriers to implementation so it can be used to its maximum efficiency in the near-term.

The results and findings from this research could be useful for air traffic controllers to improve taxi operations, for airports to increase capacity and efficiency, for airlines to save fuel, for airport designers to have analysis tools to make inform decisions, and for government agencies to assess surface performance and safety procedures at airports.

1.5 Research Approach and Thesis Outline

We developed a four-step framework as shown in Figure 3 to consider the feasibility and potential fuel and emissions savings offered by unimpeded taxiways.

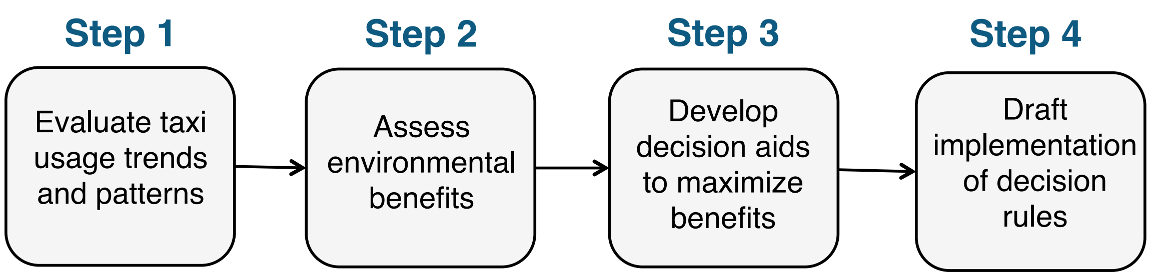


Figure 3. Four-step framework to evaluate unimpeded taxiways.

Step 1: Evaluate Current Unimpeded Taxiway Usage Trends and Patterns

In this step, Airport Surface Detection Equipment Model X (ASDE-X) data was used to study current unimpeded taxiway usage patterns at Dallas/Fort-Worth International Airport (DFW), Hartsfield-Jackson International Airport (ATL), and Detroit Metro Airport (DTW). ASDE-X data provided aircraft surface information such as flight position, speed, and time. This data was used to assess the use of the unimpeded taxiways and identified factors that dictate the frequency of its use, such as traffic trends on adjacent runways. For each airport, the analysis was based on approximately six months of ASDE-X data from 10 September 2012 to 28 February 2013. Chapter 2 describes our approach and results in detail.

Step 2: Assessment of Environmental Benefits of Unimpeded Taxiway Operations

Step 2 provided a framework that systematically evaluates environmental impact of unimpeded taxiway operations. Quantitative results of fuel burn and emission savings by using the end-around taxiway were evaluated at the three candidate airports. The fuel burn analysis is based on the International Civil Aviation Organization (ICAO) emissions databank [ICAO 2013]. This step identified the conditions under which the maximum environmental benefits are observed. Statistical analysis was used to determine the significant factors contributing to fuel burn.

Step 3: Develop Decision Aids to Maximize Environmental Benefits of Unimpeded Taxiways

Unimpeded taxiway usage trends and potential environmental benefits identified in Step 1 and Step 2 were used to develop decision aids that allow air traffic controllers to maximize these fuel burn savings. This step focused on developing decision rules such as simple rules based on always or never using the unimpeded taxiway, based on arrival time, or rules based on more detailed evaluation of the data. The performance of each decision rule is evaluated by its fuel savings compared to current operations and ease of implementation.

Step 4: Develop Draft Implementation Strategies for the Decision Rules

The final step is to draft implementation strategies for the decision rules that maximize benefits of unimpeded taxiway operations from Step 3. Application of these rules to air traffic controllers must be efficient and simple. A decision flowchart will be presented to air traffic controllers to route arriving aircraft to either the unimpeded taxiway or conventional taxiway. Taxi routing is based on maximize fuel savings depending on a combination of factors such as runway configuration, aircraft type, arrival time, and terminal gate destination.

1.5.1 Thesis Outline

A roadmap of the thesis is shown in Figure 4 that summarizes the objective, methods, and outcomes of the present research. First, current taxi operations were analyzed with ASDE-X archive data to understand the traffic trends and patterns at airports and are reported in Chapter 2. Further analysis of taxi time and fuel burn is calculated in Chapter 3. This analysis tested several factors (aircraft type, terminal gate destination, arrival time) to determine which factors are significant to fuel burn and can be used in the decision analysis.

Chapter 4 details the development of decision rules to maximize environmental benefits at ATL, DFW, DTW as examples. For fuel burn simulations two approaches were used: i) simple decision rules and ii) multi-factor decision rule. A fuel savings comparison was done for each decision rule at every airport. Conclusions from this work and recommendations for future work are presented in Chapter 5.

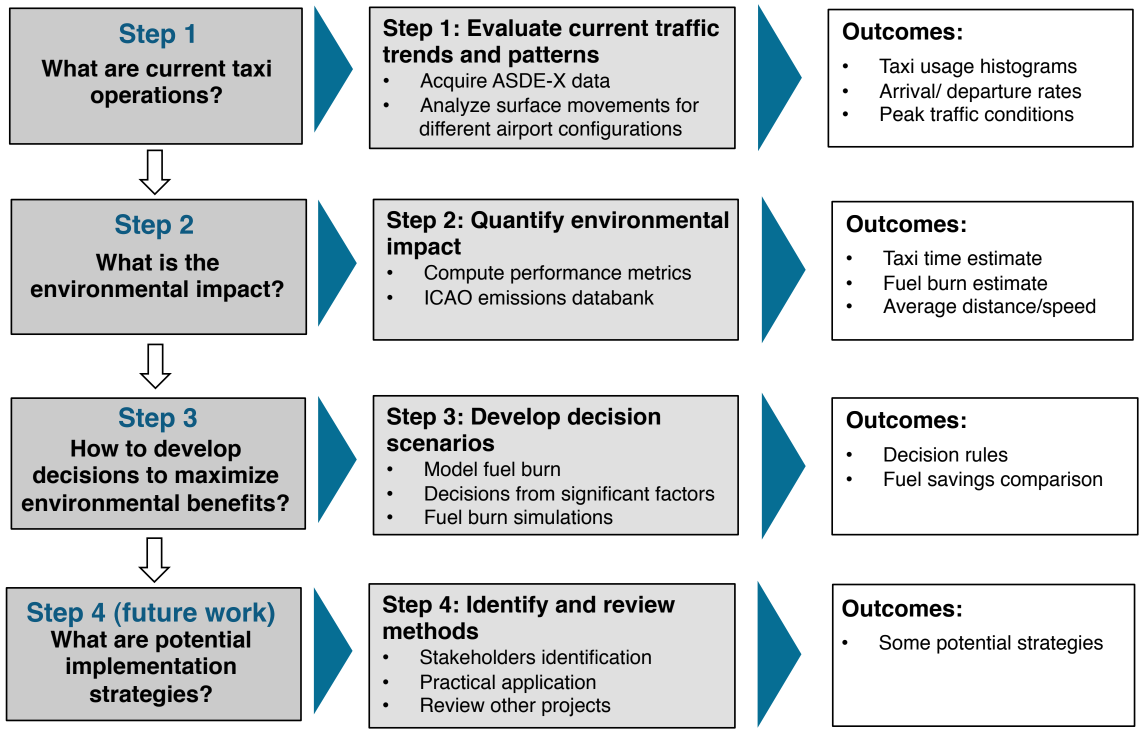


Figure 4. Roadmap of thesis with objective questions, methods, and outcomes.

CHAPTER 2. CURRENT TAXIWAY ANALYSIS

2.1 Overview of Case Study

Three candidate airports were analyzed to better understand the current end-around taxiway usage trends and patterns. The three airports with an operational EAT reviewed in this study are Atlanta/Hartsfield-Jackson International Airport (ATL), Dallas Fort Worth International Airport (DFW), and Detroit Metropolitan Wayne County Airport (DTW). Table 1 summarizes the passenger traffic and airport characteristics for ATL, DFW, and DTW. For example, DTW has on average 1,100 flights per day compared to ATL, which has over twice the number of flights with 2,700 flights per day [ACI, 2013]. Each airport varies in size, runway configurations, passenger traffic, operations among many other factors, which are important to consider in taxiway analysis.

Table 1. Characteristics comparison of ATL, DFW, and DTW for 2012.

Airport	**Average flights/day**	**Passengers per year**	**EAT distance (ft)**	**Number of terminals**	**Number of Gates**	**Number of runways**
ATL	2700	95.5 million	4200	6 ramp areas	207	5
DFW	1700	58.6 million	11400	5 terminals	161	7
DTW	1100	32.2 million	6000	2 terminals	147	6

These three airports vary greatly from passenger levels to runway configuration; therefore the analysis was tailored to each airport. ATL has a symmetrical airport with one EAT located on the north airfield. This configuration allows for direct comparison of traffic throughput with and without an EAT. We therefore considered both the north and south sides of the airport and arrivals in both west and east-flow configurations. The EAT at DFW airport is located on the southeast quadrant of the airfield. Aircraft arriving on runway 17L in south-flow configuration primarily use the EAT. An analysis was done for adjacent arrival runway 17C and departure runway 17R to determine how traffic levels on these runways effect EAT usage. The DTW analysis focused on the west airfield where the EAT is located. There are two distinct terminal areas; therefore the analysis included north and south-flow arriving aircraft to the north and south terminal gates. Different runway configurations and gate locations provide a better understanding of traffic patterns.

2.2 ASDE-X Data

Traffic trends can be better understood at airports by tracking aircraft surface movements using ASDE-X data. Airport Surface Detection System — Model X (ASDE-X) is a surveillance system using radar, multilateration and satellite technology that allows air traffic controllers to track surface movement of aircraft and vehicles. It was developed to increase controller situational awareness, reduce the risk of critical Category A and B runway incursions, and improve surface operational efficiencies.

The ASDE-X alerts air traffic controllers of potential runway conflicts by providing detailed coverage of movement on runways and taxiways. By collecting data from a variety of sensors, ASDE-X is able to track non-transponder equipped and transponder equipped vehicles and aircraft on the airport movement area. ASDE-X is able to determine the position and identification of aircraft and vehicles on the airport movement area, as well as aircraft flying on final approach to the airport.

Controllers in the tower are presented this information on a color display depicting aircraft and vehicle positions as an icon overlaid on a map of the airport's runways/taxiways. The system continuously updates the map of the airport movement area that controllers can use to enhance their situational awareness. It's particularly beneficial at night or during weather when visibility is poor. The ASDE-X system is also equipped with visual and aural alarms that will alert controllers of possible runway incursions or incidents. Figure 5 shows 35 of the busiest airports in the United States that the FAA has deployed ASDE-X with ATL, DFW, and DTW highlighted in red [SAAB, 2014].

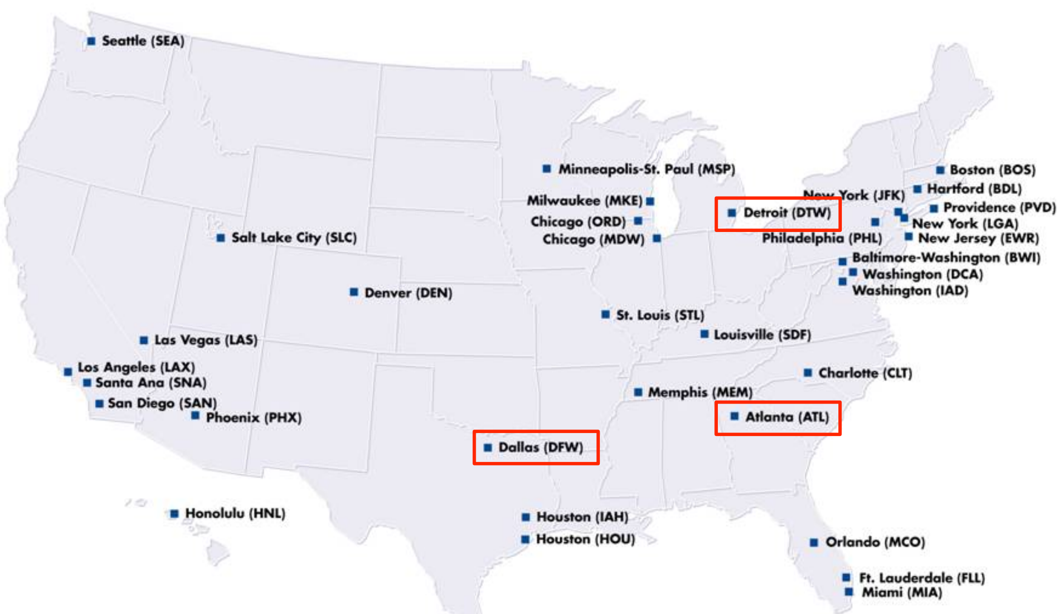


Figure 5. The 35 busiest airports in the United States with ASDE-X [SAAB, 2014].

With ASDE-X already in operation at 35 U.S. airports, there is a potential to use real-time data for system wide impact to reduce fuel burn and increase taxi efficiency.

2.3 Hartsfield-Jackson Atlanta International Airport

2.3.1 ATL Background

Hartsfield-Jackson International Airport was the world's busiest airport in 2012 by passenger traffic (92 million passengers annually) and total movements (landing and takeoff) [ACI, 2013]. Due to the increasing traffic levels, Atlanta airport has made improvements over the years to increase capacity. The most recent improvement was the 500-foot extension of runway 27R, the airport's longest runway, which opened to air traffic on July 16, 2012. The motivation to extend the runway was to increase capacity and attract larger and longer-range aircraft that can carry more fuel with the runway extension. The airport is currently undergoing $6 billion in improvements, which include expansion of taxiways to accommodate A380s, a new 12-gate international terminal, and concourse upgrades [Snedeker, 2011].

One of the improvements made at Atlanta is the end-around taxiway, known as Taxiway Victor (V). This EAT was the first one built in the United States. Taxiway Victor was completed in 24 days and began operations in April 2007. Approximately 700 aircraft per day arrive on the airport's northern most runway, Runway 8L/26R. Before the construction of Taxiway Victor, aircraft would have to wait in a line for clearance to cross the active departure runway, runway 8R/26L, to get to the terminal. According to the air traffic manager, the EAT has also improved safety by contributing to a decrease in the number of runway incursions from 22 in FY2008 to 15 in FY 2009 [DOT, 2010].

2.3.2 ATL Airport Analysis

Figure 6 is a satellite image of Atlanta airport with the main features used to analyze taxiway usage patterns. The official FAA airport diagram with runways and taxiways names is in Appendix A.1. The in-board departure runways 8R/26L and 9L/27R are highlighted in purple, while the out-board arrival runways 8L/26R and 9R/27L are highlighted in orange. There are six ramp areas, which comprise the section in between the terminals denoted in green. The taxiways analyzed for the north side of the airport are the end-around taxiway (blue) and the seven conventional taxiways (red).

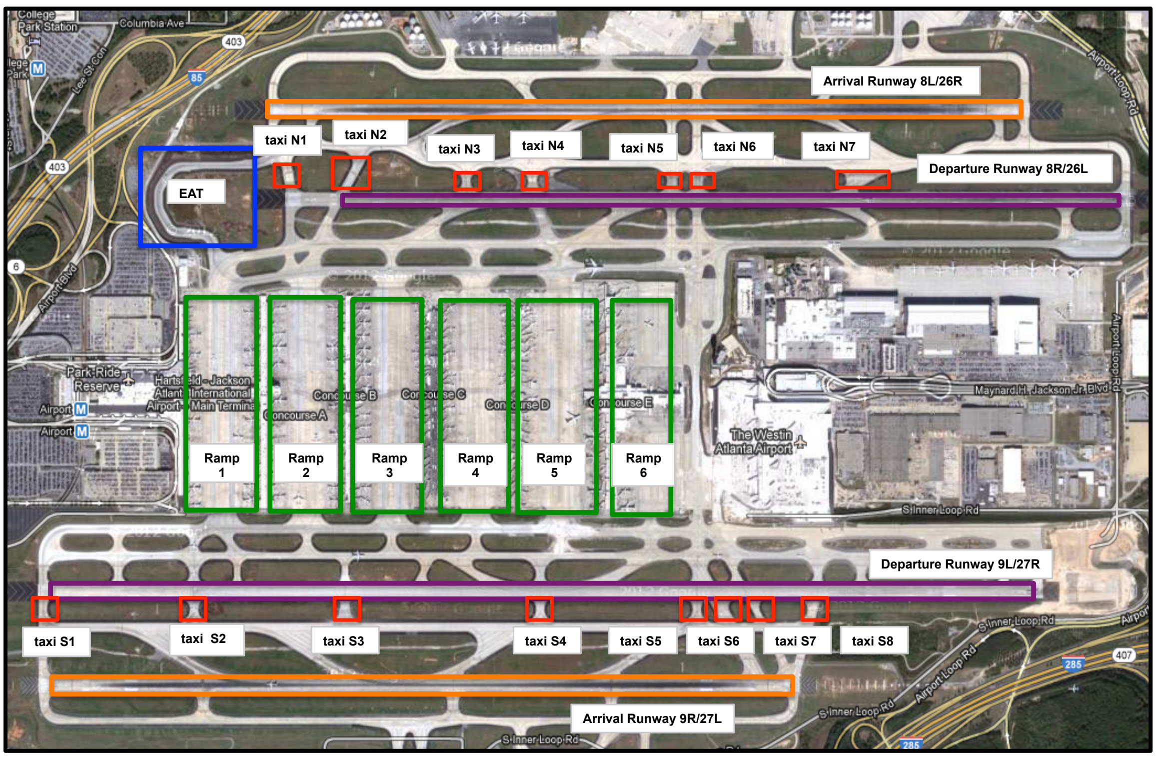


Figure 6. Atlanta Hartsfield-Jackson International Airport (ATL) diagram of departure runways (purple), arrival runways (orange), end-around taxiway (blue), conventional taxiways (red), and terminal ramps (green).

The seven conventional taxiways are defined as the taxiways aircraft take before crossing the departure runway. Aircraft usually stop and wait for clearance on the conventional taxiway before being permitted by air traffic control to cross the departure runway. For the analysis, the taxiways are defined as follows for the north airport: taxiway N1, taxiway N2, taxiway N3, taxiway N4, taxiway N5, taxiway N6, and taxiway N7. The south airport taxiways are defined as follows: taxiway S1, taxiway S2, taxiway S3, taxiway S4, taxiway S5, taxiway S6, taxiway S7, and taxiway S8.

The end-around taxiway is used in both west and east-flow configuration for runway 8L/26R, therefore the following analysis sections is divided into west-flow configuration and east-flow configuration. Due to the symmetrical layout of the runways, a comparison was done of aircraft surface movements on the north airfield (which has an EAT) and the south airfield (which only has conventional taxiways).

2.3.3 ATL West-flow Configuration

During the 6-month span, the north arrival runway was used in west-flow configuration 46% of the time and 34% for the south arrival runway. Figure 7 shows the most common taxiway routes to reach the terminal in west-flow configuration. Figure 7 (left) shows the most used route taken to reach the terminal using taxiway Victor, the end-around taxiway. Figure 7 (right) shows the conventional taxiway routes, which involve crossing the in-board runway to reach the terminal.

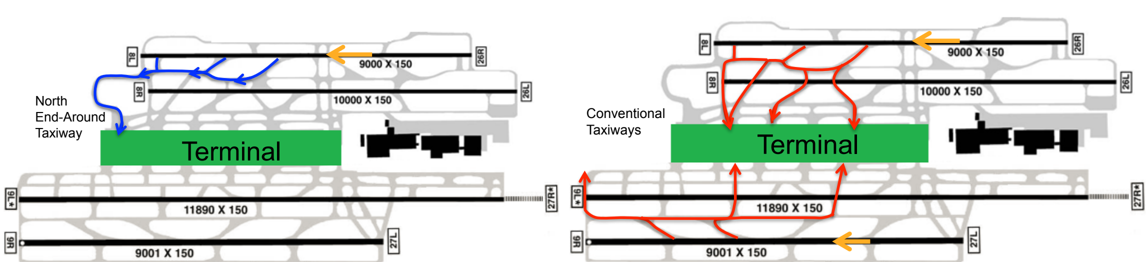


Figure 7. ATL west-flow EAT routes (left) and conventional taxiway routes (right).

Figure 8 shows the average aircraft count per day for the north taxiways. The end-around taxiway is used the most often with an average of 140 aircraft per day in west-flow configuration. All the conventional taxiways (taxi N1 – taxi N7) are used less often than the EAT.

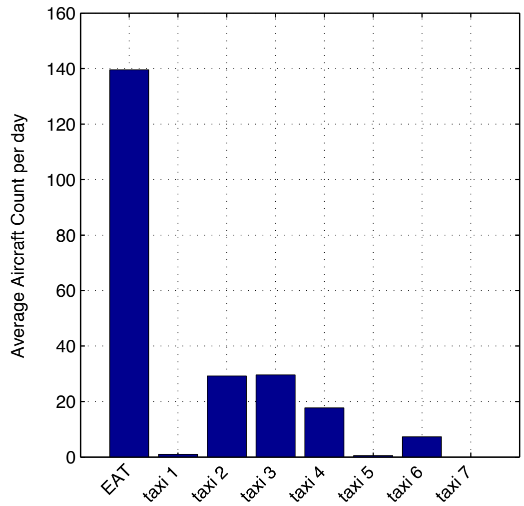


Figure 8. ATL north airfield west-flow average taxiway usage per day of arrivals on runway 26R.

Figure 9 shows the average aircraft count per hour using the EAT (blue) compared to the sum of the north 7 conventional taxiways (red). The EAT is used more than the conventional taxiways during peak traffic times (8am to 1pm and 2pm to 11pm). The conventional taxiways are used most often between 12am to 8am and 1pm to 2pm, most likely because there is low air traffic during those times. During low traffic hours, aircraft are directed to take the shortest and fastest route to the terminal, which is most likely, one of the conventional taxiways.

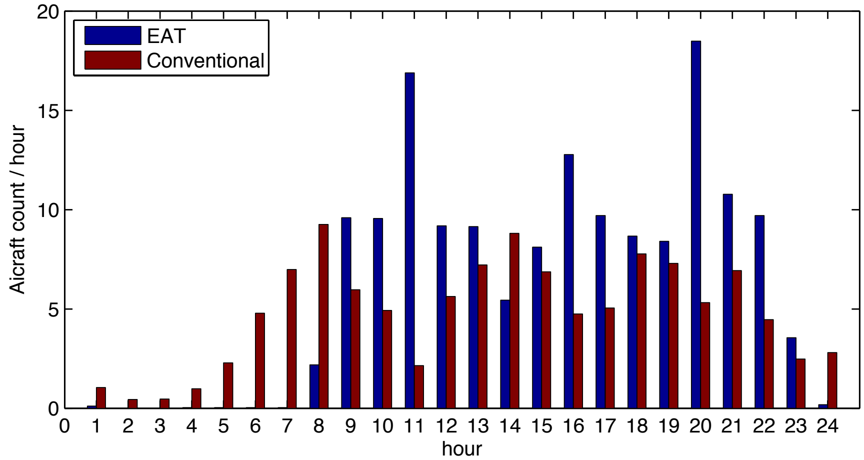


Figure 9. ATL north airfield west-flow aircraft count per hour arriving on runway 26R.

The in-board departure runway (8R/26L) throughput affects taxiway usage. Figure 10 shows the average aircraft departure per hour on runway 26L in west-flow configuration. The peak departure time is between 10am – 11am with approximately 18 departures per hour averaged over the six-month period. The maximum departure rate was 42 departures per hour, which was also observed between 10am – 11am. There is also a spike in EAT usage during this time with an average of 17 aircraft using the EAT compared to only 3 aircraft using the conventional taxiways. EAT use increases when the departure rate is high because there is a smaller separation time between departing aircraft, thus providing few opportunities for aircraft to safely cross the runway. The departure separation time is dependent on the minimum wake vortex time and the time for arriving aircraft to cross the runway.

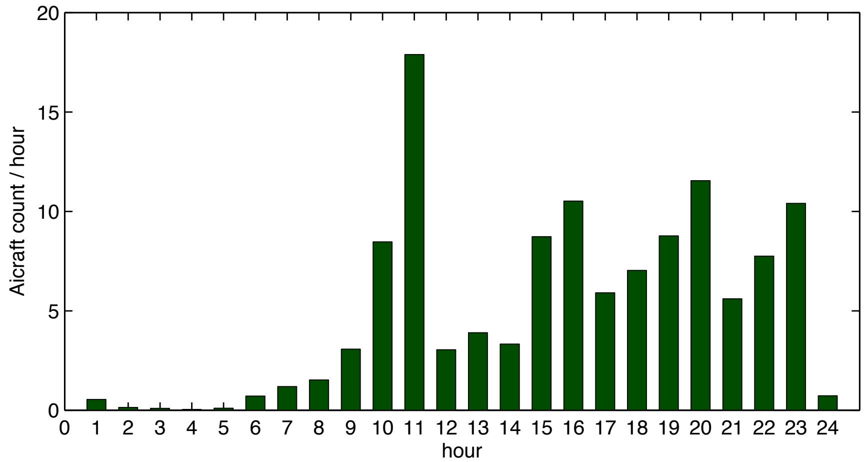


Figure 10. ATL north airfield west-flow aircraft count/hour departing on runway 26L.

2.3.4 ATL East-flow Configuration

The north airport is in east-flow configuration approximately 53% of the time; the south side of the airport is in east-flow approximately 66% of the time. Figure 11 (left) shows the airport diagram in east-flow configuration with the north end-around taxiway and south unimpeded taxiway, which are the most common routes, used to reach the terminal. On the north side of the airport, aircraft land on runway 8L and make a U-turn to take the end-around taxiway. An alternative route is the conventional taxiway as shown in Figure 11 (right). Smaller aircraft like the CRJ7 can make the sharp right turn at taxiway N6 and go straight to the terminal. Larger aircraft that need more runway length to slow down use the high-speed turn-offs and make a small U-turn to take either taxiway N6 or taxiway N7 to reach the terminal.

On the south side of the airport, aircraft arrive on runway 9L and can take several different conventional taxiways to reach the terminal. An interesting observation is that taxiway S1 is used the most often even though it requires aircraft to make a U-turn and is a longer distance to reach the terminal. After further investigation, taxiway S1 is used as an “unimpeded taxiway” which is similar to an end-around taxiway because it allows aircraft to taxi around an active runway without stopping. The south in-board departure runway is long enough for aircraft to have the starting takeoff position closer to taxiway S2 that allows taxiway S1 to be an unimpeded taxiway. Like an EAT, the benefit of using an unimpeded taxiway is to maintain a high departure throughput because departing aircraft do not need to wait for arriving aircraft to cross the runway.

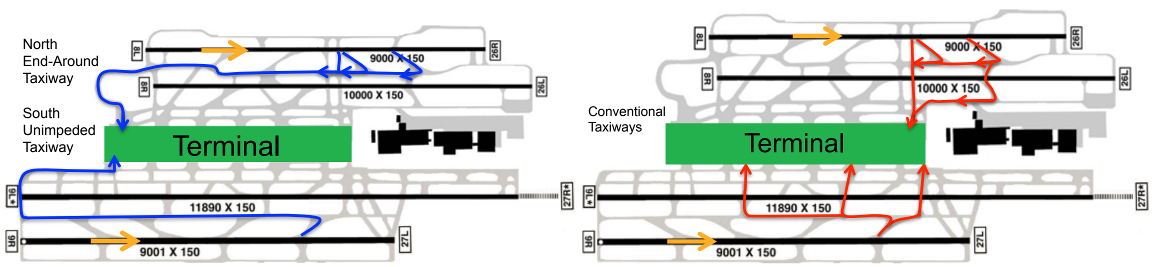


Figure 11. ATL east-flow EAT and unimpeded taxi routes (left) and conventional taxiway routes (right).

In east-flow configuration, the end-around taxiway is still used more than the sum total of the north conventional taxiways even though it is a longer distance. An average of 81 aircraft per day use the EAT. A reason for the large number of aircraft using the EAT is that aircraft arriving on 8L go around the in-board Runway 8R to maintain the desired high departure rate. Out of the conventional taxiways, taxiway N6 is used most often, with an average of 66 aircraft per day. Taxiway N6 is the most convenient and shortest route to reach the terminal. Figure 12 shows the average aircraft count per day that uses the different taxiways.

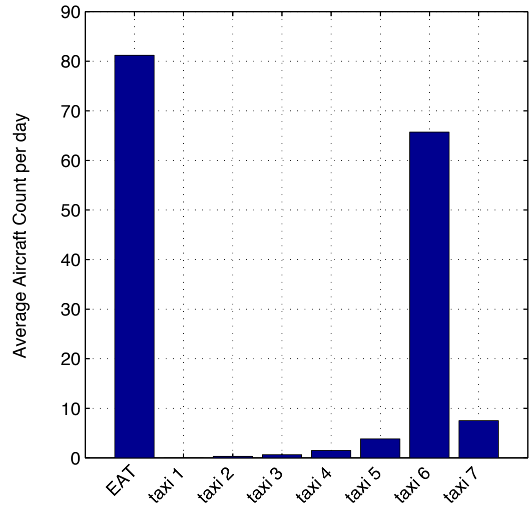


Figure 12. ATL north airfield east-flow average taxiway usage per day of arrivals on runway 8L.

Figure 13 shows the average aircraft count per hour using the EAT (blue) compared to the sum of the north 7 conventional taxiways (red). In east-flow configuration, the end-around taxiway is used more than the conventional taxiway between 8am -11am, 3pm – 5pm, 6pm – 8pm, and 9pm -11pm.

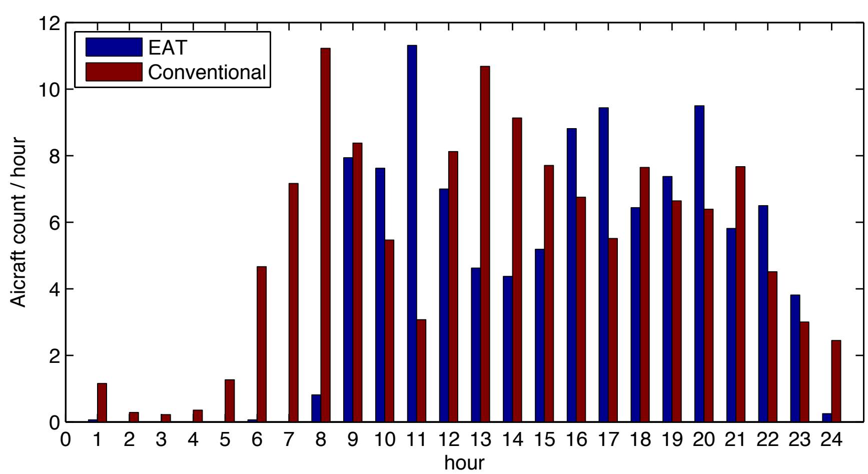


Figure 13. ATL north airfield east-flow average aircraft count per hour arriving on runway 8L.

Figure 14 shows the average aircraft departure per hour on runway 8R in east-flow configuration. The peak departure time is between 10am – 11am with approximately 18 departures per hour.

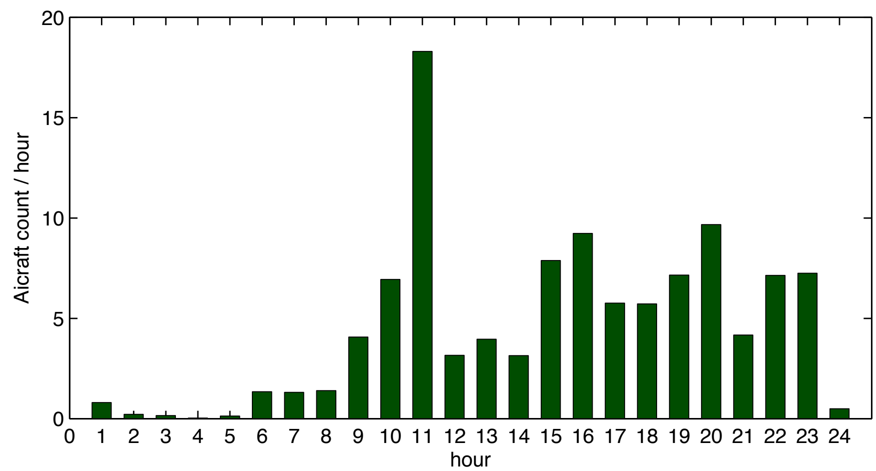


Figure 14. ATL north airfield east-flow average aircraft count per hour departing on runway 8R.

Figure 15 shows the average aircraft taxiway usage per day arriving on runway 9R. The south side of the airport has an average of 50 aircraft per day that use the unimpeded taxiway (taxi S1) in east-flow configuration. Although the unimpeded taxiway is a longer distance, it is the third most used taxi route for aircraft arriving on runway 9R in east-flow configuration. Taxiway S4 is the most common taxiway used with approximately 68 aircraft per day followed by taxiway S5 with 60 aircraft per day.

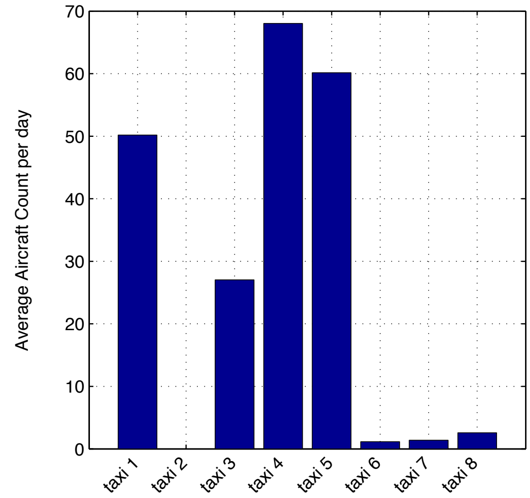


Figure 15. ATL south airfield east-flow average taxiway usage per day of arrivals on runway 9R.

Figure 16 shows the south-side east-flow aircraft count per hour arriving on runway 9R. The south side of the airport does not have an end-around taxiway, but uses taxiway S1 as an unimpeded taxiway during peak traffic hours. The unimpeded taxiway is used the most often between 9am-11am and 4pm-8pm. However, the conventional taxiways are used more often throughout the entire day.

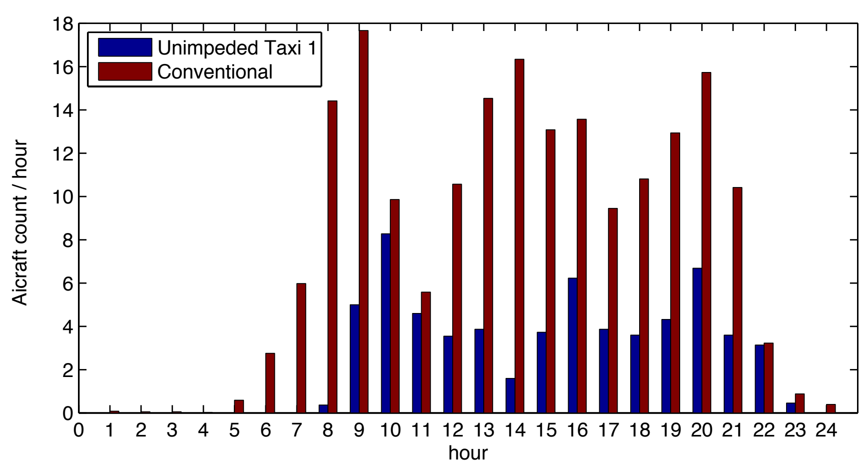


Figure 16. ATL south airfield east-flow average aircraft count per hour arriving on runway 9R.

Figure 17 is the average aircraft departure per hour on runway 9L in east-flow configuration. The peak departure time is between 10am – 11am with approximately 16 departures per hour.

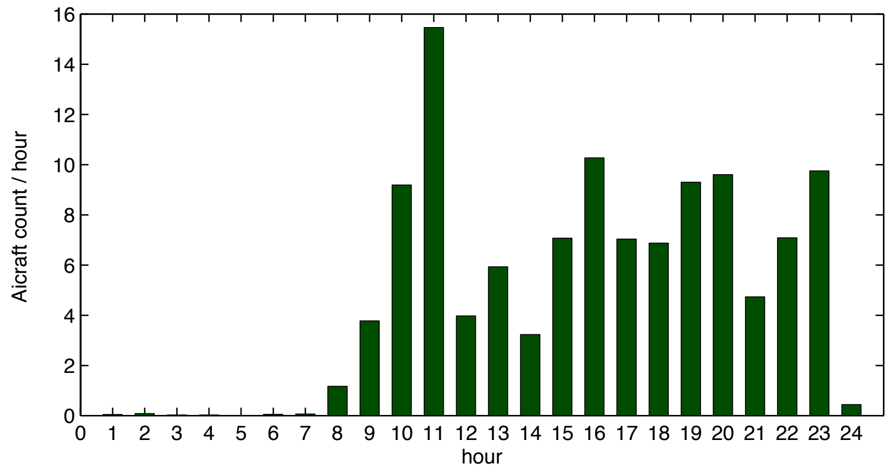


Figure 17. ATL north airfield east-flow average aircraft count per hour departing on runway 9L.

2.3.5 ATL Observations

West-flow configuration:

- Runway 26R is used 46% of the time when the north airport is in west-flow configuration and south runway 27L is used 34% of the time.
- The end-around taxiway is used the most often, with an average of 140 aircraft per day.
- Peak traffic hours for north runway 26R are 11am and 8pm and south runway 27L are 9am and 8pm.
- Peak departure for north runway 26L and south runway 27R is from 10am – 11am.

East-flow configuration:

- Runway 8L is used 54% of the time when the north airport is in east-flow configuration and south runway 9R is used 66% of the time.
- The EAT is the most used taxiway with an average of 81 aircraft per day followed by taxiway N6 with 66 aircraft per day.
- Taxiway S1 is an unimpeded taxi route in east-flow configuration and used similar to the EAT.
- Peak traffic hours for both north runway 8L and south runway 9R are 9am and 8pm.
- Peak departure for north runway 8R and south runway 9L is from 10am – 11am.

2.4 Dallas/Fort-Worth International Airport

2.4.1 DFW Background

In 1997, airport authorities released a 20-year development plan that recommended the construction of four EATs, one in each quadrant of the airport [DFW, 1997]. In accordance with this plan, the first EAT, which is located in the southeast section of DFW, entered service on 22 December 2008. None of the other planned EATs have been constructed to date. The EAT provides a path for aircraft to taxi around the in-board runways 17C and 17R. Prior to the implementation of the EAT, 17L arrivals would typically taxi via taxiway ER and cross 17C and 17R (the primary eastside departure runway). During times of high traffic conditions, this wait time contributed significantly to taxi-in delay. The EAT allows traffic to flow freely around the end of both runways. The EAT is also used by runway 17C arrivals, although less frequently. Since only departing (and not arriving) aircraft may overfly an operational perimeter taxiway, the EAT at DFW can only be used when the airport is in the south-flow configuration [AOSC, 2006].

At present, the use of end-around taxiways at DFW is not well defined. Interviews with DFW supervisors and a literature survey of the limited material available on EATs indicate that there are no formal procedures in place to guide air traffic controllers in using the EAT [Uday et al., 2011]. Instructions given to aircraft to taxi via the EAT are usually solely based on the judgment of the controller on duty.

2.4.2 DFW Airport Analysis

Figure 18 is a satellite image of the southeast quadrant of Dallas airport with the main features used to analyze taxiway usage patterns. The official FAA airport diagram with runways and taxiways names is in Appendix A.2. The runways run north and south, but the figure is oriented so the runways are horizontal to make the taxiways easy to see. The in-board departure runway 17R/35L is highlighted in purple, while the out-board arrival runways 17C/35C and 17L/35R are highlighted in orange. The terminal is denoted in green.

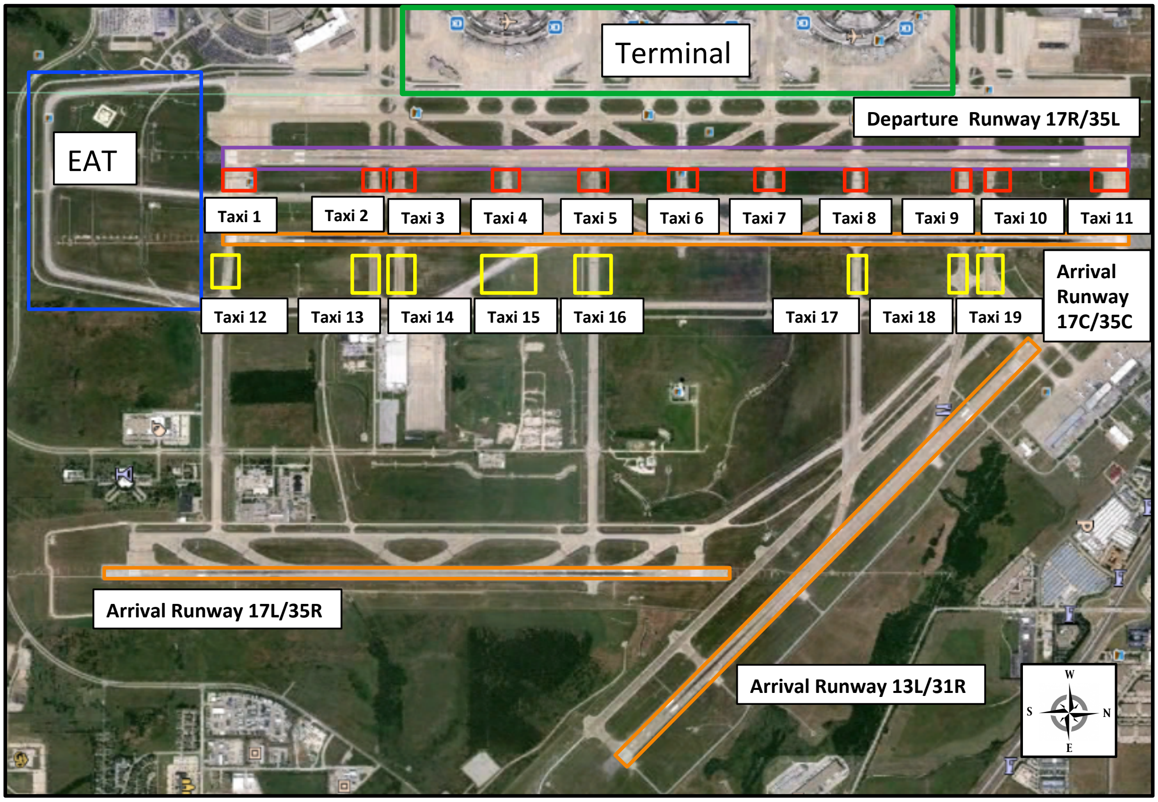


Figure 18. Dallas Fort Worth International Airport (DFW) diagram of departure runways (purple), arrival runways (orange), end-around taxiway (blue), conventional taxiways (red), and terminal (green).

The taxiways analyzed for the southeast quadrant of the airport are the end-around taxiway (blue), the conventional taxiways before crossing the departure runway (taxi 1 – taxi 11 red), and conventional taxiways before crossing the in-board arrival runway 17C/35C (taxi 12 – taxi 19 yellow). Aircraft route passing through both taxiway 1 and taxiway 12 will be denoted in the analysis as taxi 1-12. Aircraft usually stop and wait for clearance on the conventional taxiway before being permitted by air traffic control to cross an active runway.

The end-around taxiway is located in the south-east quadrant of the airport. The end-around taxiway is primarily used by runway 17L in south-flow configuration. All other runways use the end-around taxiway less than 0.1% of the time (65 out of 46817 arrivals). The analysis therefore primarily focuses on runway 17L, but also investigates adjacent traffic on runway 17C and its effects on taxiway usage.

2.4.3 DFW Runway 17L South-flow Configuration

Runway 17L is used in south-flow configuration 70% of the time. The end-around taxiway is used less than 0.1% of the time (7 out of 3771 arrivals) when runway 35R is in north-flow configuration; therefore the EAT analysis will focus on aircraft arriving south on runway 17L. Figure 19 shows the most common taxi routes when aircraft land on runway 17L in south-flow configuration. Aircraft exit the high-speed turn-off and either takes the end-around taxiway (blue) or one of the conventional taxiways (red). If the arrival runway 17C is clear then aircraft will cross and stop short of runway 17R and wait for clearance from departing aircraft or taxi along taxiway M parallel to runway 17R and cross at another point. If the arrival runway 17C is not clear, aircraft must either wait for clearance or taxi parallel to the runway on taxiway P and most likely cross using taxiway 14 or taxiway 16.

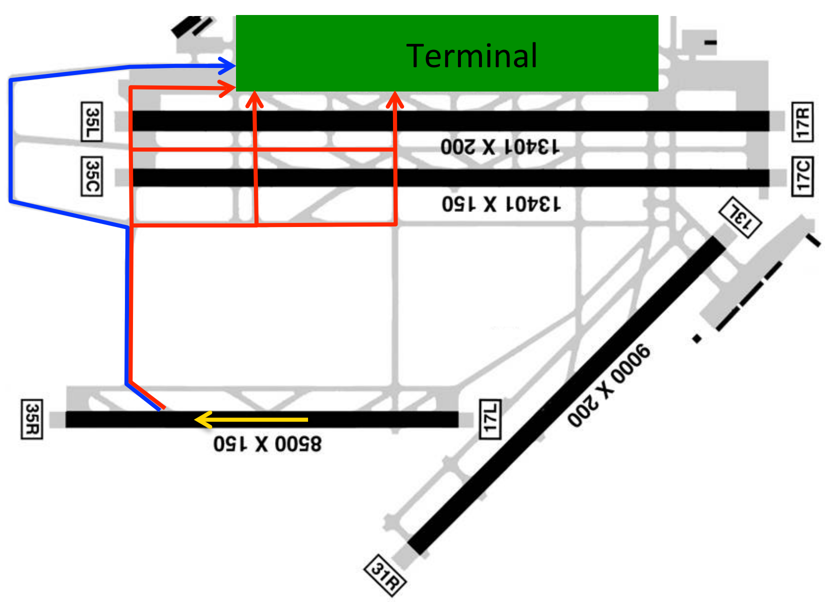


Figure 19. DFW south-flow aircraft arriving on runway 17L end-around taxiway route (blue) and conventional taxiways routes (red).

Figure 20 shows the average aircraft count per day for aircraft arriving south on runway 17L. The taxi routes were narrowed down to six taxiways after eliminating combinations of taxiways that were used less than 1% of the time. The end-around taxiway is used the most often with an average of 26 aircraft per day. The next most common taxi route is conventional taxi 1 – 12 with an average of 15 aircraft per day.

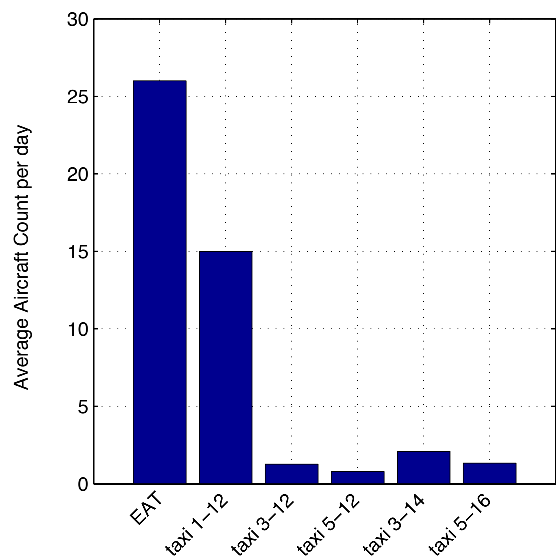


Figure 20. DFW south-flow average taxiway usage per day of arrivals on runway 17L.

Figure 20 is the average aircraft count per hour using the EAT (blue) compared to the sum of the conventional taxiways (red). The EAT is used more than the conventional taxiways during peak traffic times (9am to 12pm). The conventional taxiways are used more the EAT during all other hours of the day. During low traffic hours, aircraft are directed to take the shortest and fastest route to the terminal, which is most likely, the conventional taxiways.

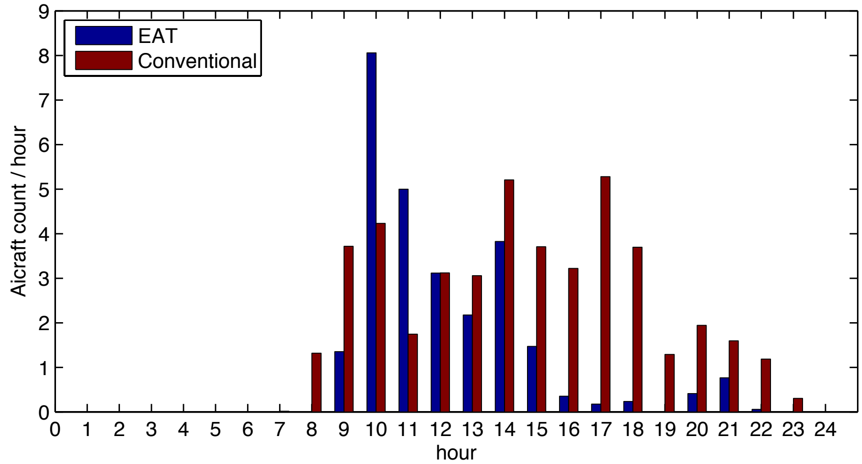


Figure 21. DFW south-flow average aircraft count/hour arriving on runway 17L.

2.4.4 DFW Runway 17C South-flow Configuration

Investigating traffic patterns on in-board arrival runway 17C provided a better understanding of taxi route trends of aircraft arriving on runway 17L. Figure 22 shows taxi routes aircraft could take when arriving south on runway 17C. Aircraft can take the end-around taxiway (blue) or one of the conventional taxiways (red).

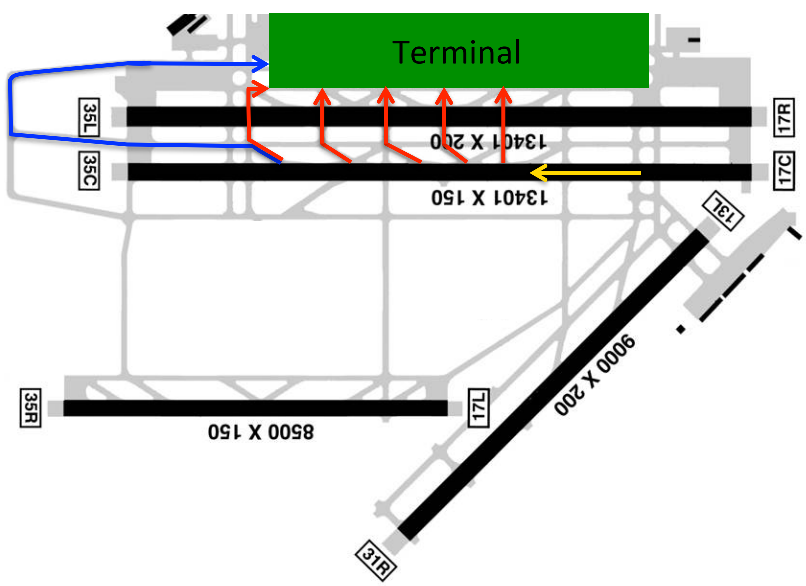


Figure 22. DFW south-flow aircraft arriving on runway 17C end-around taxiway route (blue) and conventional taxiways routes (red).

Figure 23 shows the average aircraft taxiway usage per day arriving on runway 17C. The end-around taxiway is used less than 0.1% of the time. The most used taxi route is taxiway 5 with an average of 94 aircraft per day. It is used most often because most aircraft can brake in time to make the high-speed turn-off (M4). Taxiway 3 and taxiway 6 are the next most common taxi routes both with an average of 52 aircraft per day. Aircraft arriving on runway 17C use primarily the conventional taxiways because of convenience and short distance to the terminal. Few aircraft use the end-around taxiway because it would require coordinating with arrivals from runway 17L that use the EAT.

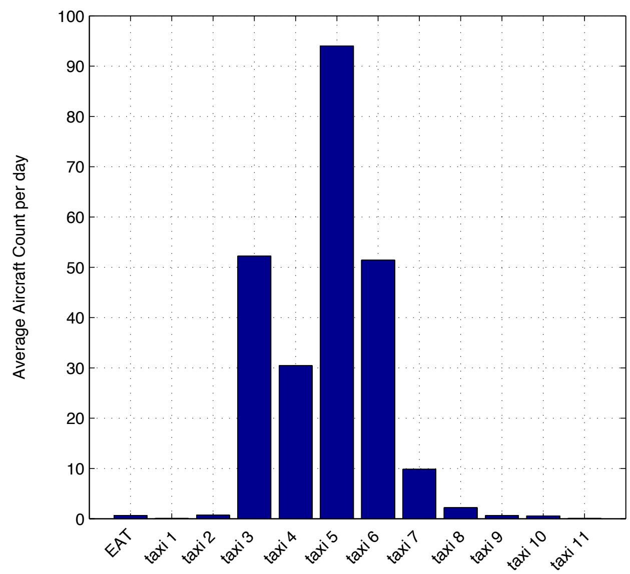


Figure 23. DFW south-flow average taxiway usage per day of arrivals on runway 17C.

Aircraft arriving on in-board runway 17C mostly use only conventional taxiways. Figure 24 shows the average aircraft arrival per hour on runway 17C in south-flow configuration. The arrival rate is relatively constant from 9am to 10pm with approximately 15-18 aircraft per hour.

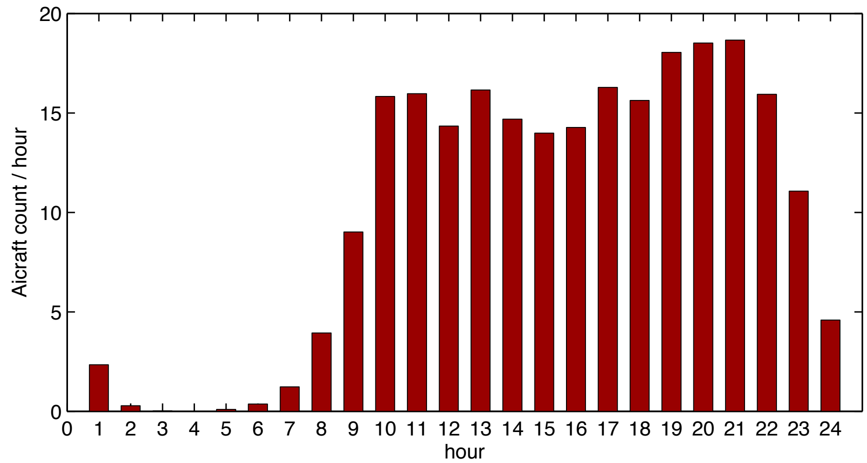


Figure 24. DFW south-flow average aircraft count/hour arriving on runway 17C.

The departure runway throughput affects the taxiway usage. Figure 25 shows the average aircraft departure per hour on runway 17R in south-flow configuration. The peak departure time is between 2pm – 3pm with approximately 24 departures per hour. The high departure rate on runway 17C corresponds to a low arrival rate on runway 17C (14 aircraft/hour) and runway 17L (6 aircraft/hour). The maximum departure rate is 46 departures per hour.

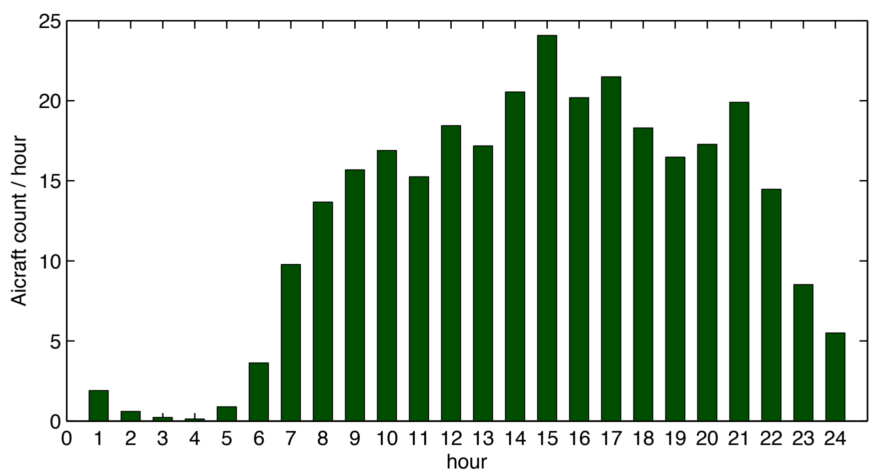


Figure 25. DFW south-flow average aircraft count/hour departing on runway 17R.

2.4.5 DFW Observations

South-flow configuration:

- Runway 17R, 17C, and 17L on the east side of the airport are in south-flow configuration 70% of the time.
- An average of 25 aircraft per day use the EAT that arrive on out-board runway 17L.
- An average of 15-18 aircraft per hour arrives on runway 17C between 9am – 10pm and uses only the conventional taxiways, primarily taxiway 5.
- Peak arrival time for runway 17L is between 9am – 10am with 12 arrivals per hour and the EAT is the primary taxiway used with 8 aircraft per hour.
- Runway 17L is used to accommodate a large number of arrivals between 9am – 2pm and tapers off the rest of the day.
- Peak departure rate is 24 aircraft per hour between 2pm – 3pm when adjacent arrival traffic is low.

2.5 Detroit Metropolitan Wayne County Airport

2.5.1 DTW Background

Detroit Metropolitan Wayne County Airport is ranked 12th in number of landings and takeoffs in North America and 17th in the world [ACI, 2013]. On average 32.2 million passengers pass through DTW per year. To meet the needs of increasing air traffic demand at Detroit airport, the newest 10 000 ft runway 4L/22R opened for operations on December 11, 2001 [DTW, 2008]. Currently, the airport has six runways and 145 gates. The airport constructed an end-around taxiway, called taxiway Quebec (Q) in 2004. Taxiway Q allows for aircraft arriving on runway 4L/22R to taxi unimpeded to the terminal without crossing the departure runway 4R/22L. The crosswind runways do not add capacity because they cannot be used simultaneously with north-south runways; therefore they are mostly used as additional taxiways.

2.5.2 DTW Airport Analysis

Figure 26 is a satellite image of the Detroit airport with the main features used to analyze taxiway usage patterns. The official FAA airport diagram with runways and taxiways names is in Appendix A.3. The in-board departure runway 4R/22L is highlighted in purple, while the out-board arrival runway 4L/22R is highlighted in orange. The north and south terminal are denoted in green. The taxiways analyzed are the end-around taxiway (blue), the conventional taxiways before crossing the departure runway (taxi 1 and taxi 2 red). Aircraft usually stop and wait for clearance on the conventional taxiway before being permitted by air traffic control to cross an active runway.

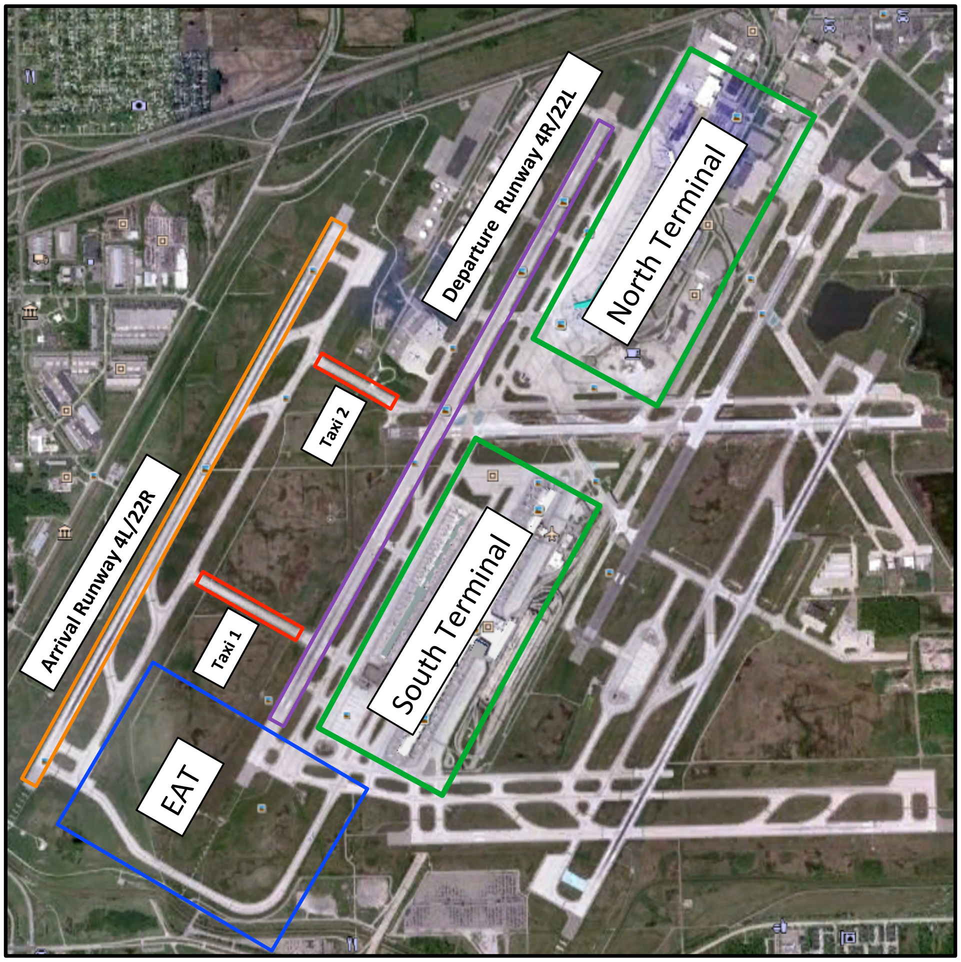


Figure 26. Detroit Metropolitan Wayne County Airport (DTW) diagram of departure runways (purple), arrival runways (orange), end-around taxiway (blue), conventional taxiways (red), and terminal (green).

The end-around taxiway is used by runway 4L/22R in both south and north-flow configuration. Detroit airport has two distinct terminals and for simplicity the analysis denotes these terminals as the north and the south terminal. The north terminal has 26 gates and the south terminal has 121 gates. The taxi time and fuel burn analysis in section 6 will take into account the different destinations to the north or south airport. The next section separates taxiway usage trends into south and north-flow configuration of runway 4L/22R.

2.5.3 DTW Runway 22R South-flow Configuration

Runway 22R is used in south-flow configuration 90% of the time. Figure 27 shows the most common taxi routes when aircraft land on runway 22R in south-flow configuration. Aircraft exit the first or second high-speed turn-off and either takes the end-around taxiway (blue) or one of the conventional taxiways (red). The end-around taxiway is an unimpeded path that circumvents the in-board departure runway 22L to reach the terminal. Taxi 1 is the conventional taxi route closest to the EAT and taxi 2 is the northern taxi route used most often when aircraft destination is the north terminal.

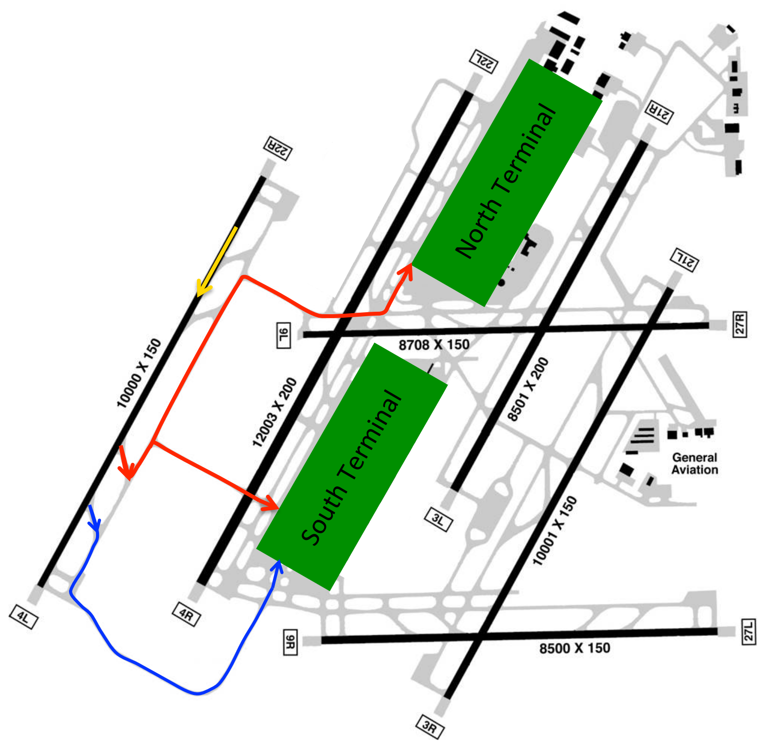


Figure 27. DTW south-flow aircraft arriving on runway 22R end-around taxiway route (blue) and conventional taxiways routes (red).

Figure 28 shows the average aircraft taxiway usage per day arriving south on runway 22R. The end-around taxiway is used the most with an average of 111 aircraft per day. Taxi 2 has an average of 32 aircraft per day followed by taxi 1 with an average of 26 aircraft per day. In south-flow configuration, the EAT is the most convenient path because it is a non-stop route and the majority of the gates are located in the south terminal.

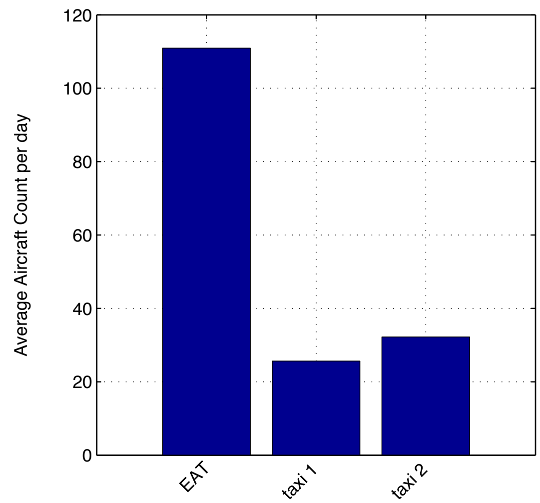


Figure 28. DTW south-flow average taxiway usage per day of arrivals on runway 22R.

Figure 29 shows the average aircraft count per hour using the EAT (blue) compared to the conventional taxiways, Taxi 1 (green) and Taxi 2 (red). The EAT is used significantly more than the conventional taxiways during most of the day between the hours of 6am to 9pm. The peak arrival time between 2pm – 3pm, which also corresponds to the time when the conventional taxiway is, used the most with an average of 14 aircraft per hour.

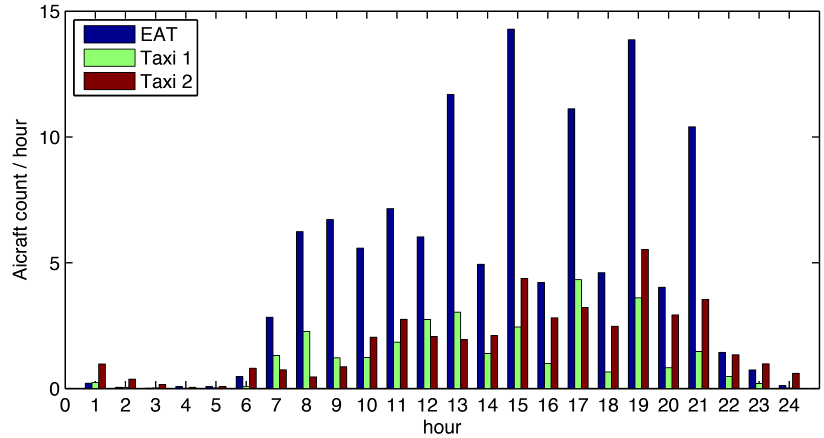


Figure 29. DTW south-flow average aircraft count/hour arriving on runway 22R.

The departure runway throughput can influence which taxi route an aircraft takes. Figure 30 shows the average aircraft departure per hour on runway 22L in south-flow configuration. The peak departure time is between 8pm – 9pm with approximately 16 departures per hour. During the peak arrival time (2pm – 3pm), the average departure rate was still high with 13 departures per hour. A high departure rate could be maintain because the majority of the aircraft during this time used the EAT.

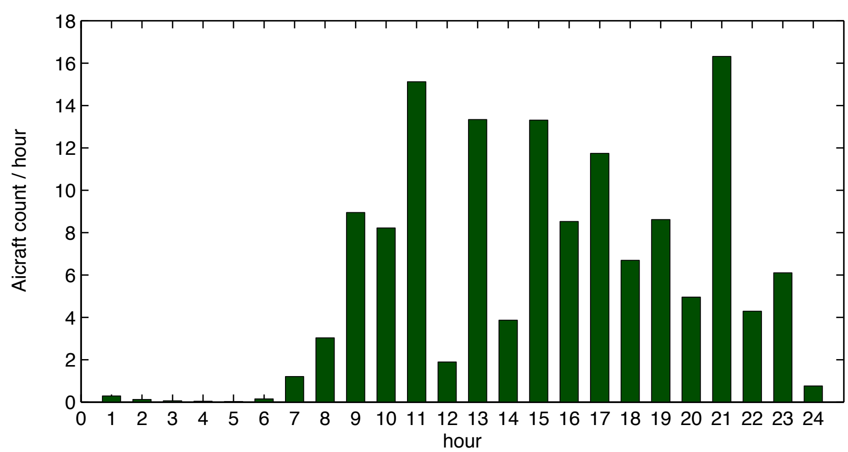


Figure 30. DTW south-flow average aircraft count/hour departing on runway 22L.

2.5.4 DTW Runway 4L North-flow Configuration

Runway 4L is used in north-flow configuration 10% of the time. Figure 31 shows the most common taxi routes when aircraft land on runway 4L in north-flow configuration. Aircraft exit the runway and either takes the end-around taxiway (blue) or one of the conventional taxiways (red). Aircraft taking the EAT must make a U-turn and head south on the parallel taxiway A to reach the end-around taxiway. Northern taxi route, Taxi 2, is the shortest taxi distance to the north terminal. Taxi 1 is about half the distance of the EAT route to reach the south terminal.

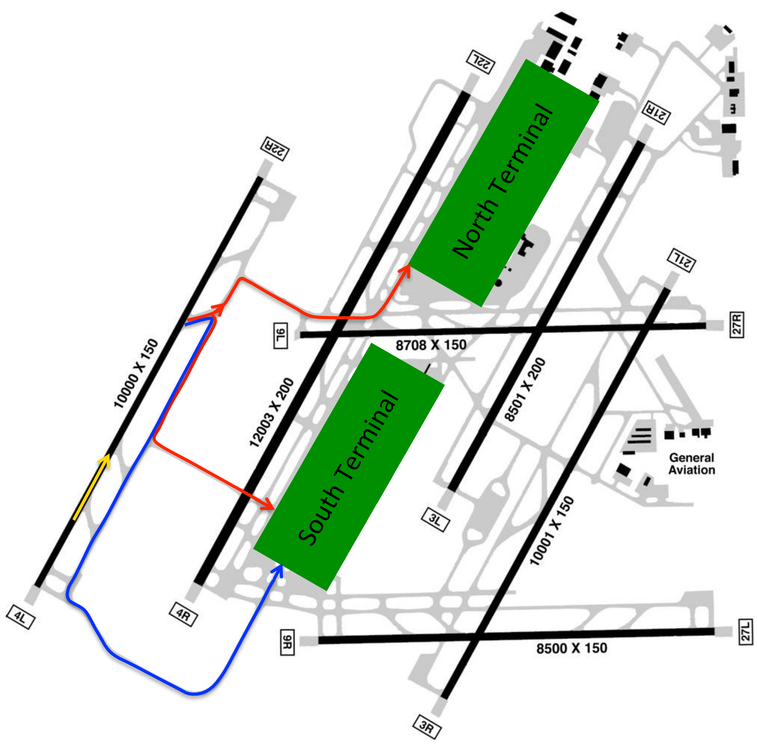


Figure 31. DTW north-flow aircraft arriving on runway 4L end-around taxiway route (blue) and conventional taxiways routes (red).

Figure 32 shows the average aircraft taxiway usage per day arriving north on runway 4L. The end-around taxiway is used the most with an average of 63 aircraft per day. Taxi 2 has an average of 42 aircraft per day followed by taxi 1 with an average of 7 aircraft per day. In north-flow configuration, the EAT is more than twice the distance of the conventional taxiways, but it is the preferred taxi route to maintain the departure rate on runway 4R. If the aircraft gate is located at the north terminal, the aircraft will most likely take Taxi 2.

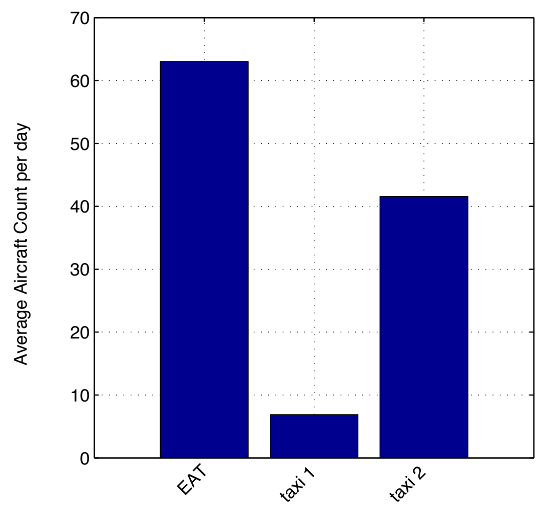


Figure 32. DTW north-flow average taxiway usage per day of arrivals on runway 4L.

Figure 33 shows the average aircraft count per hour using the EAT (blue) compared to the conventional taxiways, Taxi 1 (green) and Taxi 2 (red). The EAT is used significantly more than the conventional taxiways during most of the day between the hours of 7am to 9pm. The peak arrival time is between 2pm – 3pm, which also corresponds to the time when the conventional taxiway is used the most. The conventional taxiways are used almost equal to the EAT during certain times of the day when there is low traffic demand. For example, between 11am – 12pm both the EAT and taxi 2 have an average of 4 aircraft per hour.

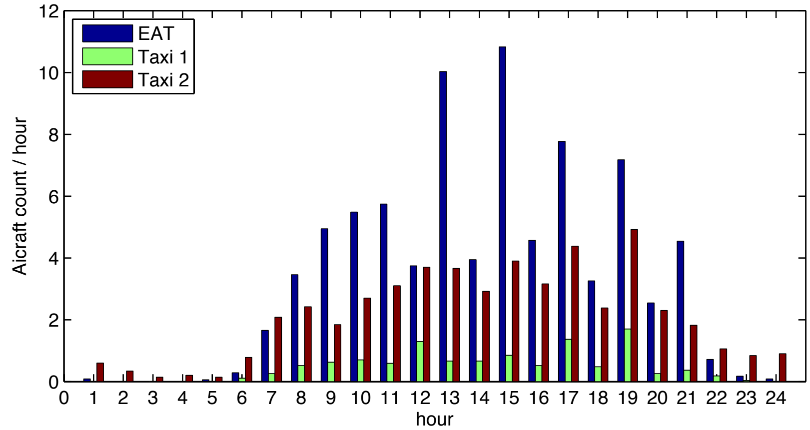


Figure 33. DTW north -flow average aircraft count per hour arriving on runway 4L.

The departure rate is affected by the arrivals on runway 4R. Figure 34 shows the average aircraft departure per hour on runway 4R in north-flow configuration. The peak departure time is between 1pm – 2pm with approximately 14 departures per hour. During the peak arrival time (2pm – 3pm), the average departure rate was still high with 13 departures per hour. A high departure rate could be maintained because the majority of the aircraft during this time used the EAT.

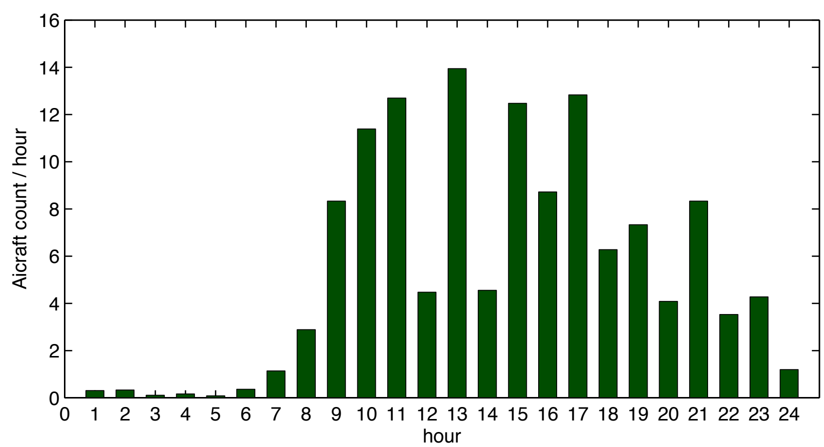


Figure 34. DTW north-flow average aircraft count/hour departing on runway 4R.

2.5.5 DTW Observations

South-flow configuration:

- Runway 22R is used 90% of the time when the west airport is in south-flow configuration.
- The end-around taxiway is used the most often, with an average of 111aircraft per day.
- Peak traffic hours for arrivals on runway 22R are 2pm – 3pm.
- Peak departure for runway 22L is between 8pm – 9pm with an average of 16 departures per hour.

North-flow configuration:

- Runway 4L is used 10% of the time when the west airport is in north-flow configuration.
- The EAT is the most used taxiway with an average of 63 aircraft per day followed by taxiway 2 with 42 aircraft per day. Taxi 1 is only used 6% of the time.
- Peak traffic hours for both north runway 8L and south runway 9R are 9am and 8pm.
- Peak departure for runway 4R is from 1pm – 2pm.

CHAPTER 3. ENVIRONMENTAL IMPACTS OF UNIMPEDED TAXIWAYS

3.1 Method Overview

The environmental impacts of the unimpeded taxiways at each airport were assessed by calculating the average taxi time and fuel burn between 10 September 2012 to 28 February 2013.The aircraft position was used to determine the taxi-route and taxi time of each aircraft from exiting the arrival runway to when it reaches the edge of the terminal area. The aircraft taxi-route was identified as either using the end-around taxiway or conventional taxiway. The taxi time, taxi distance, and average speed were calculated for each aircraft. The fuel burn and emissions were estimated from using the ICAO Engine Emissions Databank (Appendix B. 1) [ICAO, 2013]. The aircraft type and calculated taxi time from the ASDE-X data were used to estimate fuel burn, NOx emissions, and CO emissions. Appendix B. 2 is an example of the resulting matrix after systematically analyzing ASDE-X data. The following surface performance metrics and characteristics were assessed for each arrival aircraft:

- Taxi time (seconds)
- Fuel burn (kg) for single and all-engine
- Average speed (knots)
- NOx emissions for single and all-engine
- CO emissions for single and all-engine
- Number of engines
- Taxi distance (feet)

- Track number (unique identifier for each aircraft)
- Aircraft type
- Arrival time (seconds)
- Terminal area destination
- Taxi route (EAT and each conventional taxiway is numbered)
- Runway configuration (west, east, south, or north)
- Date

3.1.1 Data Analysis

A series of data analysis steps were performed to analyze aircraft surface performance and identify significant factors contributing to fuel burn. Figure 35 shows the flowchart for data analysis.

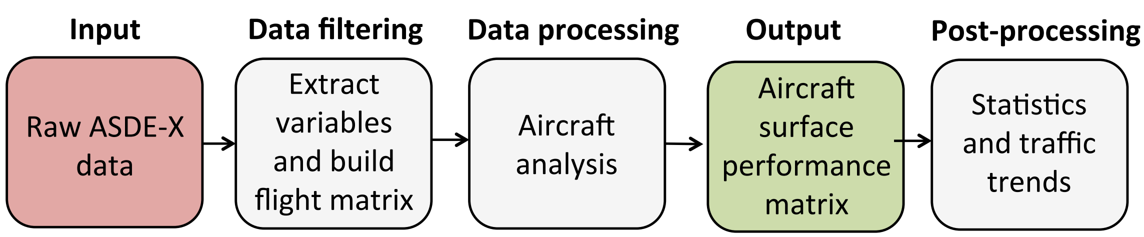


Figure 35. Data analysis flowchart.

Step 1: Input

The first step was to acquire ASDE-X data, which is the input data that provides information on surface movement of aircraft at selected airports. The raw ASDE-X data format is text files. There is one text file per hour of the day at a given airport. The ASDE-X data for ATL, DFW, and DTW airport from 10 September 2012 to 28 February 2013 is approximately 250 GB with approximately 12,500 text files.

Step 2: Data filtering

The next step is to filter the raw ASDE-X files and only extract the desired aircraft variables. The eight variables extracted were time, latitude, longitude, speed, fix (destination airport), aircraft type, callsign, and track number (unique identifier for aircraft). Matlab was used to load the text files, extract the desired variables, and build the flight matrix by combining 24 text files into one cell matrix file per day per airport. The flight matrix for one day at an airport has approximately 1 million rows of data. The ASDE-X system updates the flight data every second to track aircraft surface position.

Step 3: Data processing

The data processing step loads the flight matrix for each day to systematically analyze aircraft surface performance and traffic trends. The Matlab algorithm tracks each aircraft and identifies which taxi route it takes, the runway configuration, and aircraft type, and then calculates distance traveled, speed, taxi time, emissions, and fuel burn. One data issue that occurred was track numbers, which are supposed to be unique identifiers for aircraft, were sometimes repeated, therefore new track numbers were assigned for duplicate aircraft. Another issue encountered was Matlab could not build flight matrix larger than 8591 MB using a 64-bit Windows platform; therefore the ATL data was too large to have one flight matrix file so it was divided into north and south airport for each day.

Step 4: Output

The resulting output is given in a single condensed aircraft surface performance matrix with 18 parameters for the 6-month study period (173 days). Appendix B. 2 shows part of the ATL surface performance matrix, which includes variables such as taxi time, fuel burn, emissions, distance, taxiway, and runway configuration. For example, the data analysis at ATL had 1.2 billion rows of aircraft as input and the output surface performance matrix contains 67,000 rows corresponding to arrivals on runway 26R/8L.

Step 5: Post-processing

The final step is to use the aircraft surface performance matrix to study traffic trends and patterns and use statistical analysis to compare fuel burn and taxi time among the airports. Statistical software, SAS, was used to conduct an n-way ANOVA test to understand the sources of variation and their impact of fuel burn. Significant factors affecting fuel burn were identified and will be used later in the decision model (see Appendix C).

3.1.2 Taxi Time

Equation 1 was used to calculate the taxi time, which is defined as the time an aircraft exits the arrival runway to the time it reaches the edge of the terminal area.

$$t_{taxi} = \min(t_{term}) - \max(t_{runway}) \quad (1)$$

Taxi time is a good performance metric because it gives information on which taxi route is the fastest. The variability in taxi time also dictates the predictability for on-time performance and taxi routing efficiency. Khadilkar and Balakrishnan (2011) presented an approach to estimate fuel burn using flight data recorder (FDR) data and a linear regression model. They concluded that the total taxi time is the main component to determine fuel burn, although the number of acceleration events was also a significant factor.

The Airport System Performance Metric (ASPM) defines the average taxi-in time as the average difference between actual gate-in time and actual wheels-on time (FAA, 2014). Further investigation of our ASDE-X data revealed high variability in taxi time using this definition. This high variability could be due to several factors. For example, aircraft may be waiting for an aircraft to pushback from a gate and this waiting time is accounted for in the taxi in time. Terminal area congestion is not the focus of this research; therefore the taxi segment in the terminal area is excluded from taxi time. Taxi in end time is to the edge of the terminal area. Taxi in start time is defined as when the aircraft exits the runway instead of the ASPM definition of wheels on time. The taxi in segment from wheels on to exiting the arrival runway is excluded from taxi time because of the large variety of aircraft type in our study and pilot landing variability.

3.1.3 Fuel Burn

There are two main publically available aircraft performance data that provide fuel flows and emission indices as a function of engine thrust: the Aircraft Engine Emission Databank which was developed and maintained by the International Civil Aviation Organization (ICAO), and the Base of Aircraft Data (BADA), developed and maintained by the Eurocontrol Experimental Centre. BADA estimates fuel consumption as a function of thrust and airspeed primarily for the airborne phase of flight, therefore using it for ground fuel consumption may not be appropriate.

Our study estimated taxi fuel burn using the ICAO Databank, which is based on engine performance and emissions data obtained from full-scale engine tests at sea level. The values of fuel flow (kg/s) and emission indices (g of pollutant emitted per kg of fuel burnt) taken at 7%, 30%, 85%, and 100% rates outputs are provided in the databank for the majority of jet and turbofan commercial engines. The model also computes CO and NO_x emissions, but the average fuel burn per aircraft was used as the primary performance metric to assess environmental impact of taxi-in procedures. Carbon emissions can be estimated as 3.16 kilogram of CO_2 per kilogram of jet fuel [IATA, 2014].

The ICAO emissions databank defines taxi/ground idle as 7% of full rated power, but it does not distinguish between the different phases of taxiing. A case study at DFW showed stops and resulting accelerating events constitute approximately for 18% of fuel spent in surface operations [Nikoleris et al., 2011]. Our study accounts for the potential increase in fuel burn from accelerations by decomposing each aircraft trajectory into three taxi phases: stop and starts (accelerating after a stop), perpendicular turns, and taxi at constant speed or breaking. Table 2 is the baseline model assumptions for time and thrust levels at different taxi operation phases where $t_{p,i}$ is the time (s) aircraft i

spent on taxi phase p, T is the total taxi time, n_s is the number of stops, and n_t is the number of turns. The assumptions used in Table 2 were adapted from Nikoleris' fuel burn estimate model based on inputs from commercial airline pilots and analysis of true idle estimates in a Transportation Research Board report [Wood et al., 2008].

Table 2. Baseline assumptions for time and thrust levels of taxi operations phases.

	Taxi phase *p*	**Time (s)**	**Thrust %**
1	Stop and start ("breakaway thrust")	$t_{1,i} = 8 \cdot n_s$	9%
2	Perpendicular turn	$t_{2,i} = 6 \cdot n_t$	7%
3	Constant speed	$t_{3,i} = T - t_{1,i} - t_{2,i}$	5%

The first taxi phase accounts for aircraft stops and starts. Aircraft using the conventional taxi route must stop and wait for clearance before crossing an active runway. Breakaway thrust or accelerating from stop has been found to be as high as 9% of full rated power in a study by British Airways [Morris, 2005]. Our fuel burn estimate model models the effect of this acceleration using Nikoleris' assumption that an average duration of 8 s is needed for acceleration after a stop, consisting of 4 s to overcome inertia and 4 s to reach taxi speed. The second phase accounts for perpendicular turns at 7% of full rated power for a 6 second turn. The third taxi phase is taxiing at a constant speed, which is estimated as 5% of full rated power. These thrust setting percentages and time duration were adapted from Nikoleris' fuel burn estimate model based on commercial airline pilots and analysis of true idle estimates from the Transportation Research Board report [Wood et al., 2008]

Equation 2 calculates the total fuel consumed, TF_i, from exiting the runway to reaching the edge of the terminal area:

$$TF_i = \sum_{p=1}^{3} t_{p,i} \cdot f_{p,i} \cdot n_i \quad (2)$$

where $t_{p,i}$ is the time (s) aircraft i spent on taxi phase p, $f_{p,i}$ is fuel flow (kg/s) while aircraft i is on taxi phase p, and n_i is the number of engines aircraft i used.

In addition to the time and thrust level assumptions for estimating the three taxi phases fuel burn presented in Table 2, several other fuel burn assumptions were made in the study. The calculated fuel burn for EATs and unimpeded taxiways assumes there are no stops by definition. The data analysis also excludes small turboprop aircraft because they account for less than 1% of traffic during the study period. The aircraft used in the study using the ICAO databank are presented in Appendix B. 1.

3.2 ATL Taxi Time and Fuel Burn Estimates

3.2.1 West-flow Configuration

Table 3 is a summary of the average taxi time and fuel burn for the end-around and conventional taxiways when the runways are in west-flow configuration. Although the average taxi time for the EAT is higher than the Conventional taxiway for the north side of the airport, it is 7% lower than the average taxi time for the south conventional taxiway. The south side of the airport serves as a baseline to do a comparison with the north side of the airport because it only has conventional taxiways. The south conventional taxiways have a higher average taxi time of 4.89 minutes compared to the north EAT (4.57 mins) and north conventional taxiways (3.21 mins). The north conventional taxi time is lower than that for the south because the average taxi distance for the north conventional taxiway is 3602 ft compared to the south average taxi distance of 6244 ft. The lower taxi time for the north conventional taxiways is also partly due to them being used the most often during off-peak traffic hours. Aircraft that arrive in the early morning, midday, and late night have a lower taxi time because there is low departure traffic, which makes crossing the in-board runway faster. There is less variability in taxi time for the EAT (σ = 1.81 mins) and the north conventional (σ = 1.62 mins) than the south conventional taxiways (σ = 2.39 mins). A smaller variability in taxi time can help with more efficient scheduling of arrivals and departures.

Table 3. ATL west-flow configuration average taxi time and fuel burn statistics.

		Taxi Time (min)		Fuel Burn (kg)		Distance (ft)	Speed (knots)	Aircraft Count
Airfield	**Taxiway**	**Mean**	**Std**	**Mean**	**Std**	**Mean**	**Mean**	**Total**
North	EAT	4.57	1.81	62.08	33.35	7743	16.8	24146
	Conventional	3.21	1.62	45.05	31.41	3602	11.1	14744
South	Conventional	4.89	2.39	69.18	53.01	6244	12.6	18749

The average speed for aircraft that use the EAT is 16.8 knots compared to the north conventional taxiways (11.1 knots) and the south conventional taxiways (12.6 knots). The end-around taxiway is a non-stop path that circumvents the active runway; therefore aircraft can taxi at a higher speed for a longer distance. The conventional taxiway has a lower average speed because aircraft must slow down and stop for clearance before crossing the in-board runway to reach the terminal. Stop and starting the aircraft multiple times burns more fuel because the pilot applies the brakes and throttles up which has a higher initial fuel burn rate. Accurately accounting for stops and starts is not possible with the data provided, but could be added in future research. Therefore, the conventional taxiway fuel burn is an underestimate of the actual fuel burn.

The high variability of fuel burn is due the large variety of aircraft that use Atlanta airport. There are approximately 80 aircraft types in the study ranging from CRJ2 to a Boeing 747. The number of engines for these different aircraft types range from 2 to 4 engines, which affects the total fuel burn.

3.2.2 East-flow Configuration

Table 4 is a summary of the average taxi time and fuel burn for the end-around and conventional taxiways when the runways are in east-flow configuration. The north airfield average taxi time for the end-around taxiway is 7.08 minutes compared to north conventional taxiways (taxi N1 – taxi N7) is approximately 4.58 minutes. The south airfield has similar average taxi-times to the north airfield. The unimpeded taxiway average taxi time is 7.04 minutes and the south conventional is 4.38 minutes. The conventional taxiway is used more often during low traffic hours so there is less ground congestion to reach the terminal, which results in a faster taxi time. The EAT has a higher taxi time due to the long average taxi distance of 12709 feet. The end-around taxiway is located on the northwest of the airport so aircraft arriving east essentially make a U-turn. Similarly, the south unimpeded taxiway (taxi S1) average taxi distance is 12658 feet because the taxi route requires aircraft to turn around and take a longer taxi path that circumvents the active departing runway. The south unimpeded taxiway (taxi S1) taxi time (7.04 mins) and fuel burn (97 kg) is approximately the same as the EAT taxi time (7.08 mins) and fuel burn (101 kg).

Table 4. ATL east-flow configuration average taxi time and fuel burn.

		Taxi Time (min)		Fuel Burn (kg)		Distance (ft)	Speed (knots)	Aircraft Count
Airfield	**Taxiway**	**Mean**	**Std**	**Mean**	**Std**	**Mean**	**Mean**	**Total**
North	EAT	7.08	1.99	100.80	47.41	12709	17.8	14048
	Conventional	4.58	1.76	66.98	36.50	6702	14.5	13750
South	Unimpeded taxiS1	7.04	2.19	97.05	51.89	12658	17.8	8683
	Conventional	4.38	2.25	63.62	46.55	5195	11.7	27743

The north conventional average taxi distance is 6702 feet and the south conventional average taxi distance is 5195. Despite the average taxi distance difference of 1500 feet, the north taxi time (4.58 mins) and fuel burn (67 kg) and south conventional taxiway taxi time (4.38 mins) and fuel burn (64 kg) are about the same. The south side of the airport does not utilize the unimpeded taxiway as much as the EAT on the north side. Aircraft arriving on the south side use the conventional taxiway more during peak traffic hours, which require arriving aircraft to stop for a longer time to cross the departure runway which results in a higher taxi time.

The EAT average taxi speed (17.8 knots) is the same as the unimpeded taxiway average taxi speed (17.8 knots). Since both are continuous, non-stop taxi routes, aircraft can taxi at a higher speed. The north conventional taxiway (14.5 knots) and south conventional taxiways (11.7) have a lower average taxi speed than the EAT and unimpeded taxiway because aircraft must stop and start to cross the in-board departure runway to reach the terminal.

3.2.3 ATL Fuel Burn Summary

West-flow Configuration:

- The north conventional taxiways are used the most during off-peak hours and therefore have a lower average taxi-time (3.21 mins) and fuel burn (45 kg) compared to the EAT with a higher taxi-time (4.57mins) and fuel burn (62 kg).
- The average EAT taxi time (4.57 mins) is less than the south conventional average taxi time (4.89 mins).
- There is less variability in taxi time for the EAT (Std = 1.81 mins) and the north conventional (Std = 1.62 mins) than the south conventional taxiways (Std = 2.39 mins).
- All taxiways have high fuel burn variability due to the wide variety of aircraft types.

East-flow Configuration:

- Aircraft must make a U-turn to use the EAT in east-flow configuration.
- The south taxiway S1 is similar to the EAT because it is an unimpeded route to the terminal with has a comparable taxi time (7.04 mins) and fuel burn (97kg) to the EAT taxi time (7.08 mins) and fuel burn (101 kg).

3.3 DFW Taxi Time and Fuel Burn Estimates

3.3.1 Runway 17L South-flow Configuration

Table 5 is a summary of the average taxi time and fuel burn for the end-around and conventional taxiways when out-board arrival runway 17L is in south-flow configuration. The EAT average taxi time is 10.49 minutes and the conventional taxiway taxi time is 8.35 minutes. The EAT has a longer taxi time because the average distance to taxi along this path is 17209 feet compared to the conventional taxi route average distance is 12363 feet. One benefit of the EAT is it an unimpeded taxi route so the average speed of aircraft using the EAT is 16.2 knots while aircraft using the conventional taxiways average speed is 14.7 knots.

Table 5. DFW south-flow out-board arrival runway 17L taxi time and fuel burn.

	Taxi time (mins)		**Fuel burn (kg)**		**Distance (ft)**	**Speed (knots)**	**Aircraft Count**
Taxiway	**Mean**	**Std**	**Mean**	**Std**	**Mean**	**Mean**	**Total**
EAT	10.49	3.64	138.01	79.71	17209	16.2	4491
Conventional	8.35	2.95	110.99	67.21	12363	14.7	3704

The average fuel burn for the EAT (138 kg) is higher than the conventional taxiways (111 kg). The environmental impact of using the EAT is it burns on average 20% more fuel than the conventional taxiways. Trade-offs between the benefits of the EAT relieving ground congestion and affect on adjacent runway traffic can help assess the overall environmental impact of EAT on surface operations.

3.3.2 Runway 17C South-flow Configuration

Table 6 is a summary of the average taxi time and fuel burn for the end-around and conventional taxiways when in-board arrival runway 17C is in south-flow configuration. Arrivals from runway 17C do not use the end-around taxiway. If 17C arrivals were to use the EAT, it would require coordination with 17L arrivals since it is the primary user of the EAT. Aircraft arriving on runway 17C use only use the conventional taxiway, which takes an average of 3.79 minutes and burn an average of 50 kg of fuel. Since runway 17C is the in-board runway and much closer to the terminal, the average taxi distance is only 4717 feet compared to out-board runway 17L average conventional taxi distance is 12 636 feet. When the east airfield is in south-flow configuration, approximately 76% of arrivals land on in-board runway 17C and 24% land on out-board runway 17L. Runway 17L is used for additional arrivals during peak traffic hours. Directing runway 17L arrivals around runway 17C and runway 17R by using the end-around taxiway allows for runway 17L to operate independently and not affect adjacent runway traffic.

Table 6. DFW south-flow in-board arrival runway 17C taxi time and fuel burn.

	Taxi time (mins)		**Fuel burn (kg)**		**Distance (ft)**	**Speed (knots)**	**Aircraft Count**
Taxiway	**Mean**	**Std**	**Mean**	**Std**	**Mean**	**Mean**	**Total**
EAT	NA	NA	NA	NA	NA	NA	NA
Conventional	3.79	2.31	49.95	39.80	4717	12.3	33835

3.3.3 DFW Fuel Burn Summary

South-flow configuration:

- 24% of arrivals lands on out-board runway 17L and 76% of arrivals land on in-board runway 17C.
- Arrivals from runway 17L average EAT taxi time is 10.49 mins and average conventional taxi time is 8.35 mins.
- Aircraft arriving on runway 17C average conventional taxi time is 3.79 minutes with a taxi distance of 4717 feet.
- Aircraft arriving on out-board runway 17L average taxi distance using the EAT is 17 209 feet and the conventional taxi distance is 12 363 feet.

3.4 DTW Taxi Time and Fuel Burn Estimates

3.4.1 Runway 22R South-flow Configuration

Table 7 is a summary of the average taxi time and fuel burn of the end-around and conventional taxiways for south-flow arrival runway 22R to the South Terminal. Approximately 85% of south arrivals on runway 22R gate destination are located in the South Terminal because it has the majority of the gates with 126 gates. The EAT is used 77% of the time in this configuration and has an average taxi time of 5.95 minutes and fuel burn of 58 kg. Taxi 1 average taxi time is 5.18 minutes which is faster than the EAT, but the EAT taxi distance (15 117 feet) is twice the distance of Taxi 1 (7386 feet). The EAT is an unimpeded taxi route therefore the average speed is 25.2 knots, which allows aircraft to quickly get to the terminal even though it is a much longer distance. The EAT has a smaller variability in taxi time than the conventional taxiways because the taxi time is independent of the traffic on the departure runway.

Table 7. DTW south-flow arrival runway 22R taxi times and fuel burn to South Terminal (121 gates).

	Taxi time (mins)		Fuel burn (kg)		Distance (ft)	Speed (knots)	Aircraft Count
Taxiway	Mean	Std	Mean	Std	Mean	Mean	Total
EAT	5.95	2.28	58.04	37.17	15117	25.2	13713
Taxi 1	5.18	2.36	37.32	15.26	7386	14.1	3037
Taxi 2	6.71	2.47	42.05	42.05	11098	16.4	882

Table 8 is a summary of the average taxi time and fuel burn of the end-around and conventional taxiways for south-flow arrival runway 22R to the North Terminal. 15% of south arrivals on runway 22R gate destination are in the North Terminal because there are only 26 gates. Taxi 2 is used 96% of the time in this configuration and has an average taxi time of 6.16 minutes and fuel burn of 68 kg. Aircraft primarily use Taxi 2 if the gate destination is in the North Terminal because it is the shortest path with a taxi distance of 12940 feet.

Table 8. DTW south-flow arrival runway 22R taxi times and fuel burn to North Terminal (26 gates).

	Taxi time (mins)		**Fuel burn (kg)**		**Distance (ft)**	**Speed (knots)**	**Aircraft Count**
Taxiway	**Mean**	**Std**	**Mean**	**Std**	**Mean**	**Mean**	**Total**
EAT	10.28	3.96	95.67	63.10	36140	34.8	33
Taxi 1	6.67	1.37	75.95	35.37	14221	21.1	107
Taxi 2	6.16	1.47	67.99	32.09	12940	20.8	3074

3.4.2 Runway 4L North-flow Configuration

Table 9 is a summary of the average taxi time and fuel burn of the end-around and conventional taxiways for north-flow arrival runway 4L to the South Terminal. Approximately 83% of north arrivals on runway 4L gate destination are located in the South Terminal. The EAT is used 67% of the time in this configuration and has an average taxi time of 8.55 minutes and fuel burn of 80 kg. Taxi 1 average taxi time is 5.96 minutes and Taxi 2 is 5.57 minutes. The EAT is twice the distance of Taxi 1 and three times the distance of Taxi 2, because aircraft must make a U-turn to use the EAT. The end-around taxiway is the preferred taxi route because aircraft taxi around the in-board runway therefore the departure runway throughput is not affected by arrivals.

Table 9. DTW north-flow arrival runway 4L taxi times and fuel burn to South Terminal (121 gates).

	Taxi time (mins)		Fuel burn (kg)		Distance (ft)	Speed (knots)	Aircraft count
Taxiway	**Mean**	**Std**	**Mean**	**Std**	**Mean**	**Mean**	**Total**
EAT	8.55	3.56	80.25	54.25	20789	24.1	3052
Taxi 1	5.96	2.55	41.20	21.55	9010	15.0	338
Taxi 2	5.57	2.44	52.93	41.59	6763	12.0	1154

Table 10 is a summary of the average taxi time and fuel burn of the end-around and conventional taxiways for north-flow arrival runway 4L to the North Terminal. 17% of north arrivals on runway 4L gate destination are in the North Terminal because there are only 26 gates. Taxi 2 is used 99% of the time in this configuration and has an average taxi time of 4.69 minutes and fuel burn of 51 kg. Taxi 2 is the primary taxi route in this configuration because it is the most direct path to reach the North Terminal with a taxi distance of 8153 feet.

Table 10. DTW north-flow arrival runway 4L taxi times and fuel burn to North Terminal (26 gates).

	Taxi time (mins)		Fuel burn (kg)		Distance (ft)	Speed (knots)	Aircraft Count
Taxiway	**Mean**	**Std**	**Mean**	**Std**	**Mean**	**Mean**	**Total**
EAT	9.75	3.39	83.74	66.94	33754	34.2	4
Taxi 1	10.88	0.00	132.04	0.00	16291	14.8	1
Taxi 2	4.69	1.48	50.60	26.09	8153	17.2	922

3.4.3 DTW Fuel Burn Summary

South-flow Configuration:

- 85% of south arrivals on runway 22R gate destination are located in the South Terminal (126 gates) and 15% in the North Terminal (26 gates).
- The EAT is used 77% of the time to the South Terminal and has an average taxi time of 5.95 minutes and fuel burn of 58 kg.
- Taxi 1 average taxi time is 5.18 minutes and Taxi 2 average taxi time is 6.71 minutes to the South Terminal.
- The EAT (Std = 2.28 mins) has a smaller variability in taxi time than Taxi 1 (Std = 2.36 mins) and Taxi 2 (2.47 mins) because the taxi time is independent of the traffic on the departure runway.
- Taxi 2 is shortest and most fuel efficient path for aircraft with a gate destination in the North Terminal.

North-flow Configuration:

- 83% of north arrivals on runway 4L gate destination are located in the South Terminal.
- The EAT is used 67% of the time in this configuration and has an average taxi time of 8.55 minutes and fuel burn of 80 kg.
- Taxi 1 average taxi time is 5.96 minutes and Taxi 2 is 5.57 minutes.
- EAT taxi distance (20789 feet) is more than twice the distance of conventional taxiways, because aircraft must make a U-turn to use the EAT in north-flow configuration.
- It is not beneficial to use the EAT if the gate destination is in the North Terminal.
- Taxi 2 is shortest and most fuel efficient path for aircraft with a gate destination in the North Terminal for all configurations.

CHAPTER 4. DECISION SCENARIOS AND SIMULATIONS

4.1 Decision Method Overview

The overall objective was to develop decision rules and test whether it reduces the average aircraft fuel burn relative to current operation's average aircraft fuel burn. Figure 36 shows the flowchart for the decision method.

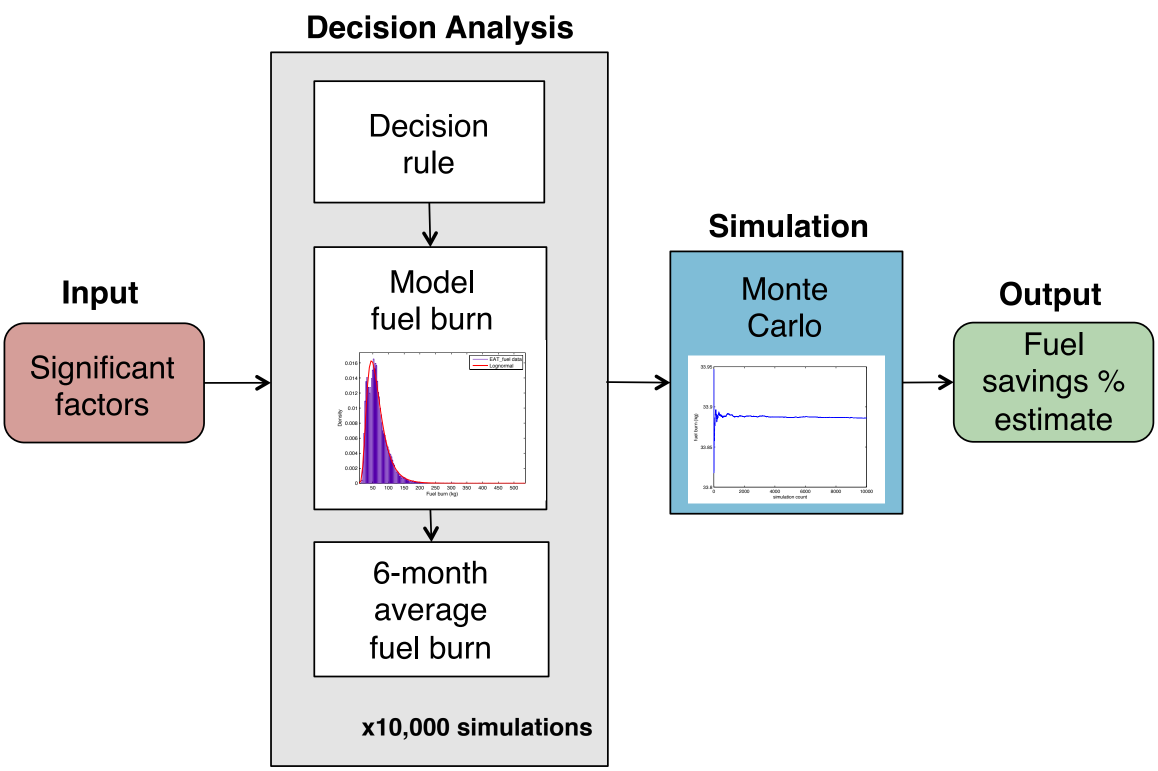


Figure 36. Flowchart of the overview of the decision method.

The decision method proceeds as follows:

Step 1 Input: Significant factors

The surface performance matrix output from Chapter 3 was used to identify significant factors contributing to the response variable, fuel burn. I used a model selection method using SAS software to determine the significant factors for each airport (see Appendix C).

Step 2: Decision Analysis

In this part of the study, several decision models were developed to maximize fuel savings. Two broad levels of tools were developed: simple rules, based on always or never using the unimpeded taxiway or based on arrival time; and a multi-factors rule based on several factors and more detailed evaluation of the data. After a decision rule is selected, a fuel burn distribution was created using fuel burn data calculated from Chapter 3. Details about modeling fuel burn distribution are discussed in section 4.3 and Appendix A.5. Then, I ran a simulation that draws a fuel burn from the distribution based on the decision rule. The average aircraft fuel burn was calculated for the 6-month period.

Step 3: Monte Carlo Simulation

A Monte Carlo simulation was conducted 10,000 times for each decision rule. The results for each airport configuration for the different decision rules are in Appendix D. The simulations were conducted in MATLAB using an Intel® Core™ i7-3770 processor with CPU @ 3.40 GHz and 8GB RAM. The 10,000 simulations took approximately between 25 minutes to 50 minutes depending on how many aircraft were in the simulation.

Step 4 Output: Fuel savings (%) estimate

Next, the average aircraft fuel burn was calculated from the 10,000 simulations. A potential fuel savings was estimated for each decision rule relative to the current average aircraft fuel burn (baseline). The output is the estimated fuel savings if the decision rule was implemented. By comparing the estimated fuel savings of the decision rules, it gives insight into which decision rule has the most potential to reduce fuel burn and emissions.

4.2 Decision Scenario

This section details the different decision scenarios for the simulations. Each decision scenario fuel burn results will be compared to the baseline case. The baseline case is the current taxi-in procedures the air traffic controllers use to direct arrivals to the unimpeded or conventional taxiways at each airport. The baseline was calculated in Chapter 3 as the average aircraft fuel burn from 10 September 2012 to 28 February 2013.

Figure 37 is the flow chart of the decision scenario method and the different decision scenarios are describes as follows:

1. The baseline was the original data where using the unimpeded taxiway was up to the discretion of the air traffic controller (current operating practice).
2. The always scenario was for all arriving aircraft to always use the unimpeded taxiway.
3. The never scenario was for aircraft to never use the unimpeded taxiway; instead have all aircraft use the conventional taxiway.
4. The arrival time scenario was based on previous observations, so the decision rule is to have all arriving aircraft during peak traffic hours use the unimpeded taxiway and have aircraft use the conventional taxiway the rest of the day (during low traffic hours).

5. The terminal scenario directed aircraft to the shortest taxi route based on the terminal gate destination.

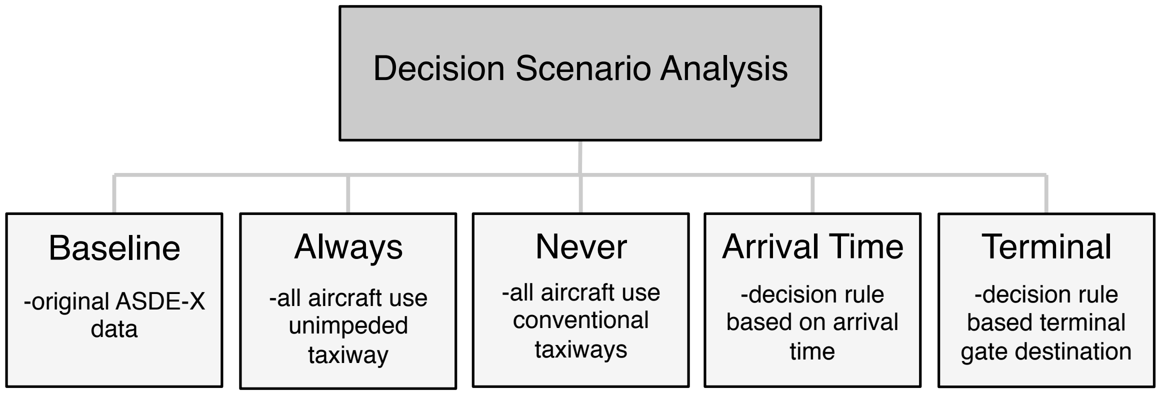


Figure 37. Decision scenario analysis flow chart.

It is important to note that always and never using the unimpeded taxiway are not realistic decision rules to implement. Always using the unimpeded taxiway would increase taxi time and fuel burn due to the long taxi distance. Never using the unimpeded taxiway would reduce adjacent runway's throughput due to increase runway crossings. I included the always and never decision rule to test the bounds of the simulation, which gave insight about the two extreme cases.

4.3 <u>Multi-factor Decision Rule</u>

Decision rules based on single factors can give us insight on how much that individual factor contributes to fuel burn. Next I developed a multi-factor decision rule based on terminal destination, aircraft type, and arrival time. A decision rule based on several factors instead of just one could potentially result in higher fuel savings. Figure 38 shows the flowchart of how the multi-factor decision rule works.

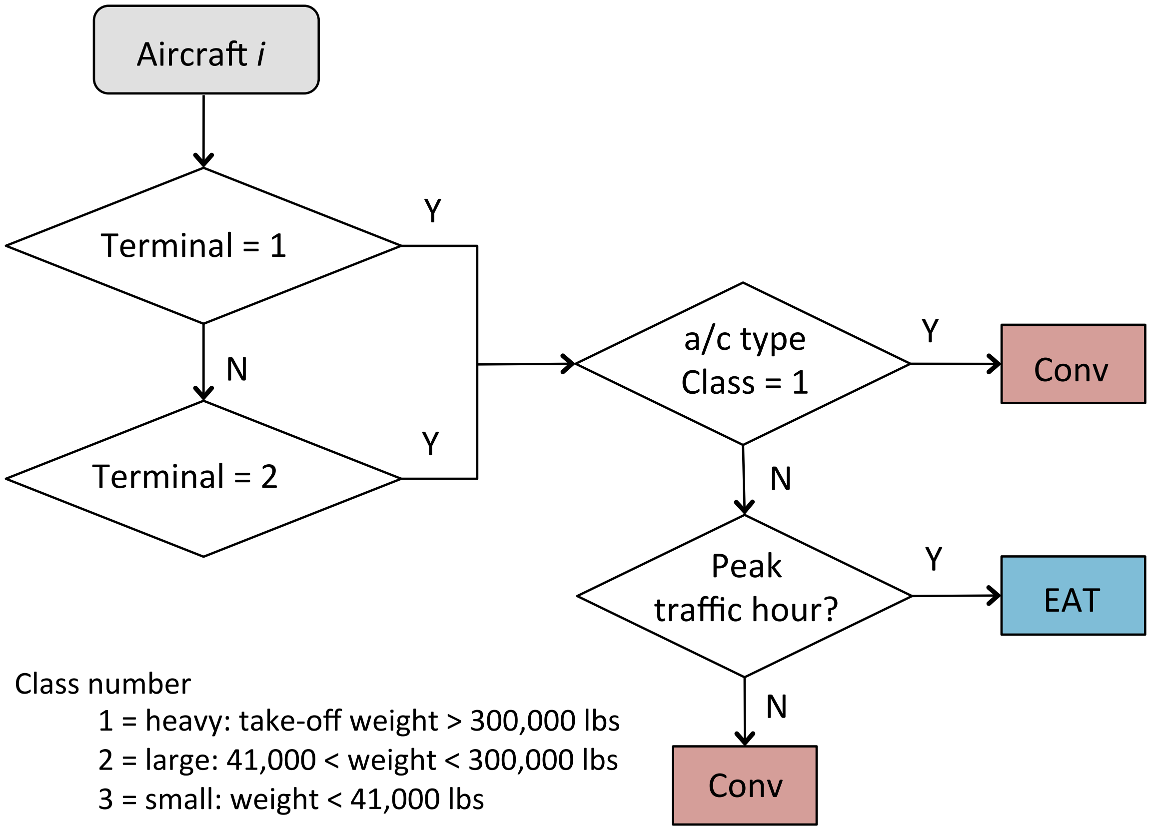


Figure 38. Flowchart of multi-factor decision rule that considers terminal, aircraft type, and arrival time as factors.

For example, let's say aircraft *i* has just arrived at Detroit Metropolitan airport. The first step is to determine which terminal it is going to. Once the terminal is determined, the fuel burn distribution is selected for that specific terminal. Next, if the aircraft is considered class 1, which is defined as heavy aircraft with a take-off weight of greater than 300,000 lbs, then it is directed to take the conventional taxiway. Heavy aircraft like the B747 have four engines, which burns more fuel so heavy aircraft have priority to use the shorter conventional taxiway. If it is not a class 1 aircraft, then the next step is to determine if the aircraft is arriving at a peak traffic hour of the day by its arrival time. If it is a peak traffic hour, then direct aircraft *i* to the unimpeded taxiway so it can taxi around the active runway and the departure rate will not be affected. Lastly, if it is not a peak traffic hour of the day then direct aircraft *i* to the conventional taxiway for a shorter and faster route to the terminal.

4.4 Modeling Fuel Burn

A probability distribution was fitted to the fuel burn data; I used the distribution to randomly generate aircraft fuel burn for each arriving aircraft. I used a standard approach based on the Kolmogorov-Smirnov test and quantile-quantile plots to determine if the distributions were a good fit to the fuel burn data for unimpeded taxiways and conventional taxiways at each airport.

Figure 39 shows an example of the procedure used to fit the appropriate fuel burn distribution for aircraft that use the EAT and conventional taxiways. A histogram was plotted for ATL west-flow arrivals on runway 26R average fuel burn for all aircraft that used the EAT between 10 September 2012 to 28 February 2013. Different distributions were fitted to the data to find the best potential fit. Figure 39 (left) shows the histogram of EAT fuel burn and the lognormal distribution (red line) distribution is the best fit with the ATL fuel burn data based on visual inspection. Figure 39 (right) shows the quantile-quantile plot (Q-Q plot) for the EAT fuel burn from the ASDE-X data versus the theoretical lognormal EAT fuel burn distribution. The lognormal distribution is a good fit because the points on the Q-Q plot lie on the line y = x except for several high fuel burn points which could be outliers. If the points lie on the line, the theoretical quantiles are in agreement with the data quantiles.

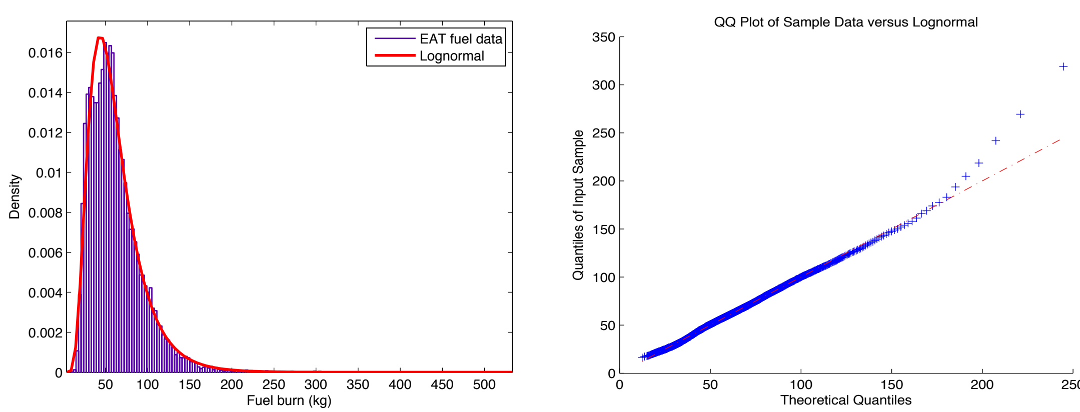


Figure 39. Left, the EAT fuel burn (blue bins) with lognormal distribution (red) for runway 26R west-flow arrivals at ATL. Right, Q-Q plot of the EAT fuel burn data versus the lognormal EAT distribution.

The lognormal distribution is appropriate because the data is skewed right because there are some aircraft with high fuel burn. The high fuel burn could be due to aircraft stopped on the airfield because the gate is not available or there is some other surface delay. The high fuel burn could also be an artifact of errors in ASDE-X data acquisition. The lognormal distribution is the best fit for west-flow arrivals on runway 26R at ATL. Table 6 is the lognormal fuel burn distribution parameter estimates. The lognormal distribution is defined by equation (3):

$$f(x|\mu,\sigma) = \frac{1}{x\sigma\sqrt{2\pi}} e^{\frac{-(lnx-\mu)^2}{2\sigma^2}}$$

$$\mu = \log\left(\frac{m^2}{\sqrt{v+m^2}}\right) \tag{3}$$

$$\sigma = \sqrt{\log\left(v/m^2+1\right)}$$

where m is the mean fuel burn and v is the standard deviation of the fuel burn data.

Table 11: Lognormal fuel burn distribution parameters for ATL west-flow runway 26R.

Lognormal Parameters	***Log mean μ***	***Log variance σ***
EAT	4.01	0.48
Conventional Taxiway	3.63	0.59

The same procedure was done to find the best-fit distribution for the fuel burn data at other airports and configurations. The fitted distributions and parameter estimates for the decision scenario models are in Appendix D (D.1 ATL, D.2 DFW, and D.3 DTW).

4.5 Monte Carlo Simulation

A Monte Carlo Simulation was done for each decision rule at every airport to estimate the average fuel burn with higher accuracy than just one simulation. Figure 40 is a plot of 10,000 Monte Carlo arrival time decision rule simulations of the average aircraft fuel burn for west-flow arrivals on runway 26R at ATL. The average fuel burn starts to stabilize around 5,000 simulations. The variability in fuel burn between simulation runs in this scenario is approximately 0.0019 kg of fuel.

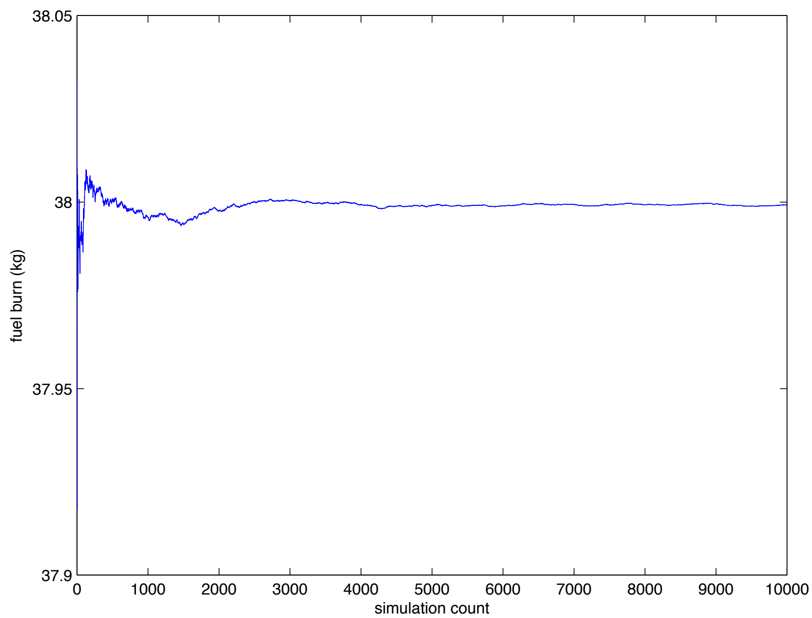


Figure 40. Plot of 10,000 Monte Carlo simulations for arrival time decision rule average aircraft fuel burn for west-flow arrivals on runway 26R at ATL.

Similar Monte Carlo simulation analysis was done for every decision rule at each airport for the different runway configurations. Appendix E presents the rest of the Monte Carlo simulations for the other runway configurations for ATL as well as DFW and DTW.

4.6 ATL Decision Simulations

At ATL, the EAT is located in the northwest quadrant of the airfield. Runway 8L/26R in east and west-flow configuration use the EAT; therefore the decision scenario analysis was done for these two configurations. The decision rules were also analyzed for south runway 9R in east-flow configuration because it uses Taxiway 1 as an unimpeded taxiway similar to the EAT.

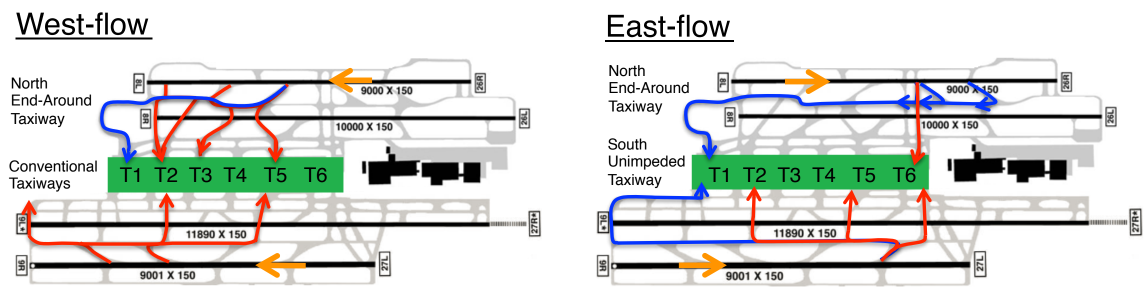


Figure 41. ATL taxi route map for west and east-flow configurations.

Table 12 is the ATL average fuel burn savings estimates relative to the baseline for the five decision rule scenarios. The percentages are based on an average fuel burn savings taken for 10,000 simulations.

Table 12. ATL average fuel burn saving estimates from decision rule simulations.

Average fuel burn per aircraft relative to baseline (%)					
Decision Rules	**Always**	**Never**	**Arrival Time**	**Terminal**	**Multi-factor**
West-flow Runway 26R north airfield	10.3%↑	-17.8% ↓	-7.8% ↓	-3.6% ↓	-8.1% ↓
East-flow Runway 8L north airfield	19.7% ↑	-18.1% ↓	-9.2% ↓	-8.7% ↓	-11.7% ↓
East-flow Runway 9R south airfield	32.4% ↑	-15.7% ↓	-8.6% ↓	-4.7% ↓	-15.5% ↓

As expected, always using the EAT increased the fuel burn significantly in all cases. Never using the EAT (or unimpeded taxiway for 9R) decreased the fuel burn the most in all cases. Arrival time is an important factor to consider when choosing a taxi route. In this rule, arriving aircraft used the EAT (or unimpeded taxiway for 9R) during peak hours as follows:

- 26R (west-flow): 10am to 1pm and 6pm to 8pm
- 8L (east-flow): 10am to 1pm and 6pm to 8pm
- 9R (east-flow): 9am to 10am and 6pm to 8pm

This rule decreased fuel burn on runways 26R, 8L, and 9R by 7.8%, 9.2%, and 8.6%, respectively. Runway 8L and 9R has the lowest taxi-in fuel burn when the unimpeded taxiway is avoided because aircraft essentially make a U-turn which results in about twice the distance to reach the gate. These results are expected because unimpeded routes are faster and burn less fuel per feet than using the conventional taxiway that must stop to cross adjacent runways during high traffic times.

The *terminal* decision rule yields an average fuel savings for runway 26R, 8L, and 9R of 3.6%, 8.7%, and 4.7%, respectively. The terminal ramp locations at ATL are spread out enough that different taxiways have a significant difference in taxi distance. The EAT is a convenient path to take when arrivals' gate destinations are in terminal ramp 1. In contrast, it would be the least beneficial to take the EAT if the gate destination is in terminal ramp 6. In this case, the conventional taxiway is the best taxiway to take to reach terminal ramp 6 especially in east-flow configuration, which is reflected in the higher fuel savings than west-flow.

The *multi-factor* decision rule has the largest fuel savings compared to the *arrival time* and *terminal* decision rule. The average fuel savings for runway 26R, 8L, and 9R are 8.1%, 11.7%, and 15.5%, respectively. This is the best decision rule because it incorporates arrival time, terminal destination, and aircraft type to bring the most fuel savings.

Although the *never* decision rule yields the most fuel burn reduction, the departure rate on the adjacent runways would have to decrease to accommodate arrival runway crossings. Using the *never* decision rule, airport throughput suffers and the runway departure rate cannot be met without increasing surface congestion, fuel burn, emissions, and wait time for arrivals and therefore is infeasible.

4.7 DFW Decision Simulation

The EAT at DFW is located in the southeast quadrant of the airfield. The decision rules were analyzed for runway 17L in south-flow configuration because it is the primary user of the EAT. The objective was to develop a decision rule to reduce fuel burn by assigning arriving aircraft to either the EAT or conventional taxiways. Figure 42 is a diagram of the taxi routes for aircraft arriving on south-flow runway 17L at DFW.

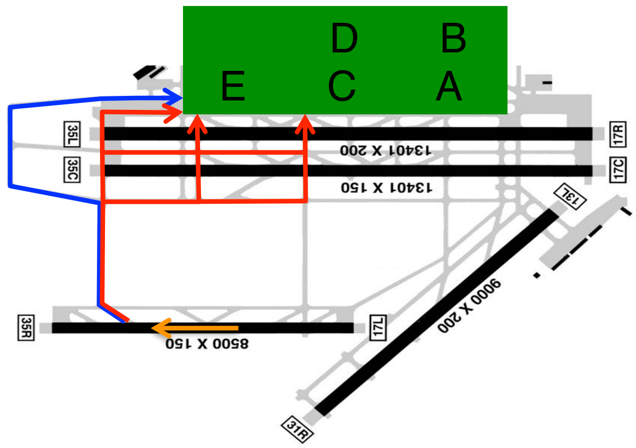


Figure 42. DFW taxi routes for south-flow runway 17L arrivals.

Table 13 is the DFW average fuel burn savings estimates relative to the baseline for the five decision rule scenarios. The percentages are based on an average fuel burn savings taken for 10,000 simulations.

Table 13. DFW average fuel burn estimates from decision rule simulations.

Average fuel burn per aircraft relative to baseline (%)					
Decision Rules	**Always**	**Never**	**Arrival Time**	**Terminal**	**Multi-factor**
South-flow Ruwnay 17L	21.7%↑	-11.4% ↓	-6.2% ↓	7.3% ↑	-20.4% ↓

As with ATL, always using the EAT increased the fuel burn, in this case by 21.7% compared to the baseline. Never using the EAT decreased the fuel burn by 11.4% compared to the baseline, but has a negative impact on the adjacent departing runway traffic. The separation time between arrivals on in-board runway 17C and departures on runway 17R would have to increase to accommodate runway crossings from arrivals on 17L. If the never scenario was used arrival aircraft would have to take the conventional taxiway, which requires waiting for a gap in both arrivals and departures before air traffic control could instruct them to cross the two active runways.

At DFW taxi fuel burn is significantly affected by traffic levels since runway 17L is used for overflow arrivals during peak traffic hours. These aircraft then use the EAT to go around primary arrival runway 17C, as discussed in Chapter 2. In the arrival time decision rule, arriving aircraft in south-flow configuration use the EAT during the peak hours as follows:

- 17L (south-flow): 9am to 11am

This rule decreased the average fuel burn by 6.2%. The terminal decision rule directs aircraft with a gate in terminal E to use the EAT since it is the closest to the EAT and have all other aircraft use the conventional taxiways. In the case of DFW, there was an increase in fuel burn of 7.3%. Even though the EAT is closest to terminal E, the EAT taxi distance is significantly longer than the conventional taxiways. Having more aircraft use the EAT resulted in an increase in fuel burn. The *multi-factor* decision rule yields the largest fuel savings of 20.4%. Adding aircraft type to the decision model has a larger fuel savings possibly due to the longer EAT distance. The EAT at DFW should only be used if necessary because of its long taxi distance. Overall, the best scenario is when the multi-factor decision rule was used because it incorporates arrival time, terminal destination, and aircraft type to bring the most fuel savings.

4.8 DTW Decision Simulation

The EAT at DTW is located on the southeast quadrant of the airfield. The decision scenario analysis was done for aircraft arriving on runway 4L/22R use the EAT in north and south-flow configuration. Since there are two distinct terminals, the North and South Terminal, we also looked at a decision rule based on terminal location. Figure 43 shows the DTW taxi route map for south and north-flow configurations.

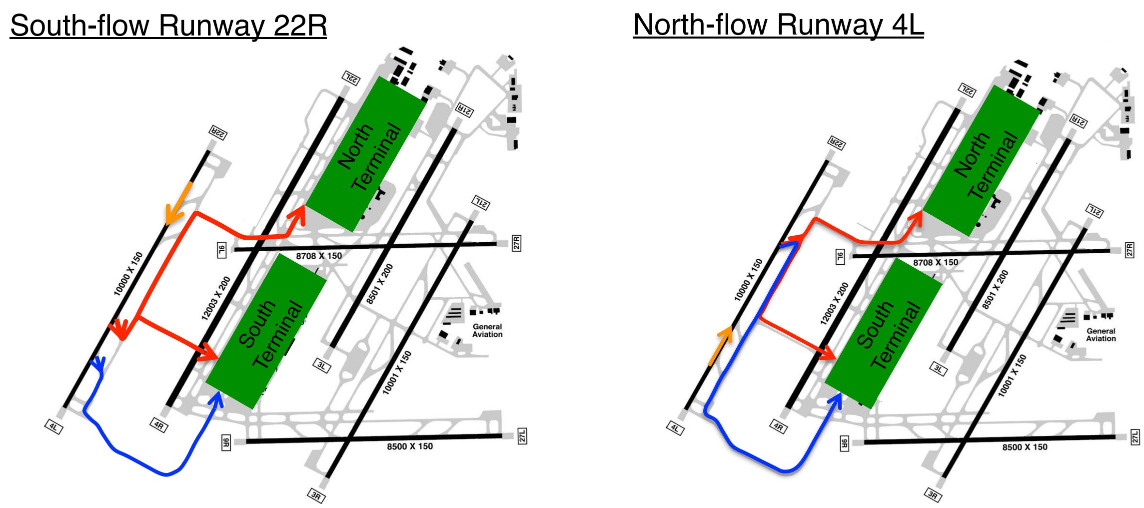


Figure 43. DTW taxi routes for north and south-flow configuration.

Table 14 is the DTW average fuel burn savings estimates relative to the baseline for the five decision rule scenarios. The percentages are based on an average fuel burn savings taken for 10,000 simulations.

Table 14. DTW average fuel burn estimates from decision rule simulations.

Average fuel burn per aircraft relative to baseline (%)					
Decision Rules	**Always**	**Never**	**Arrival Time**	**Terminal**	**Multi-factor**
South-flow Runway 22R	-0.1%↑	-2.5% ↓	-2.0% ↓	-2.5% ↓	-9.3% ↓
North-flow Runway 4L	16.5% ↑	-25.1% ↓	-17.0% ↓	-8.0% ↓	-19.6% ↓

In contrast to ATL and DFW, at DTW always using the EAT for aircraft arriving on 22R reduced the fuel burn by 0.1% compared to the baseline. Always using the EAT decreases the average fuel burn because it redirects aircraft from Taxi 2 to a slight shorter EAT route to reach the South Terminal. Like ATL and DFW, always using the EAT for aircraft arriving on 4L increased the fuel burn, in this case by 16.5%.

Like ATL and DFW, never using the EAT decreased the fuel burn, in the case of runway 4L by a large amount (25.1%). This large decrease may be due in part to the current practice of having the majority of arriving aircraft from 7 am to 10 pm use the EAT. However, as with ATL and DFW, never using the EAT negatively affects the departure rate and would likely increase total surface fuel burn because departing aircraft would have to wait for arriving aircraft to cross, and vice versa.

The *arrival time* decision rule for DTW assigned aircraft to the EAT during peak hours as follows:

- 22R (south-flow): 10 - 11am, 3 - 4pm, and 8 - 9pm
- 4L (north-flow): 10 - 11am, 3 - 4pm, and 8 - 9pm

This rule decreased fuel burn on runways 22R and 4L by 2.0% and 17.0% respectively. As noted above, the EAT is currently the primary taxi route for aircraft arriving on runway 4L between 7am and 10pm in north-flow configuration, thus large savings compared to the baseline are possible by limiting EAT use. In north-flow configuration, the EAT is twice the distance to the south terminal and three times the distance to the north terminal, so using the conventional taxiway saves more fuel in this case.

The *terminal* decision rule directs arrivals to the shortest taxi route based on their terminal gate destination. The terminal is an important factor because the taxi distance greatly varies between the North and South terminal (see Figure 43). In this rule, arriving aircraft use the EAT, Taxi 1, and Taxi 2 to the North or South terminal as follows:

- South-flow 22R: North Terminal use Taxi 2, South Terminal 30% use Taxi 1 and 70% use EAT

- North-flow 4L: North Terminal use Taxi 2, South Terminal 10% use Taxi 1, 20% use Taxi 2, and 70% use EAT

This rule decreased fuel burn on runways 22R and 4L by 2.5% and 8.0% respectively. This proposal is similar to what air traffic controllers are doing today and therefore would be fairly transparent to the operation. The primary difference is to have all aircraft with a gate destination in the North Terminal use Taxi 2 because it is the shortest route and saves fuel. The *multi-factor* decision rule has the largest fuel savings compared to the *arrival time* and *terminal* decision rule. The average fuel savings for south-flow runway 22R is 9.3% and north-flow runway 4L is 19.6%. Again, the large fuel savings for the north-flow is due to the longer EAT taxi distance, so limited EAT use can bring substantial fuel reduction. This is the best decision rule because it incorporates arrival time, terminal destination, and aircraft type to bring the most fuel savings.

CHAPTER 5. CONCLUSION AND FUTURE WORK

5.1 Conclusion

Unimpeded taxiways provide a path for arrivals to taxi independently of adjacent runway traffic. Use of unimpeded taxiways reduces surface congestion caused by aircraft waiting to cross active runways. ASDE-X data can be used to study the current traffic patterns at airports and determine which conditions yield the most environmental benefits by directing arrival aircraft to either the unimpeded taxiway or conventional taxiway. The trends and patterns of aircraft taxi routes showed that unimpeded taxiways are used the most during peak arrival and peak departure hours at all three airports. The unimpeded taxiways provide benefits such as increased departure throughput, increased safety, reduced surface congestion, increased efficient taxi-in procedures, and can yield environmental benefits in terms of reduced emissions.

The decision scenario analysis concluded the most promising decision rule at ATL, DFW, and DTW to yield the most fuel savings is based on multi-factor decision rules, which account for terminal destination, aircraft type, and arrival time. Although never using the unimpeded taxiway and only using conventional taxiways reduced fuel burn more in some cases, the airport departure rate and throughput would suffer, possibly leading to increased congestion and hence increased fuel burn and emissions. Never using unimpeded taxiways also removes the safety benefit that was originally the reason for their creation.

Monte Carlo simulation was used to run 10,000 simulations to estimate the fuel savings for each decision scenario. At ATL, the multi-factor decision rule can potentially yield an average fuel burn reduction per aircraft of 8.1% for runway 26R west-flow, 11.7% for runway 8L east-flow, and 15.5% for runway 9R east-flow. DFW airport currently uses the EAT primarily for south-flow arrivals on runway 17L. The average fuel burn per aircraft could potentially be reduced by 20.4% based on the multi-factor decision rule. DTW can use the multi-factor decision rule to potentially reduce the average fuel burn per aircraft by 9.3% for runway 22R south-flow and 19.6% for runway 4L north-flow. Other simple rules base solely on arrival time or terminal gate location also resulted in fuel burn savings ranging from 2.0% to 17.0%.

Overall, the multi-factor decision rule based on terminal destination, aircraft type, and arrival time results in a potential average aircraft fuel reduction from 8.1% to 20.4%.

5.2 Future Work

The current work has developed a methodology to assess opportunities to improve unimpeded taxiways usage for environmental benefits and taxi operation efficiency. Several directions of study to gain more insight and further develop improvements to unimpeded taxiway operations are described next.

5.3 Extend Study at Airports

Extending this methodology to other congested airports would give valuable insight to the potential system wide impact of unimpeded taxiways as a near-term operational change to reduce fuel burn. Since ASDE-X data system is available at 35 major airports across the United States, it would be easy to extend taxi operation improvement analysis within this network of airports. The infrastructure and aircraft surface detection system is already in place making implementation a feasible, near-term operational change.

5.4 Analyze Air Traffic Control Commands

Another valuable input would be to analyze recording of air traffic controller commands and evaluate the workload for ATC for current operations and compare it to when the decision model is applied. Since using unimpeded taxiways eliminates runway crossings, it can potentially reduce the workload of ATC to coordinate with arrivals and departures during a runway crossing. The human factors perspective of using unimpeded taxiways has yet to be explored.

5.5 Implementation Strategies

A field study implementing the decision model to route arrivals would provide valuable information about ease of use from an air traffic controller perspective and evaluate the impact on surface operations. Possible strategies for field-testing could be to use color-coded cards or interactive Android App on a tablet to suggest ATC to direct aircraft to the unimpeded taxiway or conventional taxiway similar to the n-control pushback rate field test done at BOS [Hansman et al., 2013].

Another important strategy to implement decision rules to maximize fuel savings of unimpeded taxiway operations is to do a cost benefit analysis for various stakeholders. A preliminary evaluation of stakeholders can be seen in Appendix F. A cost benefit analysis is an evaluation of the cost effectiveness of an operation, procedure, or program in order to see whether the benefits outweigh the costs. Trade-off studies will be an important step in the implementation strategy process to analyze in further detail the costs and benefits and find an optimal solution for stakeholders. For example, a trade-off study can be conducted to estimate the profit of a higher runway throughput for the airports versus the fuel cost for airlines. A cost benefit analysis early in the implementation strategies process will save money and conflicts that will arise later. It is important to identify and mitigate uncertainties and risks as part of the analysis. New taxi-in procedures regarding the EAT are more likely to be implemented if all stakeholders benefit and share in the costs.

LIST OF REFERENCES

LIST OF REFERENCES

Airport Council International (ACI) Air Traffic Reports (2013). Assessed 10 April 2013. <http://www.aci-na.org/content/airport-traffic-reports>.

City of Chicago, (2014), “O’Hare Modernization Program,” Accessed 17 March 2014. <http://www.cityofchicago.org/omp>.

DFW International Airport board, (1997), “Airport Development Plan”, 1997. Accessed 15 April 2013. <www.dfwairport.com/development/masterplan/index.php>.

DTW, (2008), “Breaking New Ground 2008 Report to Key Stakeholders,” September 2008.

Engelland, S.A. and Ruszkowski, L.M., (2010), “Analysis of DFW Perimeter Taxiway Operation,”10th AIAA Aviation Technology, Integration and Operations Conference 2010, ATIO 2010, 2010, Vol.2

FAA, AOSC, (2004), “Airport Obstructions Standards Committee AOSC Decision Document #03 Atlanta Runway 8R/26L End-Around Taxiway”, 12 July 2004.

FAA, AOSC, (2005), “Airport Obstructions Standards Committee (AOSC) Decision Document #06 Dallas/Fort Worth (DFW) End-Around Taxiway”, 8 June 2005.

FAA, AOSC (2006), “Airport Obstructions Standards Committee (AOSC) National Departure Case Standard for End-Around Taxiways”, 21 September 2006.

Hansman et. al, (2013), “A Decision Support Tool for the Pushback Rate Control of Airport Departures,” IEEE SMC 2013.

Hoover, F., (2007), “End-Around Taxiways,” The MITRE Corporation Center for Advance Aviation System Development (CAASD), McLean, VA, 2007.

IATA, (2014) “Operational Fuel Efficiency,” International Air Transport Association, Accessed 12 January 2014. , <http://www.iata.org/whatwedo/ops-infra/Pages/fuel-efficiency.aspx>.

International Civil Aviation Organization (ICAO), (2013), “Engine Emissions Databank,” Assessed 08 January 2013. <http://www.caa.co.uk/default.aspx?catid=702>.

Khadilkar H, Balakrishnan H., (2011), “Estimation of Aircraft Taxi-out Fuel Burn Using Flight Data Recorder Archives,” Proceedings of the AIAA Guidance, Navigation, and Control Conference 2011.

FAA, (2014), “ASPM Analysis: Definition of Variables,” Accessed 18 February 2014. <http://aspmhelp.faa.gov/index.php/APM:_Analysis:_Definitions_of_Variables>.

Marais, K., Ryenolds, T. G., Muller, D., Lovegren, J., Uday, P., Hansman, J., (2010) “Evaluation of Potential Near-term Operational Changes to Mitigate Environmental Impacts of Aviation,” 27th International Congress of the Aeronautical Sciences (ICAS), Nice, France, 2010.

Markwell, K. (2012), “Fuel Savings Initiatives O’Hare Modernization Benefits/Ground,” IATA Fuel Efficiency and Environmental Campaign October 3 – 4, 2012.

Massidda, A. and Mattingly, S.P, (2013), "Empirical Assessment of the End-Around Taxiway's Operational Benefits at Dallas/Fort Worth International Airport Using ASDE-X Data," 92nd Transportation Research Board, 13-17 January 2013.

Morris, K., (2005), "Results from a Number of Surveys of Power Settings used during Taxi Operations," EJT/KMM/1126/14.8, British Airways, London.

Nikoleris, T., Gupta, G., Kistler, M., (2011), "Detailed estimation of fuel consumption and emissions during aircraft taxi operations at Dallas/Fort Worth International Airport," Transportation Research Part D, 2011, Vol.16(4), pp.302-308.

Patterson, J. (2007). "End-Around Taxiway Screen Evaluation," National Technical Information Services (NTIS), U.S Department of Transportation, Springfield, VA, March 2007.

SAAB (2014). Airport Surface Detection Equipment Model-X in operation at 35 busiest U.S. cities. Accessed 18 February 2014. <http://www.saabsensis.com/products/airport-surface-detection-equipment-model-x-asde-x/>.

Satyamurti, S.D., Mattingly, S.P. (2007). "Implementing a Perimeter Taxiway at Dallas/Fort Worth International Airport: Evaluation of Operating Policy Impacts," Aviation: A World of Growth - Proceedings of the 29th International Air Transport Conference, IATC 2007, 2007, pp.23-36.

Snedeker, A., (2011), "Airport Moving Forward on Expansion Projects," Hartsfield-Jackson Atlanta International Airport Newsroom 06 June 2011, Assessed 9 December 2012.

Uday P. et al., (2011), “Environmental Benefits of End-Around Taxiway Operations”, 11th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, Virginia Beach, VA, 20-22 September 2011.

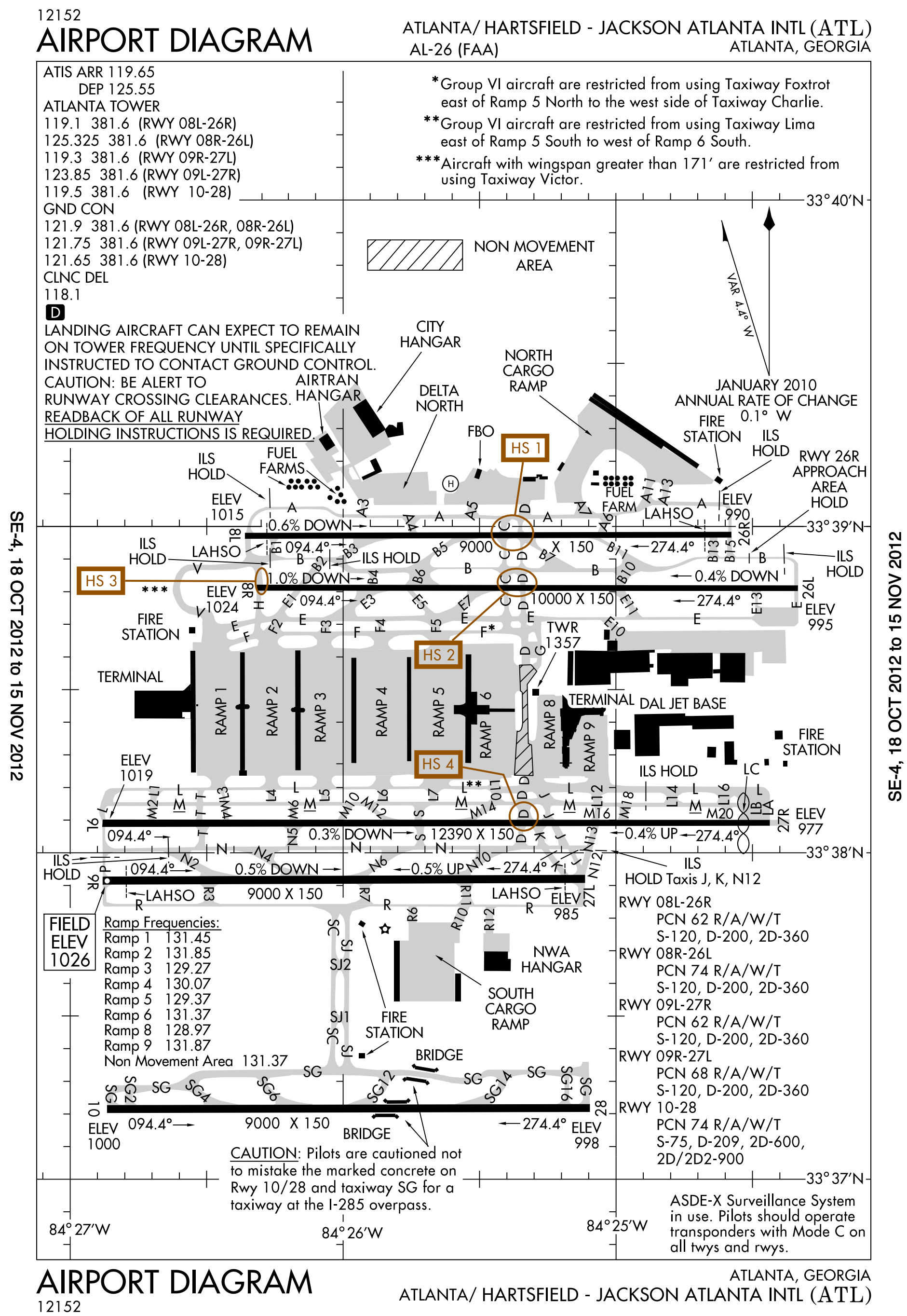
U.S. Department of Transportation (DOT), (2010), “Review of FAA’s Call to Action Plan for Runway Safety,” Report Number: AV-2010-071. Date issued: July 21, 2010.

Wood, E., Herndon, S., et al., (2008), “Aircraft and Airport-Related Hazardous Air Pollutants: Research Needs and Analysis,” Transportation Research Board 87th Annual Meeting, Washington, DC.

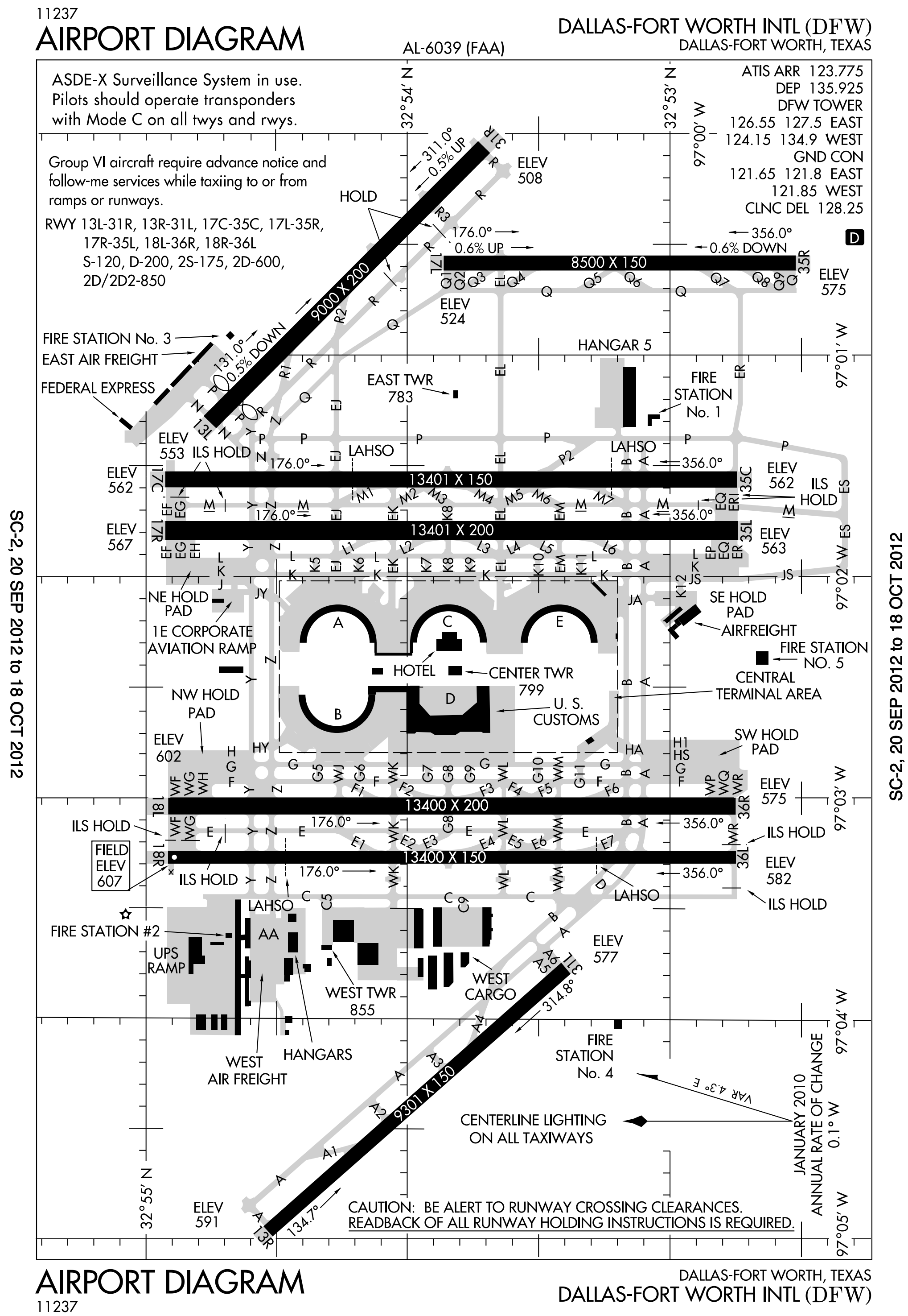
APPENDICES

Appendix A Airport Diagrams

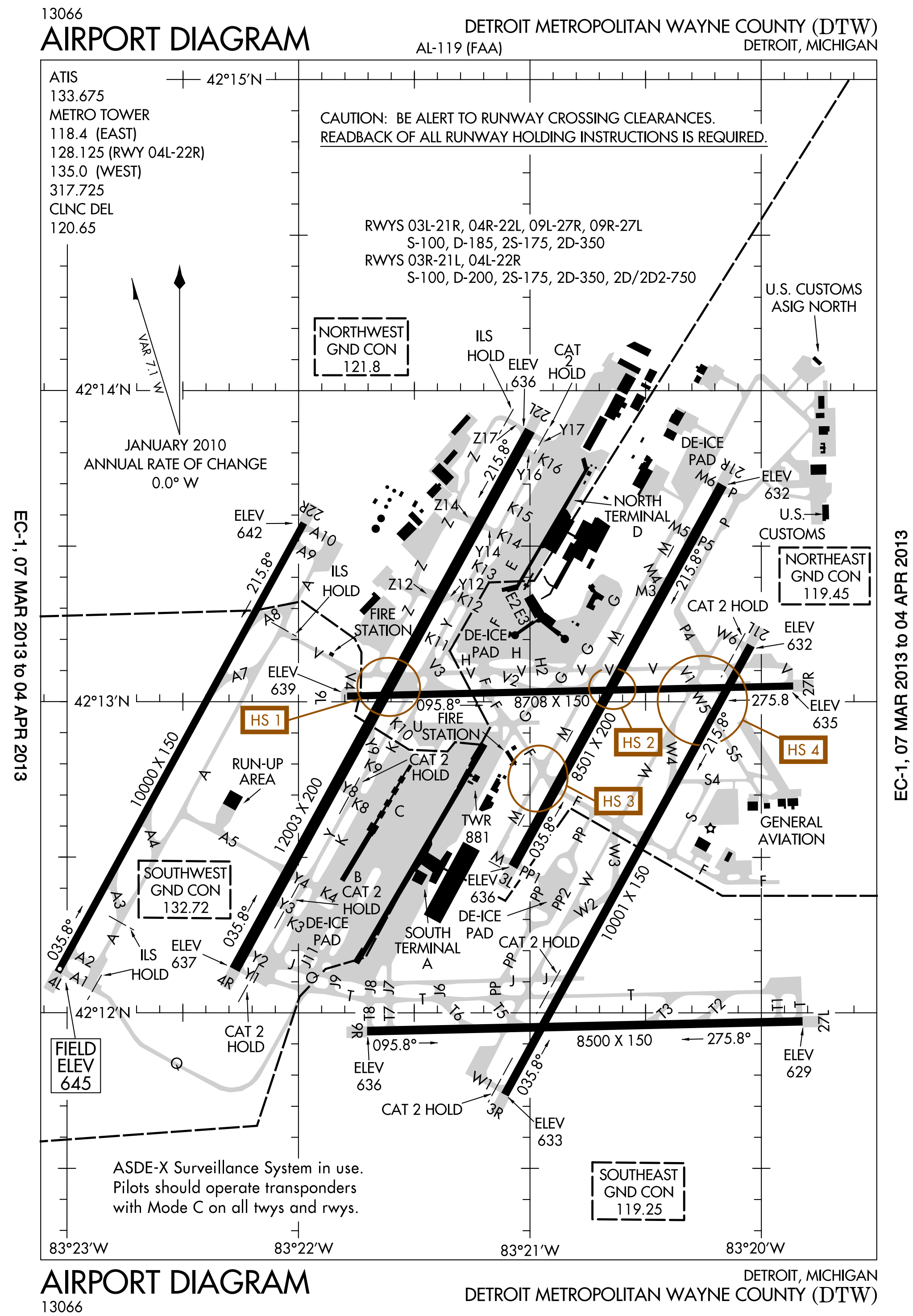
A. 1. Atlanta/ Hartsfield-Jackson International airport diagram (ATL).



A. 2. Dallas-Fort Worth International airport diagram (DFW).



A. 3. Detroit Metropolitan Wayne County airport diagram (DTW).



Appendix B Surface Performance Matrix Analysis

B. 1. ICAO Engine Emissions Databank

aircraft type	engine	number of engine	fuel flow rate *engine	fuel flow rate (kg/s)	CO (g/kg)	Nox (g/kg)	a/c class
A300	CF6-50C2	2	0.326	0.163	24.04	3.4	1
A306	CF6-50C	2	0.326	0.163	24.04	3.4	1
A310	CF6-50-C2	2	0.326	0.163	24.04	3.4	1
A319	CFM56-5-A1	2	0.2022	0.1011	17.6	4.0	2
A320	CFM56-5-A1	2	0.2022	0.1011	17.6	4.0	2
A321	CFM56-5B3/P	2	0.23	0.115	19.20	4.70	2
A330	CF6-80E1A4	2	0.454	0.227	38.09	4.62	1
A332	CF6-80E1A4	2	0.454	0.227	38.09	4.62	1
A333	CF6-80E1A2	2	0.456	0.228	42.67	4.53	1
A343	CFM56-5C2	4	0.47	0.1175	34.0	4.19	1
B712	BR715A1-30	4	0.384	0.096	16.27	5.37	2
B717	BR715A1-30	2	0.2	0.100	19.72	3.95	2
B722	JT8D-217C	3	0.411	0.137	17.89	4.05	2
B733	CFM56-3B1	2	0.228	0.114	34.4	3.9	2
B734	CFM56-3B1	2	0.228	0.114	34.4	3.9	2
B735	CFM56-3B1	2	0.228	0.114	34.4	3.9	2
B737	CFM56-7B22	2	0.21	0.105	22.80	4.50	2
B738	CFM56-7B24	2	0.218	0.109	22.00	4.40	2
B739	CFM56-7B26	2	0.226	0.113	18.80	4.70	2
B744	PW4056	4	0.752	0.188	11.60	5.0	1
B752	PW2037	2	0.304	0.152	22.36	4.1	2
B753	RB211-535E4-B	2	0.38	0.19	18.24	4.58	2
B757	RB211-535E4	2	0.36	0.18	20.33	4.4	2
B762	CF6-80A	2	0.3	0.150	28.2	3.4	1
B763	CF6-80A2	2	0.3	0.150	28.2	3.4	1
B764	CF6-80C2B8F	2	0.41	0.205	16.69	4.59	1
B767	PW-4060	2	0.426	0.213	20.32	4.9	1
B772	PW4077	2	0.464	0.232	20.2	4.2	1
B77L	PW4077	2	0.464	0.232	20.2	4.2	1
B77W	PW4090	2	0.676	0.338	11.94	4.48	1
BE40	JT15D-5	2	0.0592	0.0296	119.2	1.66	3
C550	JT15D-4	2	0.1122	0.0561	97	2.63	3
C560	JT15D-5A	2	0.0592	0.0296	119.2	1.66	3
C680	PW306C	2	0.0844	0.0422	36.35	4.26	3
C750	AE-3007C	2	0.0754	0.0377	35.07	3.2	3
CL60	CF34-3A1	2	0.0992	0.0496	42.6	3.82	2
CRJ1	CF34-3A1	2	0.0992	0.0496	42.6	3.82	2
CRJ2	CF34-3B1	2	0.0978	0.0489	47.59	3.72	2
CRJ7	CF34-8C5	2	0.128	0.064	18.25	4.6	2
CRJ9	CF34-8C5	2	0.128	0.064	18.25	4.6	2
D328	PW306B	2	0.0844	0.0422	36.35	4.26	3
DC10	CF6-50C	3	0.489	0.163	24.04	3.4	1
DC87	CFM56-2C1	4	0.512	0.128	30.7	4.0	1
DC95	JT9D-17	2	0.294	0.147	31.00	3.3	2
E135	AE3007A3	2	0.0896	0.0448	41.29	4.12	2
E145	AE3007A1	2	0.0922	0.0461	39.91	4.17	2
E170	CF34-8E	2	0.128	0.064	18.16	4.61	2
E190	CF34-10E	2	0.174	0.087	44.53	3.67	2
E45X	AE 3007A1E	2	0.095	0.0475	37.97	4.26	2
FA7X	PW307A	3	0.135	0.045	39.6	2.39	2
F900	TFE731-5AR-1C	3	0.078	0.026	47.7	3.72	2
G150	TFE731-40AR	3	0.078	0.026	47.7	3.72	3
GLF4	TAY-MK.-611-8	2	0.22	0.11	24.1	2.5	2
GALX	PW306A-5	2	0.0844	0.0422	36.35	4.26	3
H25B	TFE731-3	2	0.052	0.026	47.7	3.72	3
LR31	TFE731-2-2B	2	0.052	0.026	47.7	3.72	3
LJ31	TFE731-2-2B	2	0.052	0.026	47.7	3.72	3
LR35	TFE731-2-2B	2	0.052	0.026	47.7	3.72	3
LJ35	TFE731-2-2B	2	0.052	0.026	47.7	3.72	3
LR60	PW305A	2	0.0844	0.0422	36.35	4.26	3
LJ60	PW305A	2	0.0844	0.0422	36.35	4.26	3
MD11	CF6-80C2D1F	3	0.588	0.196	41.78	3.80	1
MD82	JT8D-219	2	0.2688	0.1344	12.63	3.6	2
MD83	JT8D-219	2	0.2688	0.1344	12.63	3.6	2
MD88	JT8D-219	2	0.2688	0.1344	12.63	3.6	2
MD90	V2525-D5	2	0.256	0.128	12.43	4.7	2

B. 2. Surface Performance Matrix

Table 15. Example of systematic analysis of taxi time, fuel burn, and other factors per aircraft.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Taxi time (sec)	**Avg speed (knots)**	**Fuel burn (kg) all engine**	**Fuel burn (kg) single engine**	**Nox (kg) all engine**	**Nox (kg) single engine**	**CO (kg) all engine**	**CO (kg) single engine**	**Num of eng**	**Taxi dist (feet)**	**Track num**	**Class num (1,2,3)**	**A/C type**	**Arrival time (sec)**	**Term Ramp 1-6**	**Taxi route 1-8**	**West/ East (1/2)**	**date**
468	6	103.19	50.81	3.84	1.92	20.93	10.46	2	12564	478	2	21	46468	3	1	2	910
303	15	67.36	32.90	2.48	1.24	13.55	6.78	2	10746	486	2	21	60163	1	1	2	910
384	9	84.95	41.69	3.15	1.57	17.17	8.59	2	12172	509	2	21	77969	2	1	2	910
264	8	40.68	19.80	2.38	1.19	12.04	6.02	2	7169	515	2	36	277	3	5	1	910
321	12	47.40	23.18	2.57	1.28	11.30	5.65	2	9315	522	2	38	636	5	1	1	910
316	10	62.05	30.34	2.28	1.14	7.98	3.99	2	10678	542	2	27	79802	1	1	2	910
201	17	56.51	27.28	1.84	0.92	7.33	3.67	2	6206	610	2	16	36672	2	1	1	910
387	13	85.60	42.02	3.17	1.59	17.31	8.65	2	12984	612	2	21	59528	3	7	2	910
337	10	66.09	32.35	2.43	1.21	8.51	4.26	2	11795	639	2	27	79665	2	7	2	910
273	18	60.04	29.25	1.86	0.93	15.40	7.70	2	6199	2218	1	23	3440	2	1	1	910
490	13	136.37	67.20	10.53	2.63	31.89	7.97	4	14690	2223	2	15	52641	4	7	2	910

- Class number
  - 1 = heavy: take-off weight > 300,000 lbs
  - 2 = large: 41,000 < weight < 300,000 lbs
  - 3 = small: weight < 41,000 lbs
- Terminal Ramp
  - ATL has 6 ramp areas between concourses
- Taxi Route
  - EAT corresponds to Taxi route 1
  - Taxi 1-7 corresponds to Taxi route 2 - 8
- Month day
  - September 10, 2012 is identified as 910

Appendix C Statistical Analysis to Identify Significant Factors

To determine significant factors, I used Statistical Analysis System (SAS) program to run a model selection to choose the best model for the response variabile, fuel burn. I usedd the subset model to identify the significant parameters and select the minimum number of parameters for the fuel burn model. Table C.1 is the top three models for ATL runway 26R/8L using the subset model selection method with the C_p criterion.

C.1 Top three models from $C(p)$ Selection Method for ATL runway 26R/8L.

The SAS System

The REG Procedure
Model: MODEL1
Dependent Variable: fuel_all

C(p) Selection Method

Number of Observations Read	66927
Number of Observations Used	66079
Number of Observations with Missing Values	848

Number in Model	C(p)	R-Square	AIC	SBC	Parameter Estimates							
					Intercept	taxitime	distance	actype	arvtime	terminal	taxiway	config
7	8.0000	0.9061	292010.933	292084	55.42046	0.16005	0.00023682	0.64195	-1.80356	-0.00001477	0.28307	0.38440
6	16.3718	0.9061	292019.306	292083	56.62981	0.16001	0.00024021	.	-1.80091	-0.00001489	0.27127	0.38279
6	119.4584	0.9059	292122.308	292186	56.35364	0.16019	0.00025004	0.34921	-1.79585	-0.00001497	.	0.43683

The C_p criterion compares the subset models with the full model.

$$C_p = \frac{SSE_p}{MSE(full)} - (n - 2p)$$

Where SSE is based on a specific chocice of p-1 variables, MSE is based on the full set of variables, and p is the number of regreession coefficients including the intercept, and n is the number of observations. A model is good according to this criterion if $C_p \leq p$. I chose the model that minimizes C_p provided the minimum C_p is smaller than p. In this case, the significant parameters are taxitime, distance, aircraft type, arrival time, terminal destination, taxi route, and runway configuration. Table C.2 shows the table for R-Squared Selection method for ATL runway 26R/8L and the results are in agreement with the C_p Selection Method. R-Squared is the correlation or goodness of fit of how well the model fits the data. The same anlaysis was performed for the other airports.

C.2 Table for R-Squared Selection Method for ATL runway 26R/8L.

The REG Procedure
Model: MODEL1
Dependent Variable: fuel_all

R-Square Selection Method

Number of Observations Read	66927
Number of Observations Used	66079
Number of Observations with Missing Values	848

Number in Model	R-Square	C(p)	AIC	SBC	Parameter Estimates							
					Intercept	taxitime	distance	actype	arvtime	terminal	taxiway	config
1	0.4606	313437.6	407515.454	407534	5.46777	0.15348	.	.	.	.	.	.
1	0.3860	365944.0	416078.093	416096	101.74703	.	.	.	-1.67211	.	.	.
1	0.2592	455148.8	428481.779	428500	16.40435	.	0.00433	.	.	.	.	.
2	0.9047	982.7067	292978.493	293006	58.64115	0.16320	.	.	-1.79714	.	.	.
2	0.6548	176789.5	378020.292	378048	68.51840	.	0.00441	.	-1.69293	.	.	.
2	0.4810	299084.3	404969.476	404997	50.03743	0.15513	.	-22.93220	.	.	.	.
3	0.9054	472.1900	292473.501	292510	57.28329	0.16469	.	.	-1.79840	.	.	0.33379
3	0.9051	673.8486	292673.450	292710	57.65386	0.16297	.	.	-1.80760	.	0.44217	.
3	0.9049	869.1988	292866.569	292903	59.36943	0.16301	.	.	-1.79547	-0.00001440	.	.
4	0.9058	243.9680	292246.489	292292	56.27270	0.16055	0.00024105	.	-1.79640	.	.	0.43379
4	0.9056	343.3317	292345.428	292391	56.82539	0.16431	.	.	-1.80530	.	0.30036	0.28149
4	0.9056	368.5642	292370.529	292416	57.99273	0.16450	.	.	-1.79679	-0.00001377	.	0.33063
5	0.9059	120.5871	292123.432	292178	57.00269	0.16017	0.00025162	.	-1.79456	-0.00001503	.	0.43473
5	0.9059	137.4279	292140.243	292195	55.90262	0.16040	0.00022961	.	-1.80280	.	0.27421	0.38130
5	0.9058	241.0928	292243.630	292298	57.53260	0.16412	.	.	-1.80367	-0.00001368	0.29877	0.27863
6	0.9061	16.3718	292019.306	292083	56.62981	0.16001	0.00024021	.	-1.80091	-0.00001489	0.27127	0.38279
6	0.9059	119.4584	292122.308	292186	56.35364	0.16019	0.00025004	0.34921	-1.79585	-0.00001497	.	0.43683
6	0.9059	127.0181	292129.855	292194	54.58660	0.16043	0.00022600	0.70192	-1.80568	.	0.28708	0.38307
7	0.9061	8.0000	292010.933	292084	55.42046	0.16005	0.00023682	0.64195	-1.80356	-0.00001477	0.28307	0.38440

Appendix D Modeling Fuel burn

Lognormal Distribution

Statistical methods were used to fit distributions to the fuel burn data for end-around taxiways and conventional taxiways at each airport. The distribution that fit best with ATL and DTW fuel burn data was the lognormal distribution in equation (4):

$$f(x|\mu,\sigma) = \frac{1}{x\sigma\sqrt{2\pi}} e^{\frac{-(lnx-\mu)^2}{2\sigma^2}}$$

$$\mu = \log\left(\frac{m^2}{\sqrt{v+m^2}}\right) \tag{4}$$

$$\sigma = \sqrt{\log\left(v/m^2+1\right)}$$

where m is the mean fuel burn and v is the standard deviation of the fuel burn data.

Normal Distribution

A standard approach based on the Kolmogorov-Smirnov test and quantile-quantile plots was used to fit distributions to the fuel burn data for end-around taxiways and conventional taxiways at each airport. The distribution that fit best with DFW fuel burn data was the normal distribution in equation (5):

$$f(x|m,v) = \frac{1}{v\sqrt{2\pi}} e^{\frac{-(x-m)^2}{2v^2}} \tag{5}$$

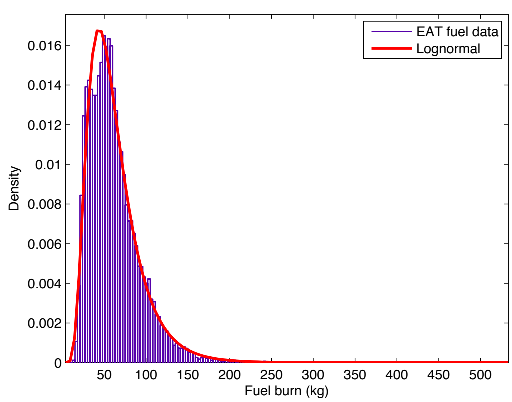
where m is the mean fuel burn and v is the standard deviation of the fuel burn data.

D.1 Atlanta/Hartsfield-Jackson International Airport

The following plots are histograms of density bins with aircraft fuel burn from ASDE-X data from 10 September 2012 to 28 February 2013. The appropriate distribution (shown as a red line) is fitted to the data. The parameters for the distribution were defined in section 7.

Figure 44 (left) shows the EAT fuel burn with a lognormal distribution for runway 26R in west-flow configuration at ATL.

Table 16 is the lognormal fuel burn distribution parameter estimates. The lognormal distribution is appropriate because the data is skewed right because there are some aircraft with high fuel burn. The high fuel burn could be due to aircraft stopped on the airfield because the gate is not available or some other delay. The high fuel burn could also be from error in ASDE-X data acquisition. Figure 44 (right) shows the conventional taxiway fuel burn with a lognormal distribution.



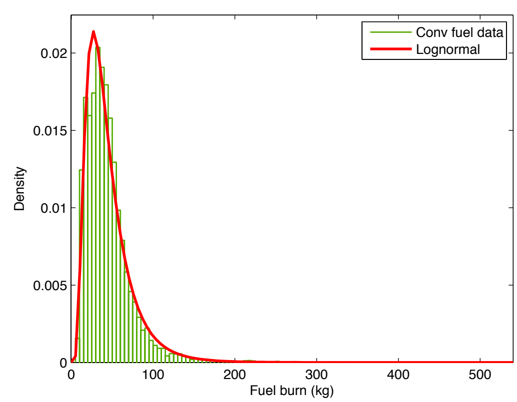


Figure 44: Left, the EAT fuel burn (blue bins) with lognormal distribution (red). Right, the conventional taxiways fuel burn (green bins) with lognormal fitted distribution (red) for runway 26R west-flow arrivals at ATL.

Table 16. ATL lognormal fuel burn distribution parameter estimates.

	Lognormal Parameters	$Log\ mean\ \mu$	$Log\ variance\ \sigma$
North West-flow Runway 26R	EAT	4.01	0.48
	Conventional Taxiway	3.63	0.59
North East-flow Runway 8L	EAT	4.50	0.48
	Conventional Taxiway	4.04	0.60
South East-flow Runway 9R	Unimpeded Taxiway S1	4.44	0.53
	Conventional Taxiway	3.91	0.73

D.2 Dallas/Fort Worth International Airport

Figure 45 (left) shows the EAT fuel burn with a normal distribution for runway 17L in south-flow configuration at DFW. Table 17 is the normal fuel burn distribution parameter estimates.

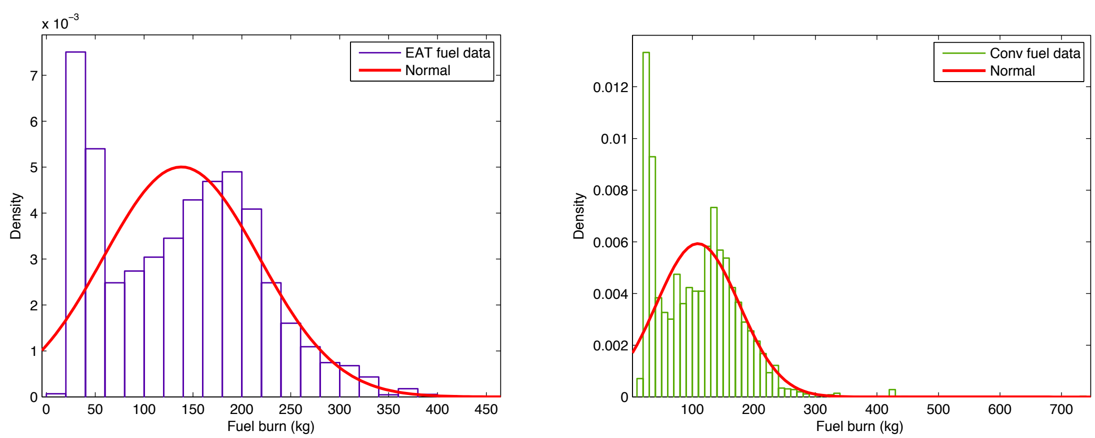


Figure 45: Left, the EAT fuel burn (blue bins) with normal distribution (red). Right, the conventional taxiways fuel burn (green bins) with normal fitted distribution (red) for runway 17L south-flow arrivals at DFW.

Table 17. DFW normal fuel burn distribution parameter estimates.

	Normal Parameters	$mean\ m$	$variance\ v$
South-flow Runway 17L	EAT	138.01	79.71
	Conventional Taxiways	108.95	67.25

The normal distribution is the best fit for the fuel burn data. Aircraft with a small fuel burn causes the first peak in the histogram. This is most likely from smaller aircraft with turboprop engines. Future research can eliminate this peak by removing aircraft belonging to the small aircraft class. The normal distribution is in agreement with mean and standard deviation of the fuel burn calculated from ASDE-X data, therefore it is the best fit. Figure 45 (right) shows the conventional taxiways fuel burn with a normal distribution. Here again, the normal distribution.

D. 3 Detroit Metropolitan Wayne County Airport

Figure 46 (left) shows the EAT fuel burn with a lognormal distribution for runway 22R in south-flow configuration at DTW. Table 18 is the lognormal fuel burn distribution parameter estimates.

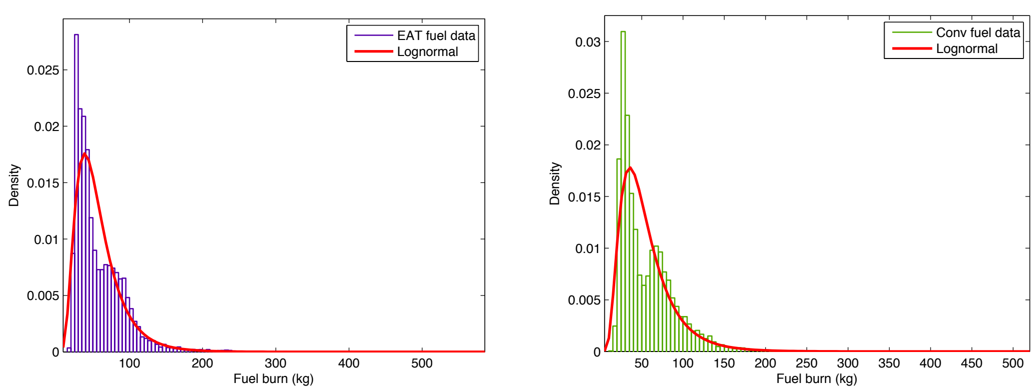


Figure 46: Left, the EAT fuel burn (blue bins) with lognormal distribution (red). Right, the conventional taxiways fuel burn (green bins) with lognormal fitted distribution (red) for runway 22R south-flow arrivals at DTW.

Table 18. DTW lognormal fuel burn distribution parameter estimates.

	Lognormal Parameters	$Log\ mean\ \mu$	$Log\ variance\ \sigma$
South-flow Runway 22R	EAT	3.92	0.51
	Conventional Taxiways	3.86	0.55
	Taxi 1 South Terminal	3.51	0.42
	Taxi 2 North Terminal	4.11	0.47
	EAT South Terminal	3.92	0.51
North-flow Runway 4L	EAT	4.23	0.53
	Conventional Taxiways	3.77	0.51
	Taxi 1 South Terminal	3.64	0.35
	Taxi 2 North Terminal	3.81	0.48
	EAT South Terminal	4.23	0.53

The lognormal distribution is appropriate because the data is skewed right because there are some aircraft with high fuel burn. The high fuel burn could be due to aircraft stopped on the airfield. The high fuel burn could also be from error in ASDE-X data acquisition. The different peaks in the histogram could be from the variation of aircraft types such as smaller turboprop engines burn less fuel than a B747 jet engine. Figure 46 (right) shows the conventional taxiway fuel burn with a lognormal distribution. The lognormal distribution is an appropriate fit for reasons similar to the EAT. There are only two conventional taxiways, which explains the two peaks in fuel burn. Figure 47 separates the conventional taxiways in Taxiway 1 and Taxiway 2.

Figure 47 (left) shows Taxiway 1 fuel burn with a lognormal distribution for runway 22R south-flow arrivals to the South Terminal. Figure 47 (right) shows Taxiway 2 fuel burn with a lognormal distribution for arrivals to the North Terminal.

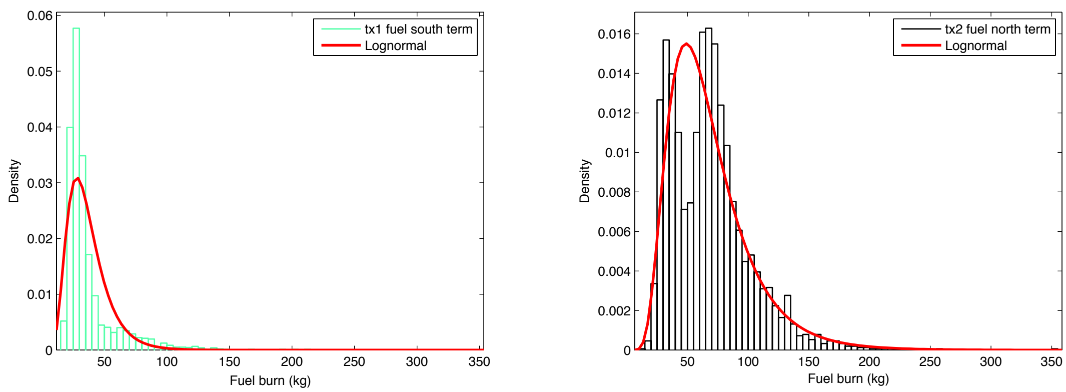


Figure 47: Left, Taxiway 1 to the South Terminal fuel burn (aqua bins) with lognormal distribution (red). Right, Taxiway 2 fuel burn (black bins) with lognormal distribution (red) for runway 22R south-flow arrivals to the North Terminal at DTW.

Appendix E Fuel burn Monte Carlo Simulation

The decision simulations in sections 4.6 – 4.8 estimated the potential fuel burn savings by averaging the fuel burn from a Monte Carlo simulation. Below is an example of how I determined how many simulation runs to do. I noticed a fluctuation in fuel burn between simulations runs; therefore I conducted a Monte Carlo simulation for 100, 1,000, and 10,000 runs until the output stabilized. 10,000 simulations was a sufficient number of runs for all five decision rules to converge to a fuel burn with low variability between runs. Table 19 is the Monte Carlo Simulation results for 10,000 runs to estimate fuel savings for ATL west-flow runway 26R. The fuel burn standard deviation are less than 0.005 kg for all the decision rules, which shows the low variability in fuel burn for 10,000 simulations. Most decision rules stabilized by 5,000 runs as seen in Figure 48- Figure 52, but the always decision rule takes close to 10,000 simulations to stabilize. To keep all the fuel burn estimates consistent, 10,000 simulations were conducted for all decision rules for every airport configuration.

Table 19. Monte Carlo Simulation results for 10,000 runs to estimate fuel savings for ATL west-flow runway 26R.

Decision rule	Always	Never	Arrival time	Terminal	Multi-factor
Average fuel burn (kg)	45.45	33.89	37.99	39.73	37.89
Fuel burn Std. dev. (kg)	0.0019	0.0032	0.0019	0.0020	0.0014
Fuel burn savings (%)	10.3%	-17.8%	-7.8%	-3.6%	-8.1%

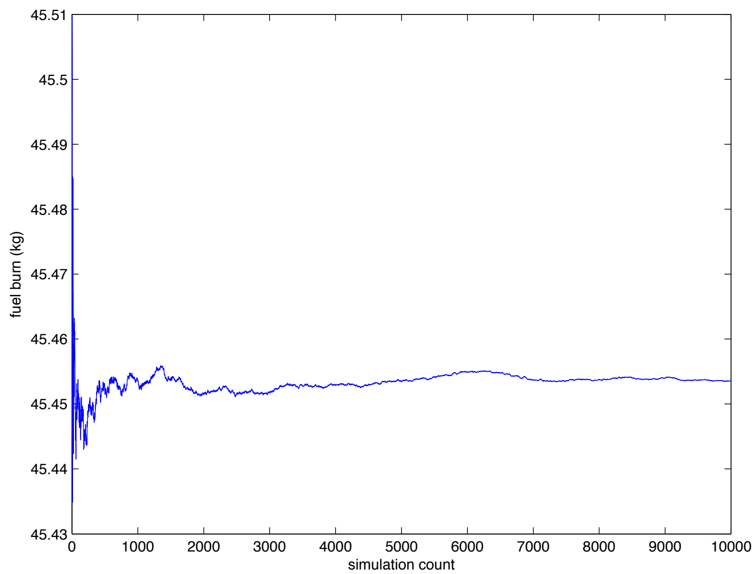


Figure 48. ATL west-flow runway 26R always decision simulation.

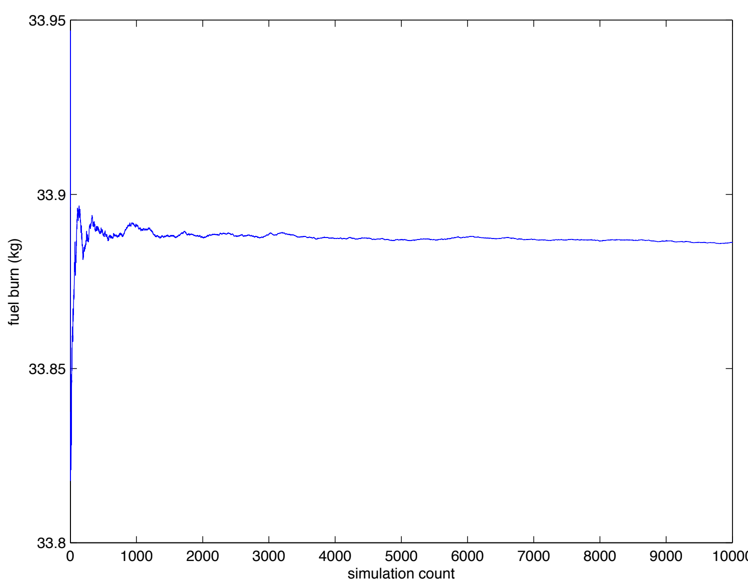


Figure 49. ATL west-flow runway 26R never decision simulation.

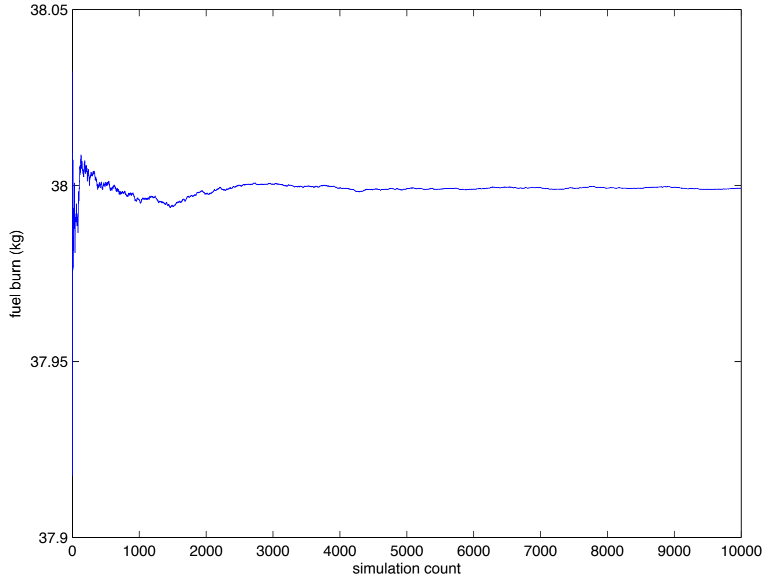


Figure 50. ATL west-flow runway 26R arrival time decision simulation.

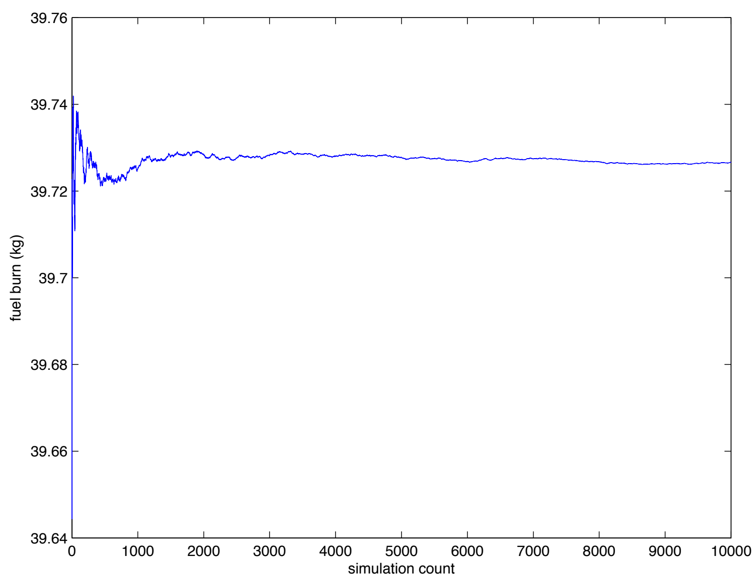


Figure 51. ATL west-flow runway 26R terminal decision simulation.

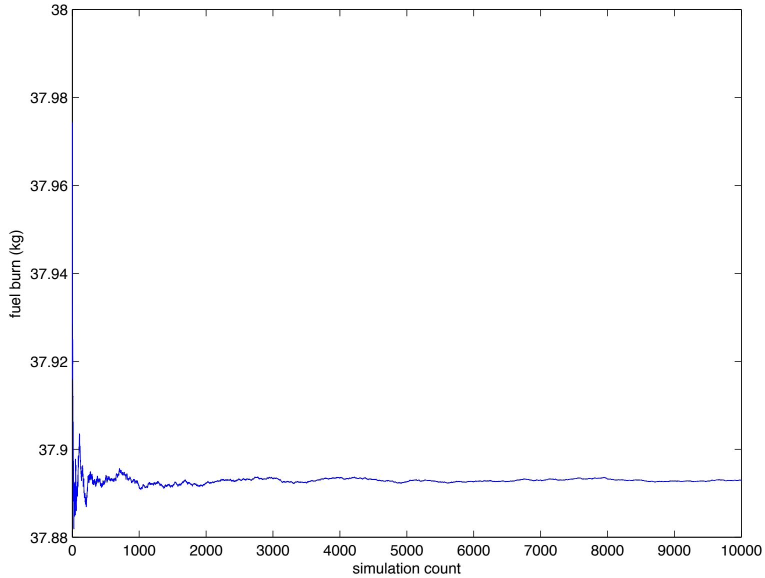


Figure 52. ATL west-flow runway 26R multi-factor decision simulation.

Appendix F Preliminary Stakeholder Analysis

Stakeholders are people or a group that has an investment, share, or interest in something. Stakeholders for implementing EAT decision rules to optimize fuel savings for taxi-in procedures include airports, airlines, air traffic control, aircraft operators (pilots), passengers, government agencies (FAA), communities around airports, and the general public. Each stakeholder's interest and concerns are detailed below. By understanding how the unimpeded taxiway decision rules impact each stakeholder, better strategies can be developed to bring faster and easier transition to implement unimpeded taxiway operational changes. Identifying major stakeholders who are affected more by changes and addressing their concerns can increase the likelihood of success. Interviews with various stakeholders can also provide information to make better decision rules that are more likely to be implemented. Direct input from minor stakeholders is not necessary for developing the decision rules, but it important to consider all groups affected by the operational change to ensure the overall success of implementation.

1. **Airports:** Airports are one of the major stakeholders because an EAT is a key part of the airport infrastructure for aircraft to taxi-in to the terminal. Airports invest in an EAT to provide safety, increase runway throughput, and reduce surface delays. The construction of an EAT is typically primarily financially supported by the airport. There is a possibility of disruption in current airport operations during the construction process. Capacity constrained airports may have more interest in EATs to reduce surface congestion and increase runway capacity. Note that potential unimpeded taxi flows are possible without added infrastructure and is dependent on current taxiways and runway configurations.

2. **Airlines:** Airlines are key stakeholders because fuel savings directly affect operating costs. Commercial airlines are the primary users of taxiways at the large airports that have or are considering EATs. New EAT decision rules can benefit airlines by increasing fuel savings for taxi-in procedures. At hub airports these savings can be significant.

3. **Air Traffic Control:** Cooperation from air traffic control is essential, as they must implement the taxi-in procedures. Some important factors to ATC include the practicality of implementing the decision rules and ease of transition from current to new procedures. Sophisticated decision rules may require high computing power or new technology, making them infeasible for near-term implementation. Simple EAT procedures could benefit ATC by relieving ground congestion, thus making it easier to direct arrivals and departures.

4. **Pilots:** Pilots require safe, simple, and predictable taxi-in procedures. For example, a human factors simulation study results show some pilots may misperceive an aircraft on the EAT as an aircraft crossing the runway and therefore abort the takeoff or think an aircraft is on the EAT, but is crossing the runway leading to a runway incursion.

5. **Passengers:** A faster taxi-in time and reduce surface delays are key factors to improve customers' air travel experience. For passengers with connecting flights more efficient taxi-in procedures increase the likelihood that they will reach their next gate in a timely manner.

6. **Government Agencies (FAA):** Aviation regulators like the FAA in the United States are crucial stakeholders in the decision-making and implementation process. The FAA must ensure that new operational changes are in agreement with existing regulations for the national air system. Safety is the highest priority for the FAA therefore new procedures for the EAT must meet the FAA safety standards.

7. **The Community:** Noise and emissions from EAT construction or more air traffic enabled by decreased surface congestion may be a concern to surrounding residence. Surrounding communities that support airport growth and improvement will allow faster implementation to new strategies. Increasing capacity at airports may be a concern for homeowners because it may increase air traffic and noise in their neighborhoods, which might depreciate the value of residences.

8. **General Public:** the overall support of the public will prompt change more quickly. The increasing concern for the environment has created a need for research in the areas of noise, emissions, and energy. The EAT decision rules improves surface operations and emphasizes the environmental benefits in terms of fuel savings. Overall, air travellers will support improvement in surface operations at airports. In terms of general aviation, the creation of an EAT may result in a longer taxi distance that might affect private aircraft owners operating from that airport.

Table 20 summarizes the unimpeded taxiway benefits for the various stakeholders discussed above. Some benefits apply to several stakeholders (e.g., increased safety benefits airports, airlines, passengers), while others apply only to a single stakeholder (e.g., airlines save fuel). Not all benefits are equal because some benefits are more important to certain stakeholders than others. It would be appropriate to assign weights to the benefits by letting stakeholders rate the extent and order of importance to them.

Table 20. Unimpeded Taxiway stakeholder benefits.

	Stakeholders	Unimpeded Taxiway Benefits		
1.	**Airports**	High throughput	Reduce surface delay	Increase capacity
2.	**Airlines**	Fuel savings	Reduce surface delay	Fast taxi-time
3.	**Air Traffic Control**	Easily direct arrivals	Reduce surface delay	Increase Safety
4.	**Aircraft Operators (pilots)**	Unimpeded taxi path	Fast taxi time	Easy taxi-in
5.	**Passengers**	Fast taxi time	Reduce surface delay	Increase Safety
6.	**Gov't Agencies (FAA)**	Low incursion risk	Increase Safety	
7.	**The Community**	Reduce emissions		
8.	**General Public**	Environmental improvement	Increase efficiency at airports	Increase airport capacity

Table 21 is a summary of EAT costs for various stakeholders. Some stakeholders have more costs than others. For example, airports have the largest direct cost of the EAT construction and indirect costs such as construction causing surface delays and closure of taxiways and runways. Other costs are more difficult to quantify and address such as the community's concern for long-term health effects and higher aircraft throughput potentially resulting in more noise in surrounding neighborhoods.

Table 21. Unimpeded Taxiway stakeholder costs.

	Stakeholders	**Unimpeded Taxiway Costs**		
1.	Airports	EAT construction	Airport construction cause surface delays	Cost of closure of taxiways/ runways
2.	Airlines	EAT and gate location determines fuel costs		
3.	Air Traffic Control	Implementation costs	New procedure costs	
4.	Aircraft Operators (pilots)	Adapting to new procedures		
5.	Passengers	Longer taxi time at peak traffic hours	Airport construction cause surface delays	
6.	Gov't Agencies (FAA)	Safety concerns such as aborted takeoffs	Potential increase incursions	
7.	The Community	Long-term health effects	Higher throughput may cause more noise	
8.	General Public	Increase emissions		

A cost and benefit analysis can objectively evaluate the costs and benefits for each decision rule applied to various stakeholders. Figure 53 is a flow chart of the process of how to conduct the cost and benefit analysis. The first step is to interview the various stakeholders such as airports and airlines. Directly communicating with the customers, users, and other people impacted by the new operational changes can provide crucial input early in the decision-making process. A wide variety of perspectives from the broad spectrum of stakeholders will provide insight on how the operational changes affect the entire system. The next step is to identify the benefits and quantitatively evaluate (where possible) the costs for each stakeholder. The interviews from the various stakeholders can also be used to provide a more detailed list of direct and indirect costs and benefits. A trade-off study can then be used to investigate the optimal decision rule that balances costs and benefits across the stakeholders. The last step is to implement the best decision rule that brings the most fuel savings while considering the costs and benefits of the stakeholders. By communicating to the stakeholders early in the decision process and clearly defining the costs and benefits will make implementing EAT decision rules faster and easier.

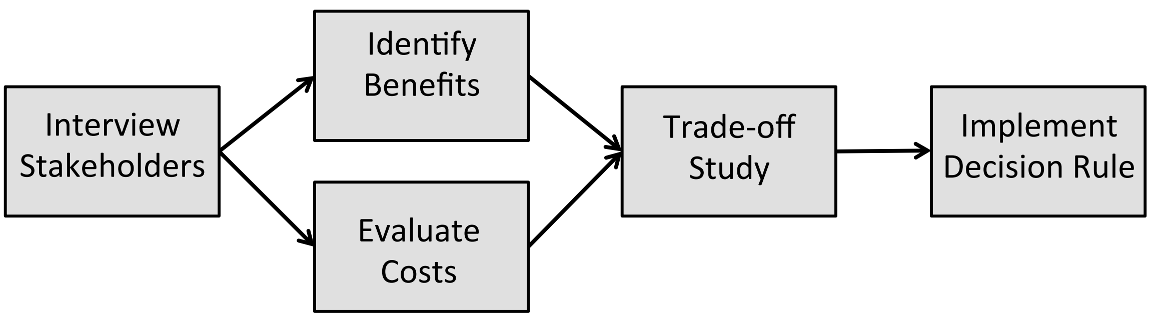


Figure 53. Costs and Benefit Analysis Flow Chart.

Support from stakeholders makes it easier to implement new strategies. A more detailed analysis of the costs and benefits to implement new EAT decision rules add to a stronger proposal to stakeholders. My research study focused on taxi-in fuel burn from arrivals, but a more detailed analysis of taxi-out fuel burn for departures would provide a more comprehensive environmental impact analysis for the entire surface operations at airports. Cost and ease of implementation are important factors to ensure near-term operational changes are in fact feasible in the near future.