A METHODOLOGY FOR ANALYSIS OF METROPLEX AIR TRAFFIC FLOWS

by

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DEDICATION

I dedicate this dissertation to my parents, Kuppaswamy Rao Belle and Savitha Belle.
I am grateful to Dr. Lance Sherry for being my dissertation director. I would like to thank him for helping me stay motivated and focused through the years. Without his expertise, support and guidance this would not have been possible.

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<td>Dallas Fort Worth International Airport</td>
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<td>Fort Lauderdale–Hollywood International Airport</td>
<td>FLL</td>
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<td>Four Dimension</td>
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<td>Instrument Landing System</td>
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<td>Instrument Meteorological Conditions</td>
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<td>John Wayne–Orange County Airport</td>
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<td>Midway International Airport</td>
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<td>Multi-function Control and Display Unit</td>
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<td>National Airspace System</td>
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<td>National Offload Program</td>
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<td>Newark Liberty International Airport</td>
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<td>Performance Based Navigation</td>
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<td>Radius to Fix</td>
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<td>Required Navigation Performance</td>
<td>RNP</td>
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<td>Required Time of Arrival</td>
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ABSTRACT

A METHODOLOGY FOR ANALYSIS OF METROPLEX AIR TRAFFIC FLOWS

Akshay Belle, Ph.D.

George Mason University, 2013

Dissertation Director: Dr. Lance Sherry

A key determinant of the airspace capacity serving a metropolitan area with multiple airports is the extent of interaction between arrival and departure flows between the airports. The airports for some “metroplexes” are geographically located such that under certain wind and weather conditions, there exist conflicts between the flows. This results in excess costs from ground holding for departures and airborne holding for arrivals.

Advances in aircraft navigation technology (i.e. Performance Based Navigation) have created opportunities to improve arrival flow efficiencies and de-conflict metroplex flows. The adoption of these technologies has been slow and haphazard due to uncertainties in the estimates of the Return-on-Investment (ROI), the need for collaboration and simultaneous equipage across competing stakeholders, and the allocation of benefits to parties that choose not to equip but gain benefits when their competition equips. Together these issues have created a “modernization stalemate.”
The recent availability of high fidelity surveillance track data coupled with aerodynamic models and weather data have created an opportunity to provide detailed Return-on-Investment analysis of metroplex traffic flows that includes the real-world complexities of traffic flows and aircraft trajectories. This type of analysis provides accurate benefits assessment for various flow and equipage configurations.

This dissertation describes a holistic methodology that uses high fidelity surveillance track data coupled with aerodynamic models and weather data to quantify the benefits of existing and proposed concepts-of-operations and technologies that require simultaneous equipage and development of collaborative procedures by multiple stakeholders.

The methodology includes six algorithmic functions: (1) terminal area flow analysis to characterize of flow and track assignment, (2) analysis of the effects of metroplex flow conflict for arrival holding patterns, (3) estimates of the performance metrics (e.g. times, distance and fuel burn) for terminal area flows and holding patterns, (4) estimates of the benefits of PBN approach procedures at an airport, (5) estimates of the benefits of metroplex airspace de-confliction, and (6) estimates of the return on investment for the equipped operator.

A case study analysis of the benefits of the introduction of a Required Navigation Performance (RNP) approach procedure for air traffic arrival flows in the Chicago Terminal Radar Approach Control (TRACON) is described. The analysis showed that the airspace used to service both, the Chicago O'Hare International Airport (ORD) and the Chicago Midway International Airport (MDW) experiences a flow conflict (13C ILS arrivals at MDW and 22L departures at ORD) on an average 1.6% of the time per year.
When the metroplex airspace is de-conflicted by the introduction of an RNP approach for 13C at MDW, the direct airline operating cost per year is reduced on an average by $.04M at MDW and $1.33M at ORD. The savings at MDW are from elimination of holding patterns and the fuel burn saving of a shorter RNP approach over the ILS approach. At ORD the savings are from a reduction in departure delays. The ratio of the total benefits distributed between flights at MDW and ORD is 1:33 in favor of non-equipped ORD departures. This is equivalent to 1:9 per flight ratio in favor of non-equipped ORD departures.

The methodology also enabled the evaluation of the introduction of additional RNP approach procedures to other runways at MDW to improve the benefits for the equipped arrivals to MDW. This has the potential of saving an average 660K gallon per year of fuel for arrivals at MDW. At $3/gallon this amounts to a savings of an additional $1.97M per year.

The methodology also enabled the evaluation of an “optimal runway configuration,” based on wind magnitude/direction and flow fuel burn efficiency, to further improve the benefits for the equipped arrivals to MDW. This has the potential of saving an average of 890K gallons per year of fuel for arrivals at MDW. At $3/gallon this amounts to a savings of an additional $2.67M per year.

With these accumulated savings, the RNP approach does not yield a positive ROI at MDW. The carrier at MDW will have to perform at least a half million RNP approaches per year throughout its network, saving at least 33 kg of fuel per approach on an average to break-even in 10 years at a discount rate of 5%.
This analysis demonstrates the economics behind the “modernization stalemate.”

The equipping airline cannot turn a positive ROI in a reasonable time-frame while the non-equipped, competing airlines (i.e. free-riders) benefit significantly more than the equipping airline. Mandating equipage is inefficient as all aircraft do not need to equip to improve the efficiencies. Government subsidies for equipage and preferential service incentives for equipage must be calibrated to the asymmetric benefits computed by this methodology.
CHAPTER 1: INTRODUCTION

The term Metroplex refers to a system of airports serving a large Metropolitan area (FAA, 2012e). The airports in a metroplex are often in close proximity to each other and can have interdependent arrival and departure procedures (JPDO, 2007). In the United States (U.S) the Federal Aviation Administration (FAA) has identified 21 metroplexes (FAA, 2012e).

Metroplexes are a critical component of the nation’s economy and the air transportation system. The 33 ASPM1 airports at the 21 U.S metroplexes account for more than 48% of the total operations in the NAS’s hub2 airports (FAA, 2012f). The metropolitan regions these airports serve account for 35% (United States Census Bureau, 2012) of the nation’s population (314 million as of 2012) and 44% (U.S. Department of Commerce, 2012) of the gross domestic product (U.S GDP in 2012 was $15.68 trillion).

Given the interconnected nature of the air transportation system, a reduction in capacity at the metroplexes results in delays that propagate through the entire system (DeLaurentis & Ayyalasomayajula, 2010; Laskey, Xu, & Chen, 2012).

A key determinant of the capacity of the metroplex airspace is the extent of interaction between flows of aircraft in the airspace (terminal airspace) surrounding the

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1 The Aviation System Performance Metrics (ASPM) database system currently provides detailed data on flights to and from the ASPM airports (currently 77) (ASPM System Overview, 2012).
2 U.S airports that have .05% or more of the total passenger boarding per year (FAA, 2012a)
metroplex. In some metroplexes, the geometry of the airports and its procedures is such that under certain wind and weather conditions there exists conflicts between flows that require excessive ground holding for departures at one airport and airborne holding for arrivals at the neighboring airport. This results in a reduction in effective capacity of the metroplex airspace, while increasing the potential for added delays and costs to passengers and airlines.

There are six metroplexes in the U.S which have flow conflicts between neighboring airports due to their close proximity and the interdependent arrival and departure procedure, shown in Table 1 (Clarke et al., 2011)

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<th>Metroplex</th>
<th>Ops per day (Year 2012)</th>
<th># Major Airports</th>
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<tr>
<td>1</td>
<td>New York</td>
<td>3257</td>
<td>3</td>
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<tr>
<td>2</td>
<td>Chicago</td>
<td>3055</td>
<td>2</td>
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<td>3</td>
<td>Los Angeles</td>
<td>2797</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>Dallas</td>
<td>2236</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>San Francisco</td>
<td>1903</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>Miami</td>
<td>1734</td>
<td>2</td>
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Recent advancements in aircraft navigation and approach capabilities have created opportunities to improve arrival flow efficiencies and de-conflict metroplex flows.
1.1 Required Navigation Performance Approach and Metroplex De-confliction

Airspace navigation has evolved from point-to-point navigation enabled by conventional ground-based navigation systems, to area navigation (RNAV) enabled by a combination of ground-based navigation, inertial referencing systems, and satellite based navigation system (see Figure 1). Further, the addition of monitoring and altering systems on board the aircraft has enabled the aircraft navigation system to monitor its navigation performance, and to identify for the pilot the level of navigation compliance during an operation. The level of navigation compliance is defined by the Required Navigation Performance (RNP) and depends on the aircraft equipment and the navigation infrastructure (FAA, 2012g). These navigational advancements referred to as Performance Based Navigation (PBN), have enabled the implementation of precise curved path approach procedures in the terminal airspace that improve flow efficiencies and de-conflict metroplex airspace.

![Diagram of conventional ground-based navigation, RNAV, and RNP]

Figure 1: Performance Based Navigation (PBN) has enabled the implementation of precise curved path approach procedures in the terminal airspace that improve flow efficiencies and de-conflict metroplex airspace (Source: Ray 2013)
The precise curved path PBN procedure for terminal airspace is called RNP 0.3 approach with Radius to Fix (RF) leg. The “RNP 0.3” is the level of performance required for the approach i.e., the aircraft are required to maintain centerline within 0.3 nautical miles (NM) 95 percent of the time and twice the RNP value, or 0.6 NM, 99.999 percent of the time, and the RF leg refers to the curved path between two fixes (see Figure 2). Using the RNP 0.3 approach with RF leg, aircraft are contained along a precise curved path, allowing safe navigation near high terrain, obstacles and airspace occupied by other flows of air traffic (Ray, 2013).

Figure 2: Using the RNP 0.3 approach with RF leg, aircraft are contained along a precise curved path, allowing safe navigation near high terrain, obstacles and airspace occupied by other flows of air traffic.

The RNP approach was first deployed in 1996 at Juneau airport in Alaska by Alaska Airlines to improve access and schedule reliability (FAA, 2009). The approach at Juneau during bad weather using conventional ground-based instrument landing system
(ILS) approach (requiring long unobstructed approach path) was not possible due to the tightly encircled mountains. The RNP approach allowed aircraft to navigate with increased precision around the high terrain and to the final approach of the runway. Since then, RNP approach has been deployed world-wide to improve access and schedule reliability to airports in mountainous regions affected by bad weather (details in section 2.5)

In recent years, the use of RNP approach capability has been extended to de-conflicting metroplex airspace. The airspace is de-conflicted by using the curved path RNP approach to make the final approach on to the runway shorter compared to the conventional ILS approach (see Figure 3). This separates the flow of aircraft to one airport away from the flows arriving or departing from a nearby airport.

Figure 3: RNP approach “cuts-the-corner” on the final approach to de-conflict terminal area airspace.
The de-confliction of airspace enables the airports at the metroplex to maintain capacity in the event of conditions (low visibility and winds from certain direction) that would otherwise cause the metroplex flow conflict and the resulting drop in capacity of the airspace surrounding the metroplex.

The U.S metroplexes identified as candidates for flow de-confliction are Chicago and New York (FAA, 2012h). The FAA has implemented an RNP approach with RF leg at Midway International Airport (MDW) to de-conflict the Chicago metroplex and is currently testing the curved path RNP approach at John F Kennedy International Airport (JFK) to de-conflict flows at the New York metroplex (FAA, 2012h).

1.1.1 Chicago Metroplex De-confliction

Chicago metroplex is the second largest metroplex in the U.S in terms of traffic volume, with 3055 operations per year (ASPM 2012). It has two airports, the Chicago O'Hare International Airport (ORD) and the Chicago Midway International Airport (MDW) within thirteen nautical miles (NM) of each other. During low ceiling and visibility, and winds from the south east direction, aircraft arriving at MDW are required to use the Instrument Landing System (ILS) on runway 13C. The ILS approach to 13C starts 10.1 NM from the runway threshold and interferes with departures from runway 22L at ORD (see Figure 4 (a)). This is overcome by tactical time sharing of the common airspace, resulting in ground delay for ORD departures and airborne holding for MDW arrivals. Using the new RNP approach with radius to fix leg, aircraft can approach runway 13C without interfering with aircraft departing from runway 22L at ORD (see Figure 4 (b)). This approach procedure results in de-conflicting the metroplex airspace.
**1.2 Challenges with Implementing RNP**

To enable the RNP approach, the air navigation service providers (ANSPs) must design and approve RNP approaches, and train air traffic controllers. In addition, airlines must equip with RNP equipment, train the crew and achieve certification to fly the procedure. The adoption of RNP approach by airlines has been slow, primarily due to: (a) issues with estimating the Return-on-Investment (ROI) and (b) the “free rider” issue, i.e., the allocation of benefits to parties that choose not to equip but gain benefits when their competition equips.

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![Diagram](image.png)

Figure 4: Using the new RNP approach with radius to fix leg to runway 13C at MDW, aircraft can approach runway 13C without interfering with aircraft departing from runway 22L at ORD.
1.2.1 Estimating the Return on Investment

Equipping with RNP approach capability is expensive. The FAA estimates the cost of adding the equipment to a new aircraft at the time of purchase is $260,000 and the cost of retrofitting an existing aircraft is $525,000 (FAA, 2012i). In addition, the airlines have to account for cost of training and certification of the crew, and the cost of down time associated with retrofitting the aircraft with the new equipment.

The primary benefit of this technology to individual airlines is fuel savings during instrument meteorological conditions (IMC) i.e., low ceiling and visibility, from:

(a) Shorter track distance in the terminal airspace compared to conventional instrument approach procedures

(b) Elimination of airborne holdings that would otherwise occur due to the metroplex flow conflict.

Ideally an airline would want to perform the precise curve path RNP approaches as often as possible and save on fuel burn. However, the candidate airports where RNP approach procedures are being implemented have IMC conditions on average less the 15% of the time in a year. Further, the percentage of time there are flow conflicts at metroplexes is further less. For instance, an analysis of ASPM data for years 2007 to 2012 shows MDW experiences IMC on average 13% of the time per year and a potential flow conflict at Chicago metroplex can occur on average 1.6% of the time per year. This lowers the potential use of RNP approach and the associated fuel burn savings.

The uncertainly in the costs associated with equipping and the actual usefulness of the RNP approach make it difficult to estimate the ROI and thus can prevent the airlines from equipping.
1.2.2 Free rider Issue
For metroplex operations, the additional cost of flow conflict is not evenly distributed among airlines operating at the airports and therefore the benefits from de-confliction by equipage can favor airlines at one airport more than the other. Also, only the airlines at the airport whose arrival flow is causing the airspace conflict are required to equip with the new capability.

For instance, the additional delay cost of flow conflict at Chicago metroplex was estimated at sixteen times more for airlines at ORD than MDW (Devlin, Mills, Porter, & Sprong, 2012). The addition of an RNP approach for arrivals at MDW de-conflicts the airspace and will require the airlines at MDW to equip. This results in airlines at ORD benefitting from investments made by airlines at MDW. This is referred to as the free rider issue.

The competitive nature of the business and the asymmetry in the distribution of benefits may keep airlines from making the investment in the new technology.

1.2.3 Research Questions
The fundamental research questions related to the RNP approach equipage and the associated challenges with it are:

1. Does airline investment in RNP approach capability yield an acceptable Return on Investment (ROI)?
2. Does an airline equipping with RNP approach capability offer a competitive advantage?
3. Are there opportunities to improve ROI?
4. What portfolio of incentives/strategies exists to achieve airline equipage?
1.3 **Gaps in the Literature**
A review of the existing literature (see section 2) shows the research questions above have not been addressed so far. Further, there are gaps in the type of analysis and the underlying methodology that need to be addressed.

1.3.1 **Benefits analysis gaps.**
The costs of metroplex flow conflicts and the potential benefits associated with the de-confliction have been analyzed from a system-wide perspective (Clarke et al., 2011; Devlin et al., 2012). The cost and benefits have been expressed in terms of system-wide delays, cancellation and fuel burn. The benefits and ROI from investing in the new PBN approach capabilities to individual airlines have not been analyzed. This is an oversight as airlines make investment based on their benefits, not system-wide benefits.

The fuel burn benefits are computed using time-in-mode method, which assume constant fuel burn rate for a given mode (e.g., descent, climb, and cruise) (Clarke et al., 2011). The main benefits of RNP approach to individual airlines are in terms of fuel burn savings from shorter and more efficient trajectories in the terminal airspace. Hence, it is important to compute fuel burn savings of RNP approach by taking into consideration the actual trajectories of aircraft in the terminal airspace.

The cost of airborne holding as a result of the metroplex flow conflict have not been analyzed and quantified. This can be done by analysis of recently available track data.

1.3.2 **Methodological gaps**
The analyses of metroplex de-confliction are based on simulated de-coupled route structure (Clarke et al., 2011) or delay analysis of operational data (ASPM) (Devlin et al.,
These do not capture the actual real-world complexities of traffic flows and aircraft trajectories in the terminal airspace.

The analyses using track data are limited to prescribing methodologies to cluster track data, identifying variation in flows and detecting anomalies (Dorfman, Daily, Gonzalez, & Kondo, 2012; Enriquez, 2013; Levy, 2003; Vempati & Ramadani, 2012).

There is lack of a systematic methodology to characterize flows in the terminal airspace for the purpose of differentiating and comparing performance of terminal flows in terms of track distance/time and fuel burn.

1.3.3 Summary of Gaps in the Literature

The existing metroplex de-confliction analyses have been performed from a system-wide perspective using simulated de-coupled routes or low fidelity operational data.

There is a need for a systematic methodology that uses high fidelity surveillance track data coupled with aerodynamic fuel burn model and weather data to estimate the efficiencies and costs of metroplex terminal air traffic flows for assessing benefits of associated concept-of-operations and technologies to individual airlines. This dissertation will address these gaps.

1.4 Research Objectives

The recent availability of high fidelity surveillance track data coupled with aerodynamic fuel burn models, and airport wind and weather data have created an opportunity to provide detailed analysis of metroplex traffic flows to include the real-world complexities of traffic flows and aircraft trajectories.
The objective of this dissertation is to develop a holistic methodology that leverages the accuracy of the high fidelity surveillance track data to:

1. Estimate the Return on Investment of the new PBN approach procedures to individual airlines. This has the following sub objectives:
   a. Estimate the track distance/time and fuel burn performance of the new PBN approach procedures to compare it to conventional approach procedures (i.e., ILS approaches).
   b. Use existing RNP approach flows to model additional potential RNP approaches to other runways at an airport and estimate their associated benefits.
   c. Estimate the fuel burn benefits of using the Optimal Runway Configuration model (see sections 1.9.2, 3.6.2 and 4.4.2).
2. Estimate the benefits of metroplex de-confliction to capture magnitude of the asymmetry and the potential for simultaneous adoption of the technology by the competing stakeholders.

1.5 Summary of the Methodology
This dissertation describes a holistic methodology to use high fidelity surveillance track data coupled with aerodynamic models and weather data to quantify the efficiencies and costs of metroplex terminal area air traffic flows. This methodology assesses the benefits of proposed terminal airspace concepts-of-operations and associated technologies that require simultaneous equipage and development of collaborative
procedures by multiple stakeholders (airlines and ANSPs). The methodology includes the following six functions:

1. Perform terminal area flow analysis.
2. Analyze effects of metroplex flow conflict.
3. Define performance metrics and estimate the performance of terminal flows and holding patterns.
4. Estimate the benefits of metroplex airspace de-confliction.
5. Estimate the benefits of PBN approach procedures to an airline at an airport.
6. Estimate the return on investment for the equipped operator.

The first three functions are the building blocks of the overall methodology, which are used to develop models (in functions four, five and six) that annualize benefits of PBN approaches to the metroplex and the individual airlines.

1.6 Unique Contributions

The unique contributions of this dissertation are:

1. A systematic methodology that characterizes terminal flow and estimates the performance of terminal air traffic flows by integrating high fidelity surveillance track data, aerodynamic fuel burn model and airport wind and weather data.
2. A methodology that uses track data of existing RNP approach flows at an airport to model additional potential RNP approach flows to other runways at the airport.
3. A methodology that determines the optimal runway configuration by ranking a set of feasible (for the given wind and meteorological conditions) runway configurations based on the weight average fuel burn for runways and selecting the runway configuration with the lowest (best) terminal area fuel burn performance.

4. A methodology for estimating the cost of holding pattern using surveillance track data.

5. Synthesis of micro and macro benefits analysis model that uses high fidelity surveillance track data and low fidelity operational data to estimate:
   
   a. The benefits of metroplex de-confliction and the associated asymmetry to competing stakeholders, to understand the potential for simultaneous adoption of the technology by the competing stakeholders.
   
   b. The benefits of PBN approach procedures to airlines at an airport based on the airport’s arrival flow performance statistics, while taking into consideration the use of additional PBN approaches and runway configurations.
   
   c. The ROI of PBN approach procedure to individual airlines.

6. Application of the methodology for an analysis of Chicago Metroplex TRACON (C90) to estimate:
a. The performance of RNP approach to runway 13C by performing at TRACON flow analysis at MDW.

b. The cost of holding for 13C arrivals MDW due to conflicts with departures from 22L at ORD.

c. The annualized benefits of RNP approach to ORD and MDW from de-confliction of flows.

d. The annualized benefits of using Optimal Runway Configuration and RNP approach procedures to all major runways (13C, 31C, 22L, 4R) at MDW.

e. The Return on Investment (ROI) of RNP approach for the majority air carrier at MDW (Southwest Airlines).

1.7 **Summary of Results –Chicago Metroplex TRACON (C90) Case Study**

The methodology for metroplex air traffic flow analysis is demonstrated in a case-study of the benefits of the introduction of a Required Navigation Performance (RNP) approach procedure for air traffic arrival flows in the Chicago Terminal Radar Approach Control (TRACON), known as C90.

The analysis shows that this airspace, used to service both ORD and MDW, experiences a flow conflict (between 13C ILS arrivals at MDW and 22L departures at ORD) on an average 1.6% of the time per year. This results in holding patterns for 13C arrivals and departure delays for ORD departures. The additional airline direct operating cost per year on an average due this flow conflict is $0.04M for MDW arrivals and $1.33M for ORD departures. The metroplex airspace is de-conflicted by the introduction
of RNP approach to runway 13C at MDW. The ratio of the potential benefits (reduction in additional costs) between airlines at MDW and ORD is 1:33 in favor of ORD departures (non-equipped operators) as a result of the de-confliction. Therefore, there is no competitive advantage for airline at MDW to equip with RNP approach capability. However, the successful de-confliction of Chicago metroplex relies on achieving complete equipage for airlines operating at MDW.

The methodology is applied to perform arrival flow analysis at MDW to compare the performance of the new RNP approach to the conventional approach procedure in order to assess the benefits of the new procedure to the metroplex and to individual airlines. The RNP approach to 13C burns 14% less fuel than the corresponding ILS approach and 25% more fuel than the corresponding visual approach on an average. This limits the benefits of the current RNP approach to runway 13C to the IMC days (1.6% of the time).

Also, without efficient merging and spacing, the benefits of precise curved path RNP approach are not completely achieved as the "vectors" between the final waypoint on the STAR and the start of the RNP approach introduce as much variation in flight tracks as the ILS flows.

The methodology also enables the evaluation of the introduction of additional RNP approach procedures to other runways at MDW. This has the potential of saving on average 660K gallon per year of fuel for arrivals at MDW. At $3/gallon this amounts to a savings of $1.97M per year.

The analysis also identifies an opportunity to select optimal runway configuration at MDW based on wind magnitude/direction and flow fuel burn efficiency. The use of
optimal runway configuration along with the additional RNP approach procedure has the potential of saving on average 890K gallons per year of fuel for arrivals at MDW. At $3/gallon this amounts to a savings of $2.67M per year.

The results from the analysis are used to estimate the ROI of investing in RNP approach for the major carrier (Southwest Airlines) at MDW. The results show the RNP approach does not yield a positive ROI for Southwest Airlines at MDW. The carrier will have to perform at least half a million RNP approaches per year throughout its network, saving at least 33 kg of fuel per approach on average to break-even in 10 years at a discount rate of 5%.

In conclusion, from an airline perspective (Southwest), the benefits of equipping with RNP approach capability for a single airport (MDW) does not yield a positive ROI. Also, for metroplex markets in which airlines compete there is no competitive advantage in equipping due to the free rider issue. In the case of Chicago metroplex, the competing airlines at ORD get up to 33 times more benefits compared to airlines at MDW from the de-confliction of flows in the metroplex airspace. This amount to 1:9 ratio per flight.

1.8 Strategies to Equipage of RNP
The market based approach relies on the inherent benefits of a technology to sell itself and achieve the desired equipage. In the case of metroplex flow de-confliction and RNP approach capability there are three major issues that negate the benefits of the RNP approach: (a) the terminal area vectoring for merging and spacing required to ensure safe separations, (b) limited potential use of the approach capability i.e. limited to IMC days as fuel burn performance of visual approaches are better than RNP approaches in most
cases and (c) the free rider issue i.e. the asymmetric benefits to the competition serving the market. These issue and the high costs of equipage result in low ROI for the airlines.

Operational incentives can be provided to early adopters of the technology to overcome the free-rider issue, however these have limited scope. For instance, as a part of the FAA’s Best Equipped Best Served (BEBS) program, a proposal to provide operational incentives in the form of priority arrival slots to equipped operators during traffic flow management initiatives (TMIs) like ground delay program (GDP) was investigated (AhmadBeygi, Bromberg, Elliott, Lewis, & Sud, 2013). Implementation of such TMIs will need new decision support tools and the associated training for the controllers to manage the duration of the program and allocation of slots based on the level of equipage. Also, the priority system will create equity issues for non-equipped operators resulting from excess delay allocation and will increase overall NAS delays due to network wide delay propagation (as a result of large delays for some flights). For example, 15 minutes for four flights can be more easily absorbed by the network than 1 hour delay for a single flight.

In cases of market failure, a theoretical case can be made to provide financial incentives to airspace system users to equip with costly avionics (Post, Wells, Bonn, & Ramsey, 2011). In the case of RNP, the benefits of the operational changes, while disproportionate, not only benefit the equipped operator but also other operations and the system as a whole. This asymmetry in distribution of benefits causes market failure. In such cases financial incentives can be provided to defray the cost of avionics. The financial incentives can be use of public funds, or creation of a tax pool that would tax
every stakeholder proportional to the benefits accrued from the operational change. This will require accurate estimates of benefits to individual stakeholders, which can be done using this methodology.

Finally, the last option in the interest of modernization is to mandate the equipage. A federal mandate will ensure modernization of NAS required to meet the future demand (necessary for the growth of the nation). However, for metroplex flow de-confliction a mandate is not economically feasible. The overall cost to equip is higher than the additional airline operating cost due to metroplex flow conflict by orders of magnitude. The additional airline operating cost due to flow conflict at Chicago and New York are $4.5M and $3M (Devlin et al., 2012); whereas the cost to airlines to equip with RNP approach capability is in the hundreds of million ($175M for Southwest Airlines). Also the lack of RNP approaches will restrict the use and the potential benefits of the approach capability. For instance, at Chicago metroplex the airlines at ORD will not have any direct benefits from equipping unless new procedures are put in place to make use of the capability. Therefore, before a mandate to equip for RNP approaches is made the following key issues need to be addressed:

a. The air navigation service providers (ANSPs) must design and approve RNP approaches to all possible runways at all major airports for airlines to use.

b. The ANSPs must train air traffic controllers to smoothly merge and space aircraft at the start of the RNP approach.
1.9 Potential Applications of the Methodology

1.9.1 Analysis tool
The development of the capability to conduct benefits assessment of new concepts-of-operations and technologies using surveillance track data coupled with aerodynamic fuel burn models significantly improves the accuracy and reliability of benefits assessments. The methodology presented in this dissertation can be used to develop an analysis tool that can be used by policy-makers (Air Navigation Service Providers) and investors (Airlines) to better understand where the costs and benefits are accrued.

1.9.2 Optimal Runway Configuration
The Optimal Runway Configuration model built as a part of the methodology can be used in determining the optimal runway configuration for the tower control manager at the airports (see Figure 5). In current practice the runway configuration is determined based only on the wind direction. An alternate approach is to select optimal runway configuration by ranking a set of feasible (for the given wind and meteorological conditions) runway configurations based on the weight average fuel burn for runways and selecting the runway configuration with the lowest (best) terminal area fuel burn performance. The results of the dissertation show that there is potential for further fuel saving using this approach.
Figure 5: Current method for Airport runway configuration use only wind information. The proposed new method uses wind, traffic volume on each flow and estimated fuel burn.
CHAPTER 2: LITERATURE REVIEW

This chapter is organized as follows: section 2.1 describes the metroplex, the flow conflict at metroplexes and the metroplex de-confliction Con-Ops; section 2.2 reviews the previous research on metroplex air traffic flow analysis; section 2.3 reviews previous research on terminal area flow analyses using track data; section 2.4 reviews previous research on aircraft fuel burn analyses using track data; section 2.5 reviews RNP deployment worldwide; section 2.6 describes the challenges with achieving RNP equipage and the potential for use of a mandate for achieving airline equipage; and section 2.7 provides a summary of literature review and the key gaps in the literature.

2.1 Metroplex Definition

The term “metroplex” was first coined and copyrighted by North Texas Commission (NTC) in 1972, to refer to the larger metropolitan area around Dallas and Fort Worth in Texas (NTC, 2013).

The Joint Planning and Development Office\(^3\) (JPDO), defines metroplex as a group of two or more adjacent airports whose arrival and departure operations are highly interdependent (JPDO, 2007; pg B-6).

The Federal Aviation Administration (FAA) defines metroplex as a geographic area covering several airports serving major metropolitan areas and a diversity of aviation

\(^3\)JPDO was created to manage the implementation of Next Generation Air Transportation System (NextGen) in the United States (U.S)
stakeholders such as National Airspace System (NAS) users, FAA, and other lines of business and airport operators (FAA, 2012e). As a part of the NextGen improvement program called the Optimization of Airspace and Procedures in the Metroplex (OAPM), the FAA has identified 21 metroplexes (Table 2) in the U.S.

Metroplexes are a critical component of the air transportation system and the economy. The 33 ASPM\(^4\) airports at these 21 metroplexes account for more than 48% of the total operations in the NAS’s hub\(^5\) airports (FAA, 2012f). The metropolitan regions these airports serve account for 35% (United States Census Bureau, 2012) of the nation’s population (314 million as of 2012) and 44% (U.S. Department of Commerce, 2012) of the gross domestic product (U.S GDP in 2012 was $15.68 trillion).

Table 2: Metroplexes in the U.S, number of major airports in the metroplex, Operations per day, Population and Gross Domestic product.

<table>
<thead>
<tr>
<th>Sl.no</th>
<th>Metroplex</th>
<th># of ASPM Airports</th>
<th>Ops per day - ASPM 2012</th>
<th>Population-Year 2012</th>
<th>Gross Domestic Product - Year 2012 in $</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>New York</td>
<td>3</td>
<td>3257</td>
<td>1.98E+07</td>
<td>1.36E+12</td>
</tr>
<tr>
<td>2</td>
<td>Chicago</td>
<td>2</td>
<td>3055</td>
<td>9.52E+06</td>
<td>5.71E+11</td>
</tr>
<tr>
<td>3</td>
<td>Los Angeles</td>
<td>4</td>
<td>2797</td>
<td>1.31E+07</td>
<td>7.66E+11</td>
</tr>
<tr>
<td>4</td>
<td>Atlanta</td>
<td>1</td>
<td>2542</td>
<td>5.46E+06</td>
<td>2.95E+11</td>
</tr>
<tr>
<td>5</td>
<td>District of Columbia</td>
<td>3</td>
<td>2434</td>
<td>5.86E+06</td>
<td>4.49E+11</td>
</tr>
<tr>
<td>6</td>
<td>Dallas</td>
<td>2</td>
<td>2236</td>
<td>6.70E+06</td>
<td>4.20E+11</td>
</tr>
<tr>
<td>7</td>
<td>San Francisco</td>
<td>3</td>
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<td>4.46E+06</td>
<td>3.60E+11</td>
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<tr>
<td>8</td>
<td>Miami</td>
<td>2</td>
<td>1734</td>
<td>5.76E+06</td>
<td>2.74E+11</td>
</tr>
</tbody>
</table>

\(^4\) The Aviation System Performance Metrics (ASPM) database system currently provides detailed data on flights to and from the ASPM airports (currently 77) (ASPM System Overview, 2012).

\(^5\) U.S airports that have .05% or more of the total passenger boarding per year (FAA, 2012a)
2.1.1 Metroplex Flow Conflict

A key determinant of the airspace capacity serving a metropolitan area with multiple airports is the extent of interaction between arrival and departure flows between the airports. The airports for some “metroplexes” are geographically located such that under certain wind and weather conditions, there exist conflicts between the flows (Atkins, 2008; Clarke et al., 2011; Devlin et al., 2012). This results in excess costs from ground holding for departures and airborne holding for arrivals to resolve the conflict temporarily.

The U.S metroplexes that have interdependent or coupled arrival and departure flows are New York, Chicago, Los Angeles, Dallas, San Francisco and Miami (Clarke et al., 2011).

The New York Metroplex contains three major commercial airports - Newark Liberty International Airport (EWR), John F. Kennedy International Airport (JFK) and LaGuardia Airport (LGA), as well as, another major general aviation airport— Teterboro.
Airport (TEB)—within a circle of radius 10 nm. New York airspace is the most complex metroplex in the U.S. The configuration and operations of the airspace depend on the runway configurations at the various airports within the metroplex (Clarke et al., 2011). For instance, landing on runway 13L is a frequent and favored operation at JFK using the Parkway visual approach (FAA, 2012h). When the visual approach must be discontinued, air traffic controllers can ILS approach to runway 13L. This approach, however, has many impacts on the other New York City airports. The final approach segment for the ILS approach is much longer than the visual final approach and it conflicts with LGA’s airspace. This forces LGA to use runway 13 for arrivals and creates a conflict between LGA and TEB arrivals allowing only one of the two airports to receive arrivals at a time. Due to these conflicts, JFK ILS 13L approach is rarely used, only being implemented when strong southeast winds eliminate the possibility of using any other runways for arrivals (AhmadBeygi et al., 2013).

The Chicago metropolitan area includes two OEP airports - Chicago O’Hare International Airport (ORD) and Chicago Midway International Airport (MDW)—less than 15 nm from each other. During low ceiling and visibility, and winds from the south east direction, aircraft arriving at MDW are required to use the Instrument Landing System (ILS) on runway 13C. The ILS approach to 13C starts 10.1 NM from the runway threshold and interferes with departures from runway 22L at ORD. This is overcome by tactical time sharing of the common airspace resulting in ground delay for ORD departures and airborne holding for MDW arrivals.
The Los Angeles metroplex has Los Angeles International Airport (LAX) and three airports - Van Nuys Airport (VNY), Long Beach Airport (LGB) and John Wayne-Orange County Airport (SNA) – within 20 NM of each other. The close proximity of these airports causes their arrival and departure paths to cross over and under each other and some of the airports also compete for arrival and departure fixes (Clarke et al., 2011).

The Dallas metroplex has two airports – Dallas Fort Worth International Airport (DFW) and Dallas Love Field airport (DAL) – less than 15 miles of each other. The runway configurations at DFW and DAL are typically aligned, therefore simultaneous visual departures from DAL are not allowed in north flow because their departure paths head toward the DFW departure paths (Clarke et al., 2011). When using instrument-landing-system (ILS) approaches in south flow, only a single stream of arrivals to DAL is allowed to avoid dependency with DFW arrivals because the extended final approach courses of the two airports converge (Clarke et al., 2011).

The Miami Metroplex has two OEP airports - Miami International Airport (MIA) and Fort Lauderdale–Hollywood International Airport (FLL) - within 20 NM of each other. The two airports have interdependent procedures due to their close proximity. However, traffic volume at airports in this metroplex is relatively moderate as compared with many other metroplexes and therefore the dependencies are less severe (Clarke et al., 2011).

2.1.2 Metroplex De-confliction Con-Ops
Metroplex flow conflicts can be resolved temporally or spatially. Further, the temporal or spatially de-confliction can be tactical (short-term) or strategic (long-term) (Clarke et al., 2011).
The tactical-temporal approach involves air or ground holding and speed adjustments by air traffic control (Clarke et al., 2011). The tactical-spatial approach involves vectors (horizontal and/or vertical) by air traffic control (Clarke et al., 2011). The tactical approaches are short term fixes and result in reduced safety margin and an increase in controller workload and costs of operations for the airlines.

The strategic-temporal approach involves NAS wide four dimensional trajectory (4D-T) schedule optimization that de-conflicts aircraft trajectory by assigning each aircraft a Required Time of Arrival (RTA) at the conflicting fixes (Clarke et al., 2011). The flows of aircraft are de-conflicted as long as each aircraft is able to meet its RTA.

The strategic-spatial approach involves redesign of airspace around the metroplex to de-couple conflicting procedures (Clarke et al., 2011). This can be achieved through design of new precise curved path PBN procedure for terminal airspace called RNP 0.3 approach with Radius to Fix (RF) leg. The “RNP 0.3” is the level of performance required for the approach i.e., the aircraft are required to maintain centerline within 0.3 nautical miles (NM) 95 percent of the time and twice the RNP value, or 0.6 NM, 99.999 percent of the time, and the RF leg refers to the curved path between two fixes (see Figure 2). Using the RNP 0.3 approach with RF leg, aircraft are contained along a precise curved path allowing safe navigation near high terrain, obstacles and airspace occupied by other flows of air traffic (Ray, 2013).

To fly the RNP0.3 w/RF leg approach procedure an aircraft should be equipped with Global Positioning System (GPS) with Approach Capability, or RNP capable Flight Management Computer (FMC). The FMC should be capable of using both ground based
navigation aids such as Distance Measuring Equipment (DME) and space-based GPS. It should also be capable of displaying the RF legs (Jeppesen Briefing Bulletin, 2005).

The FAA has implemented an RNP approach with RF leg at Midway International Airport (MDW) to de-conflict the Chicago metroplex (for details see section 1.1) and is currently testing the curved path RNP approach at John F Kennedy International Airport (JFK) to de-conflict flows at the New York metroplex (FAA, 2012h).

2.2 **Review of Metroplex Analyses**

Research related to the metroplex flow analysis is categorized as follows:

1. Metroplex Flow Conflict Analysis Methodology
2. Metroplex De-Confliction Benefits Metrics

2.2.1 **Metroplex Flow Conflict Analysis Methodology**

Metroplex flow conflict analysis and de-confliction benefits analysis have been conducted using simulated de-coupled routes (Clarke et al., 2011) and low fidelity operational data (Devlin et al., 2012; Donaldson & Hansman, 2011). The high fidelity surveillance track data is used to estimate excess path length flown by aircraft as a result of the flow conflict (Atkins, 2008) and to visualize the interaction between the various flows at the metroplex (Atkins, 2008; Donaldson & Hansman, 2011).

Metroplex flow conflicts have been analyzed at New York (Clarke et al., 2011; Devlin et al., 2012; Donaldson & Hansman, 2011), San Francisco (Atkins, 2008) and Chicago (Devlin et al., 2012) metroplexes.
Clarke et al (2011) identify two strategies, temporal and spatial, to de-conflict New York metroplex operations. The benefits of de-conflicting the airspace using the temporal strategy is done using a scheduling algorithm that determines nominal fix-crossing and departure time to de-conflict flows temporarily. The benefits of de-conflicting the airspace using the spatial strategy is estimated using simulated de-couple routes. The simulation is performed using the New York Airport and Airspace Delay Simulation Model (SIMMOD).

Donaldson & Hansman (2011) analyze New York metroplex using airport operational data (ASPM) to quantify the inefficiencies found in different configurations, and the track data is used to identify the procedures that are likely constraining the airspace. The research prescribes a methodology to identify bottlenecks and their effect on capacity at metroplex airports. The analysis shows that the capacity of the metroplex is lower than the sum of the runway capacities of individual airports in the metroplex and that this capacity gap is due to conflict of flows in the metroplex airspace.

Devlin et al (2012) estimates the Airline Direct Operating Cost (ADOC) due to flow conflicts at New York and Chicago metroplexes. The analysis is conducted by using the airport configuration and weather information in the ASPM data. The data is used to identify time periods when airspace conflicts. The total minutes of arrival and departure delay and the number of cancelled flights are computed for the conflict periods. These are compared to the delays and cancelled flights during similar calendar and schedule time periods when the airspace conflict did not occur. Finally, the Airline Direct Operating
Cost (ADOC) due to the excess delay and cancellation as a result of airspace conflict are estimated.

Atkins (2008) analyzes San Francisco metroplex to generalize metroplex phenomenon i.e. interdependencies and sharing of resources (airspace, fixes, and routes) between proximate airports that result in reduced capacity or efficiency (Atkins, 2008). A detailed description of the operational issue at the San Francisco metroplex for two commonly used flows patterns, the West Plan and the South-East Plan is described. The analysis is conducted using the Enhanced Traffic Management System (ETMS) track data, using the Surface Operations Data Analysis and Adaptation (SODAA) tool. The ETMS data is used to visualize various flows in the San Francisco metroplex and to compute excess path length flown by aircraft as a result of flow conflict.

2.2.2 Metroplex De-confliction Benefits Metrics

The costs of metroplex flow conflicts and the potential benefits associated with the de-confliction have been analyzed from a system-wide perspective (Clarke et al., 2011; Devlin et al., 2012).

The costs of metroplex flow conflict have been expressed in terms of total Airline Direct Operating Cost (ADOC) per year (Devlin et al., 2012). The additional ADOC at New York metroplex (due to flow conflict between JFK and LGA) is $751,100 at JFK and $2,268,100 at LGA (Devlin et al., 2012). The additional ADOC at Chicago metroplex (due to flow conflict between MDW and ORD) is $275,000 at MDW and $4,365,000 at ORD (Devlin et al., 2012)
The benefits of de-coupling metroplex flows have also been expressed in terms of reduction in system-wide delays and fuel burn (Clarke et al., 2011). At New York metroplex the benefits of de-coupling the airspace spatially and temporarily is estimated using simulated de-couple routes using the New York Airport and Airspace Delay Simulation Model (SIMMOD). The results show that when applied separately the spatial and temporal de-confliction result in delay reduction of 28% and 60% respectively. Combined together the hybrid de-confliction resulted in delay reduction of 79% (Clarke et al., 2011). The de-coupled routes resulted in a system-wide fuel burn savings of 11%. The fuel burn benefits are computed using time in mode method, which assumes constant fuel burn rate for a given mode (descent, climb, and cruise) (Clarke et al., 2011)

2.2.3 Need for Analysis using High Fidelity Surveillance Track Data
The successful implementation of the metroplex de-confliction Con-Op (i.e., using new precise curved path PBN approach procedures to spatially de-couple conflicting metroplex flow) relies on achieving the airline equipage at the metroplex airports. Airlines invest in equipage for two reasons: (a) if the benefits of the equipage yield an acceptable ROI and (b) if equipage is required to meet regulatory requirements.

The metroplex flow conflict analyses have been performed from a system wide perspective and not from an individual airline’s benefit perspective (Atkins, 2008; Clarke et al., 2011; Devlin et al., 2012; Donaldson & Hansman, 2011). The benefits and ROI from investing in the new PBN approach capabilities to individual airlines have not been analyzed. This is an oversight as airlines make investment based on their benefits and not system-wide benefits.
The metroplex flow de-confliction benefits analysis have been performed using simulated de-coupled routes (Clarke et al., 2011) or low fidelity operational data (Devlin et al., 2012). They do not capture the interaction between conflicting flows and their associated costs. The cost of airborne holding as a result of the metroplex flow conflict has not been analyzed and quantified.

The primary benefits of the precise curved path PBN approach procedures to individual airlines is in fuel burn savings from more shorter and more efficient trajectories in the terminal airspace. To compute the fuel burn savings of these approach procedures, the actual trajectories of aircraft in the terminal airspace must be taken into consideration.

There is a lack of a systematic approach to quantify the potential savings in fuel burn to airlines in using new PBN (RNP approach) approach procedures instead of conventional approaches. An assessment of benefits of fuel burn savings from RNP approach requires detailed track flow analysis that compares performance of RNP approach flows to convectional flows.

There is a need for a detailed analysis using high fidelity surveillance track data that captures real-world complexity of traffic flows and aircraft trajectories, characterizes terminal area flows and compares flows using statistics of flow performance metrics (i.e. track distance, time, fuel burn in the terminal airspace).

2.3 **Review of Track Flow Analyses**

The National Offload Program (NOP) data has flight track data for Terminal Radar Approach Control Facilities (TRACONs). The flight track data contains an
identifying flight number and flight status (arrival, departure, or overflight), as well as, position reports of latitude, longitude, altitude, and time-of-report (DeArmon et al. 2011).

A sample plot of Chicago TRACON (C90) NOP track data is shown in Figure 6. The metroplex terminal operations are a complex interaction of flows. To understand the effects of these interactions the individual flows at metroplex airports need to be analyzed. This section reviews existing research in the area of terminal track flow analysis to identify gaps in the existing methodology for characterizing and computing performance metrics for terminal area air traffic flows.

Figure 6: Traffic flow interaction at Chicago Metroplex
Levy (2003) presents a methodology for the mathematical characterization of three-dimensional airspace traffic flows from flight position data (Levy, 2003). The methodology uses the mean and the standardized skew of Normalized Cross-Track Distance (NCTD) to rank tracks and pick a typical track (or back bone) characterizing a flow. The NCTD is defined as the ratio of the cumulative cross-track distance and track-line distance. The NCTD value compares the tracks with the typical track to identify the traffic pattern. Three traffic patterns are defined based on the efficiency of the tracks, ‘expedite’, ‘nominal’ and ‘delay’. Statistics are reported for each traffic pattern in terms of the NCTD rank and, the length, duration and ground speed of the tracks. The analysis identifies and compares traffic patterns within a flow; it does not extend the methodology to compare traffic patterns between different flows.

Dorfman et al (2012) analyze the vertical profile flight tracks using track data (Dorfman et al., 2012). The flows are defined by a start point and an end point (referred to as way-triangles in the analysis) and all tracks that pass through the start and the end point are assigned to the flow. The analysis highlights inefficiencies and potential for improvements in the vertical profiles of aircraft. The analysis does not compute cost of level off in terms of fuel burn and does not compare various flows in the terminal area.

Vempati & Ramadani (2012) present a methodology to measure the utilization of procedures implemented across the National Airspace System (NAS) (Vempati & Ramadani, 2012). The flight tracks are assigned to a procedure by checking the vertical and lateral proximity of the track to the published procedures along the track length. The paper focusses on the accuracy with which a flight track is assigned to a procedure. The
assignment count is validated against the pilot-controller voice communications, the airline reported RNP usage and the scratch pad tally maintained as the TRACON. The analysis does not compute performance metric for the flow, nor does it analyze the relative performance of flow with respect to each other.

Enriquez (2013) presents a methodology identifying temporally persistent flows in the terminal area via spectral clustering (Enriquez, 2013). Spectral clustering uses graph partitioning approach to accomplish the grouping of flights. The paper explains the application and challenges of applying spectral clustering to group flight tracks into flows. The clustering algorithm is sensitive to the values of the clustering tolerance and requires calibration. The application of the methodology is limited to identifying irregular terminal operations, detecting flows that do not adhere to any of the published procedures and recommending a need to publish more RNAV procedures.

Gariel, Clarke, & Feron (2007) describe a methodology to analyze impact of TRACON capacity on terminal area delay and airport efficiency (Gariel, Clarke, & Feron, 2007). The analysis uses track data to estimate the arrival rate of aircraft in the TRACON, the number aircraft vectored in the terminal area and the delays associated with vectoring. These estimates are then used to build and calibrate a TRACON queuing and landing simulation model, which evaluates the impact of TRACON capacity on terminal area delays and airport efficiency. The analysis is limited to estimating delays and runway utilization as a function of TRACON capacity.

In summary the research on terminal flow analysis so far is limited to clustering of track data into flow. The methodologies have not been extended to computing
performance metrics (in particular fuel burn) for terminal flow. Also, there is lack of a systematic approach in characterizing terminal area flows for comparing the performance of new PBN approach procedures with conventional approach procedures. The key benefit of new PBN approach to airlines is in terms of fuel burn savings. The next subsection review existing research on fuel burn analyses.

2.4 Review of Fuel burn analyses

Fuel costs currently constitute the largest fraction (29%) of an airline’s operating cost (A4A Cost Index, 2012); therefore, it is important to evaluate and compare performance of terminal area flow using fuel burn estimates. This section presents a review of research on aircraft fuel burn analysis.

The fuel burn benefits of de-coupled metroplex airspace are computed using the standard fuel burn rate in the Landing and Takeoff (LTO) cycle of the International Civil Aviation Organization (ICAO) (Clarke et al., 2011). The ICAO fuel burn model uses a linear time-in-mode method, which assumes constant fuel burn rate and a standard duration (time) for a given mode (descent, climb, and cruise). The fuel burn for each aircraft type is estimated as the product of standard fuel burn rate and time for a given mode.

A comparison of the actual fuel burn information from aircraft’s flight data recorder (FDR) and the ICAO model shows that total fuel burn for both departures and arrivals is overestimated by the ICAO method (i.e., actual fuel burn is between 70-85% of the ICAO maximum for each engine) (Patterson, Noel, Senzig, Roof, & Fleming, 2009). The comparative analysis is based on data collected for 2824 flight records, from 5
different airlines, with 14 unique engine combinations. The result suggests that while using ICAO method may be appropriate in comparative policy analyses, it is not suitable for comparing performance of flow in the terminal area, which has a tremendous variety in track profile of flow patterns.

Fuel burn for terminal area flows can be estimated within ±5% actual fuel consumption using a regression model to estimate the thrust specific fuel consumption (Senzig, Fleming, & Iovinelli, 2009). The co-efficient of the regression expression are estimated for each airframe/engine combination based on aircraft performance data for an expected range of terminal-area operations. However, the use of this approach is limited by the availability of accurate fuel burn data required to accurately estimate the regression coefficients.

An aerodynamic model that uses actual flight trajectory, standard fuel flow and drag models can estimate fuel burn for terminal area flows within ±5.4% of the actual value (Chatterji, 2011). This is provided accurate information is available for the wind, flight’s position report and initial mass (Chatterji, 2011).

In summary a review of research on fuel burn model suggest that using standard time in mode and fuel burn rate will fail to capture the variation the vertical and lateral profile of terminal flows. The primary benefits of the precise curved path PBN approach procedures to individual airlines is in fuel burn savings from more shorter and more efficient vertical trajectories that do not level off in the terminal airspace. Using a hybrid fuel burn model that uses high fidelity surveillance track data coupled with aerodynamic models and weather data will capture the benefits of more shorter and efficient PBN
approach procedures in the terminal airspace. The level accuracy of the fuel burn model based on actual trajectory provides enough motivation to use them in estimating and comparing performance of terminal flows

2.5  **Review of RNP deployment world wide**

This section describes worldwide deployment of RNP approach. The deployment of RNP approach procedures in the U.S, Canada, Australasia, Asia, Europe and South America are described in the following subsections. The benefits gained from implementation of RNP are summarized in the last subsection

2.5.1  **RNP deployment in the United States**

A summary of RNP approach deployment in the U.S is shown in Table 1. The RNP approach was first used in 1996 at Juneau Airport in Alaska by Alaska Airlines to improve access and schedule reliability (FAA, 2009). The approach at Juneau during bad weather using conventional ground-based instrument landing system (ILS) approach (requiring long unobstructed approach path) was not possible due to the tightly encircled mountains. The RNP approach allowed aircraft to navigate with increased precision around the high terrain and to the final approach of the runway.

In 2002, Horizon Airlines, a subsidiary of Alaska Airlines, initiated implementation of RNP approach procedures for airports in its network (Aviation Today, 2002). Horizon is a regional carrier in the northwestern United States. It operates from airports in mountainous terrain that are situated around its hubs, Seattle-Tacoma International Airport (SEA) and Portland International Airport (PDX). The use of RNP
for approaches resulted in increased access, lower approach minima and schedule reliability at all its airports.

<table>
<thead>
<tr>
<th>Year</th>
<th>Airline</th>
<th>Fleet Type</th>
<th>Location</th>
<th>Issue</th>
<th>Benefit type</th>
<th>Benefit Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996</td>
<td>Alaska Airlines</td>
<td>737-700,-900,-400,-200QC, MD-80</td>
<td>Started at Juneau, Alaska</td>
<td>Terrain, Bad weather</td>
<td>Increased Access - Lower Approach Minima, DA, Schedule Reliability</td>
<td>-</td>
</tr>
<tr>
<td>2002</td>
<td>Horizon Airlines</td>
<td>Dash 8, CRJ 700</td>
<td>Horizon's network</td>
<td>Terrain, Bad weather</td>
<td>Increased Access - Lower Approach Minima, DA, Schedule Reliability</td>
<td>-</td>
</tr>
<tr>
<td>2007</td>
<td>Southwest</td>
<td>737NG, 737Classics</td>
<td>Southwest hubs (BWI, MDW, DAL, LAS, HOU, PHX)</td>
<td>Operational inefficiency</td>
<td>Operating Cost, Schedule Reliability</td>
<td>-</td>
</tr>
<tr>
<td>2009</td>
<td>ConocoPhillips</td>
<td>737-700</td>
<td>Deadhorse, Alaska</td>
<td>Terrain, Weather</td>
<td>Increased Access</td>
<td>12650 gallons of fuel, 250 tons of CO2 reduction per year</td>
</tr>
<tr>
<td>2012</td>
<td>JetBlue</td>
<td>A320</td>
<td>KJFK, New York</td>
<td>Operational inefficiency</td>
<td>Operating Cost, Schedule Reliability</td>
<td>18 gallons fuel savings per flight</td>
</tr>
</tbody>
</table>
In 2007, Southwest Airlines contracted with GE Aviation – formerly Naverus – to develop tailored RNP approach procedures for all its operations. The cost of this transformation is estimated at $175 million (Hughes, 2008). The RNP approach so far had been adopted by airlines operating at terrain challenging high altitude airports to increase access and improve schedule reliability. Southwest Airline is the first airline to implement RNP approach with goal of reducing fuel burn and emissions, by having more efficient approaches compared to the conventional approaches.

In 2009, ConocoPhillips Airlines implemented RNP approach for its operations into Deadhorse Airport (PASC), Alaska. Depending on the runway in use, the new procedures were reported to reduce CO₂ emissions by at least 250 tons and jet fuel consumption by at least 12,650 gallons annually (GE Aviation, 2011).

In 2012, as a part of the joint venture with FAA, JetBlue conducted test flight into JFK using an RNP approach on to runway 13L. The precise curved path approach procedure cuts corner on the final approach and is expected to reduce fuel burn by 18 gallons per flight (Aviation Today, 2012b).

2.5.2 RNP deployment in Canada
RNP approach was first implemented in Canada, at Kelowna International Airport (CYLW) in 2003, by WestJet. Like Alaska, airports in Canada are affected by terrain and weather. The implementation of RNP approach at CYLW resulted in 41 Nautical Miles (NM) track-miles savings per flight (GE Aviation, 2011). This corresponds to 0.5 tons of fuel savings and 1.6 tons of CO₂ reduction per flight. WestJet currently has about 50 RNP
approaches into 18 airports in Canada. These procedures save on average 10 track-miles per flight (GE Aviation, 2011).

<table>
<thead>
<tr>
<th>Year</th>
<th>Airline</th>
<th>Fleet Type</th>
<th>Location</th>
<th>Issue</th>
<th>Benefit type</th>
<th>Benefit Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>WestJet</td>
<td>737-600, 700,-800</td>
<td>Started at Kelowna, Canada</td>
<td>Terrain restricted ILS DA, Weather</td>
<td>Lowered DA by 310 feet, fewer diversion in bad weather.</td>
<td>41 NM track mile saving, 516kg of fuel, 1.6 ton CO2 reduction.</td>
</tr>
</tbody>
</table>

### 2.5.3 RNP deployment in Australia

RNP approach was first implemented in Australasia, at Queenstown International Airport (NZQN) in 2004, by Air New Zealand and Qantas (GE Aviation, 2011). The goal of implementing the RNP approach was to improve schedule reliability, which was affected by the terrain and weather at NZQN. The RNP approach resulted in 11NM track-miles savings per flights. This corresponds to 0.2 ton of fuel savings and 0.6 tons of CO₂ reduction per flight (GE Aviation, 2011).

<table>
<thead>
<tr>
<th>Year</th>
<th>Airline</th>
<th>Fleet Type</th>
<th>Location</th>
<th>Issue</th>
<th>Benefit type</th>
<th>Benefit Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>Air New Zealand</td>
<td>A320s</td>
<td>Queenstown, New Zealand</td>
<td>Terrain, Bad weather</td>
<td>New DH 250ft, Schedule Reliability</td>
<td>11NM track mile saving per procedure, 192kg of fuel saving, 603kg of CO2</td>
</tr>
<tr>
<td>Year</td>
<td>Aircraft</td>
<td>Location</td>
<td>Issue</td>
<td>Solution</td>
<td>CO2 Reduction</td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>----------</td>
<td>----------</td>
<td>-------</td>
<td>----------</td>
<td>---------------</td>
<td></td>
</tr>
<tr>
<td>2004</td>
<td>Qantas Airways 737s</td>
<td>Queenstown, New Zealand</td>
<td>Terrain, Bad weather</td>
<td>New DH 250ft, Schedule Reliability</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>2006</td>
<td>Qantas and Others 737s</td>
<td>Brisbane, Australia</td>
<td>Operational inefficiency</td>
<td>Successful sequencing of RNP and Non-RNP flights</td>
<td>2.6 minutes saved per flight, 126kg of fuel, 390kg of CO2 reduction</td>
<td></td>
</tr>
</tbody>
</table>

In 2006 Brisbane Green project was initiated by Airservices Australia in collaboration with GE Aviation, Qantas Airways and Civil Aviation Safety Authority of Australia (CASA). The goal of this project was successful sequencing of RNP and Non-RNP flights into Brisbane Airport (YBBN). The new procedure saved on an average 2.6 minutes per flight (Airservices Australia, 2008). This resulted in 126 kg fuel savings and 390 kg CO2 reduction per flight.

### 2.5.4 RNP deployment in Asia

In 2007, Chinese Airlines in Asia started to use RNP approaches to improve access and schedule reliability at in high altitude airports in Tibet and China. In 2009, China Southern became the first airline to use tailored RNP approach for a wide-body (A330) aircraft into Lhasa airport (LXA), a mountainous high altitude airport (GE Aviation, 2011)
### Table 6: RNP deployment in Asia

<table>
<thead>
<tr>
<th>Year</th>
<th>Airline</th>
<th>Fleet Type</th>
<th>Location</th>
<th>Issue</th>
<th>Benefit type</th>
<th>Benefit Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>Air China</td>
<td>A319</td>
<td>Linzhi, Tibet</td>
<td>Terrain, Bad weather</td>
<td>Increased Access to Linzhi, Schedule Reliability</td>
<td>-</td>
</tr>
<tr>
<td>2009</td>
<td>China Southern</td>
<td>A330</td>
<td>Lhasa, Tibet</td>
<td>Terrain, Bad weather</td>
<td>Increased Access to Lhasa, First for a wide body aircraft</td>
<td>-</td>
</tr>
<tr>
<td>2009</td>
<td>China Eastern</td>
<td>A319, B737</td>
<td>Lhasa, Tibet, Yushu, China</td>
<td>Terrain, Bad weather</td>
<td>Increased Access to Lhasa</td>
<td>-</td>
</tr>
<tr>
<td>2010</td>
<td>Sichuan Airlines</td>
<td>A319</td>
<td>Lhasa, Tibet, Lijiang, China</td>
<td>Terrain, Bad weather</td>
<td>Increased Access to Lhasa</td>
<td>-</td>
</tr>
<tr>
<td>2012</td>
<td>Eithad</td>
<td>A330-200</td>
<td>Abu Dhabi, UAE</td>
<td>Operational inefficiency</td>
<td>Operating Cost, Schedule Reliability</td>
<td>9% fuel burn savings</td>
</tr>
<tr>
<td>2012</td>
<td>IndiGo</td>
<td>A320</td>
<td>Kochi, India</td>
<td>Operational inefficiency</td>
<td>Operating Cost, Schedule Reliability</td>
<td>400kg fuel saving per flight</td>
</tr>
</tbody>
</table>

In 2012, Eithad Airline became the first airline in the middle-east to use RNP approach. By redesigning the horizontal and vertical flight paths of flights coming from the west, this new technology will reduce noise overflying the city of Abu Dhabi and optimize fuel consumption. Etihad estimates fuel consumption will be reduced between 100 kg and 200 kg per approach, which will result in a reduction of CO2 emissions by at least 20,000 tons per year (Aviation Today, 2012a)
In 2012, Indigo Airline flew its first RNP approach into Kochi International Airport (COK). Indigo is a low cost carrier operating in India. The new procedure is expected to save 400kg of fuel per flight (Air Transport World, 2012).

2.5.5 RNP deployment in Europe and South America

RNP in Europe is driven by the Minimum CO2 in Terminal Maneuvering Area (MINT) project. The first MINT demonstration flight took place on the 16th of June 2009, using the newly developed RNP procedure into Stockholm-Arlanda Airport (ESSA). The new procedure resulted in 20 NM track-mile savings (Euro Control, 2012a).

<table>
<thead>
<tr>
<th>Year</th>
<th>Airline</th>
<th>Fleet Type</th>
<th>Location</th>
<th>Issue</th>
<th>Benefit type</th>
<th>Benefit Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>NovAir</td>
<td>A321</td>
<td>Stockholm Arlanda, Sweden</td>
<td>Operational inefficiency</td>
<td>Operating Cost, Environment</td>
<td>20NM track-mile savings per flight.</td>
</tr>
<tr>
<td>2009</td>
<td>LAN Airlines</td>
<td>A319</td>
<td>Cuzco, Peru</td>
<td>Terrain, Bad weather, Diversion</td>
<td>Increased Access, Schedule reliability</td>
<td>-</td>
</tr>
</tbody>
</table>

LAN airlines deployed RNP approach for its A319 fleet at Cuzco Airport (SPZO) in May 2009. Prior to the deployment of RNP, about 10% of LAN’s arrivals into SPZO would be diverted, due to a combination of poor weather and low visibility coupled with the surrounding rugged terrain (GE Aviation, 2011).
2.5.6 Summary of RNP deployment
The application of RNP for approach provides benefits in terms of improved access, schedule reliability and savings in track miles and fuel burn. For about 70% of the airlines, RNP approach procedures improved access to airports located in mountainous terrain and affected by bad weather most of the time. Redesign of the horizontal and vertical flight paths using RNP 0.3 approach with RF leg can optimize fuel consumption. Depending upon the relative location of the start of the RNP approach with respect to the approach direction, the new procedure can save 10 to 40 nautical miles in the terminal airspace. This corresponds to 20 to 100 gallons of fuel savings and 0.5 to 1.6 tons of CO₂ reduction per flight.

2.6 Achieving Equipage for Required Navigation Performance Approach
The RNP 0.3 approach with RF leg capability is a key enabler for the metroplex de-confliction Concept-of-Operations (ConOps). However, for the ConOps to be fully functional, aircraft must be equipped with the associated avionics (FAA, 2012g).

The challenge for the Federal Aviation Administration (FAA) is that the adoption of RNP approach technology by airlines has been slow and haphazard, as equipping with RNP approach capability is expensive. The FAA estimates the cost of adding the equipment to a new aircraft at the time of purchase is $260,000 and the cost of retrofitting an existing aircraft is $525,000 (FAA, 2012i). The airlines also have to account for cost of training and certification of the crew and the down time associated with retrofitting the aircraft with the new equipment. In addition, the need for collaboration and simultaneous equipage across competing stakeholders and the allocation of benefits to parties that
choose not to equip but gain benefits when their competition equips have created a “modernization stalemate.”

Programs like Best Equipped Best Serve (BEBS) are being developed by the FAA to provide airlines operational incentives to equip with the technology (FAA, 2012h). The proposed operational incentives are in the form of priority arrival slots to equipped operator during traffic flow management initiatives (TMIs) (AhmadBeygi et al., 2013). The proposed TMI identifies periods (on flow conflict days) when equipage based priority can be applied. During these time periods, referred to as exclusionary periods, the metroplex flows are de-conflicted by only allowing equipped aircraft at the airports. This allows metroplex to resume normal operations, but penalizes flights that are not equipped to fly the procedure required to de-conflict the metroplex.

The implementation of such TMIs will need new decision support tools and the associated training for the controller to manage the duration of the program and allocation of slots based on the level of equipage (AhmadBeygi et al., 2013)

2.6.1 Mandate for Achieving Equipage
Airline equipage for improving capacity and/or safety of the NAS has been achieved through mandates. A summary of past modernization mandates are as follows:

The use of Very High Frequency (VHF) radio instead of High Frequency (HF) radio was mandated in 1961 to improve operational efficiency. The mandate requires two-way VHF radio communications for conducting flight operations on and around all controlled airports throughout the country (FAA, 2012b). The VHF radio provides higher
bandwidth and voice clarity. Higher bandwidth means availability of more number of channels, which boosts’ airspace capacity.

Transponders were mandated in 1978. The mandate requires all aircraft operating in Terminal Radar Service Areas (TRSAs) and Terminal Control Areas (TCAs) to have transponders to report identity (Mode A) and altitude (Mode C) installed by July 1981 (FAA, 2012b). An aircraft equipped with a beacon transponder can provide the terminal controller automatically with information on its identity, altitude, range, and bearing. This improves air traffic control service in terms of being able to safely handle higher level of traffic. Under the old system, the controller obtained an aircraft's altitude and identity only through voice contact with the aircraft's pilot.

The Traffic Collision Avoidance System (TCAS) was mandated in 1981 to prevent mid-air collision and improve NAS level of safety (FAA, 2012b). TCAS is a safety monitoring system independent of air traffic control, which monitors the airspace around an aircraft for other aircraft equipped with a corresponding active transponder and warns pilots of the presence of other transponder-equipped aircraft which may present a threat of mid-air collision. In the event of a potential mid-air collision the system also maneuvers the aircraft involved to avoid collision.

The Wind Shear equipage was mandated in 1988 (FAA, 2012b). Wind shear is a difference in wind speed and direction over a relatively short distance in the atmosphere. Presence of wind shear in the final approach to landing results in a decrease in aircraft’s airspeed and an increase in the sink rate. This results in ground contact before the runway threshold (crash landing). The pilot must adjust the airspeed to deal with the effect of
wind shear. The mandate requires all turbine-powered airliners seating 30 passengers or more to carry equipment to warn pilots when they encounter low-altitude wind shear and provide them with information needed to escape safely (FAA, 2012b).

The Reduced Vertical Separation Minima (RVSM) equipage was mandated in the U.S following a mandate in Europe in 2002, to increase capacity of airspace for flight level (FL) 290 to 410. The mandate requires all aircraft and flight crews operating in the NAS between flight level (FL) 290 to 410, to be RVSM compliant as of January 20, 2005 (FAA, 2012g). RVSM certified aircraft uses a certified altimeter which has an Altimetry System Error\(^6\) (ASE) of less than 245 feet (Euro Control, 2012c). The reduced ASE enables the reduction of vertical separation requirement to 1000 feet from a previous requirement of 2000 feet for flight level (FL) 290 to 410. RVSM enhances ATC flexibility, mitigates conflict points, enhances sector throughput, reduces controller workload and enables crossing traffic. Operators gain fuel savings and operating efficiency benefits by flying at more fuel efficient flight levels and on more user preferred routings (FAA, 2012g).

2.7 Summary of Literature Review

The term Metroplex refers to a system of airports serving a large Metropolitan area (FAA, 2012e). The airports in a metroplex are often in close proximity to each other and can have interdependent arrival and departure procedures (JPDO, 2007).

Metroplexes are a critical component of the nation’s economy and the air transportation system. A key determinant of the airspace capacity serving a metropolitan

\(^6\) ASE is the difference between the altitude that the pilot, ground controller and aircraft systems believe the aircraft to be at and the actual altitude
area with multiple airports is the extent of interaction between arrival and departure flows between the airports. The airports for some “metroplexes” are geographically located such that under certain wind and weather conditions conflicts exist between the flows. This results in excess costs from ground holding for departures and airborne holding for arrivals.

Air traffic flows at a metroplex can be decoupled by re-design of airspace (metroplex de-confliction Con-Op) through implementation of new precise curved path PBN procedure for terminal airspace called RNP 0.3 approach with Radius to Fix (RF) leg. Using the RNP 0.3 approach with RF leg, aircraft are contained along a precise curved path allowing safe navigation near high terrain, obstacles and airspace occupied by other flows of air traffic (Ray, 2013).

The successful implementation of the metroplex de-confliction Con-Op (i.e. using new precise curved path PBN approach procedures to spatially de-couple conflicting metroplex flow) relies on achieving the airline equipage at the metroplex airports. Airlines invest in equipage for two reasons: (a) if the benefits of the equipage yield an acceptable ROI and (b) if equipage is required to meet regulatory requirements.

The metroplex flow conflict analyses have been performed from a system wide perspective and not from an individual airline’s benefit perspective (Atkins, 2008; Clarke et al., 2011; Devlin et al., 2012; Donaldson & Hansman, 2011). The benefits and ROI from investing in the new PBN approach capabilities to individual airlines have not been analyzed. This is an oversight as airlines make investment based on their benefits and not system-wide benefits.
There is a need for a systematic methodology that uses *high fidelity surveillance* track data coupled with *aerodynamic fuel burn model* and *weather data* to estimate the efficiencies and costs of metroplex terminal air traffic flows for assessing benefits of associated concept-of-operations and technologies to individual airlines. This dissertation will address these gaps.
3 CHAPTER 3: METHODOLOGY

The recent availability of high fidelity surveillance track data coupled with aerodynamic fuel burn models, and airport wind and weather data have created an opportunity to provide detailed analysis of metroplex traffic flows to include the real-world complexities of traffic flows and aircraft trajectories.

This section describes a holistic methodology that uses high fidelity surveillance track data coupled with aerodynamic models and weather data to quantify the efficiencies and costs of metroplex terminal area air traffic flows.

This methodology is intended for assessing benefits of proposed terminal airspace concepts-of-operations (e.g. metroplex de-confliction using RNP approach) and associated technologies that require simultaneous equipage and development of collaborative procedures by multiple stakeholders (airlines and ANSPs).

An overview of the methodology is shown in Figure 7. The methodology includes the following six functions:

1. Perform terminal area flow analysis: this involves characterizing terminal flows and assigning track data to each flow.

2. Analyze effects of metroplex flow conflict: this includes holding pattern analysis using track data
3. Define performance metrics and estimate the performance of terminal flows and holding patterns: this involves estimating the performance metrics for terminal area flows and holding patterns, in particular the fuel burn using track data and aerodynamic fuel burn model.

4. Estimate the benefits of metroplex airspace de-confliction: this involves identifying the effects of the metroplex flow conflict, annualizing the severity of the effects and estimating the benefits of de-conflicting the metroplex.

5. Estimate the benefits of PBN approach procedures to an airline at an airport: this involves annualizing the benefits of using the new PBN approach procedures to all possible runways at an airport, in addition to using the optimal runway configuration.

6. Estimate the return on investment for the equipped operator: this involves estimating the Net Present Value (NPV) based on the investment made in equipping and the annual benefits from using the new technology.

The first three functions are the building blocks of the overall methodology. These involve analysis of surveillance track data to estimate the track distance/time and fuel burn performance for terminal air traffic flows and holding patterns in the metroplex airspace. These building blocks are used to develop models (in functions four, five and six), that annualize benefits of PBN approaches to the metroplex and the individual airlines.
Figure 7: Overview of the methodology

This chapter is organized as follows: section 2.1 contains a summary of the data sources used; section 3.2 describes a methodology for TRACON arrival flow analysis using track data; section 3.3 describes a methodology for holding pattern analysis; section 3.4 describes a methodology for computing track distance, time and fuel burn using track data; section 3.5 describes a methodology for metroplex de-confliction benefits analysis; section 3.6 describes a methodology for benefits of future PBN approach procedure; section 3.7 describes a methodology for estimating airline’s return on investment for the new PBN approach capability; and section 3.8 contains a summary of the method of implementation.

3.1 Data Sources
This section provides a description of the data used in the model.
3.1.1 ASPM Data
The Aviation System Performance Metrics (ASPM) online access system provides detailed data on flights to and from the ASPM airports (currently 77) and all flights by the ASPM carriers (currently 22), including flights by those carriers to international and domestic non-ASPM airports. ASPM also includes airport weather, runway configuration, and arrival and departure rates. (ASPM System Overview, 2012).

In the methodology, the ASPM data is used to identify days with potential metroplex flow conflict, get airport runway configuration, estimate the count of arrivals and departures get airport weather and wind conditions.

3.1.2 NOP Data
The National Offload Program (NOP) service is operated by the FAA (FAA, 2012c). It collects NAS operational data daily. One of the data items collected is flight tracks for Terminal Radar Approach Control Facilities (TRACONs). Flight tracks contain identifying flight number and flight status (arrival, departure, or overflight), as well as position reports including (latitude, longitude, altitude, and time-of-report) (DeArmon et al. 2011).

In the methodology, the NOP track data is used to estimate the performance of terminal arrival flows at an airport, estimate the cost of holding, and visualize and identify metroplex flow conflicts.

3.1.3 BADA Data
Base of Aircraft Data (BADA) is an Aircraft Performance Model (APM) developed and maintained by EUROCONTROL through active cooperation with aircraft
manufacturers and operating airlines. For more information about BADA refer (Euro Control, 2012b).

In the methodology, the BADA is used to determine the aircraft performance related information i.e., equations and coefficients for aircraft drag, lift, thrust specific fuel consumption and stall speeds required for fuel burn computation.

3.1.4 BTS Airline On-Time Data
The Bureau of Transportation Statistics (BTS) was established as a statistical agency in 1992 (BTS, 2012). The BTS mission is to create, manage, and share transportation statistical knowledge with public and private transportation communities and the Nation (BTS, 2012).

In the methodology, BTS airline On-time data is used to compute the number of excess cancelled flights as a result of metroplex flow conflict.

3.1.5 NFDC Data
The National Flight Data Center (NFDC), within the Aeronautical Information Management (AIM) directorate of Mission Support Services, is the central authority and official repository within the FAA responsible for the collection, validation and quality control of aeronautical information disseminated to support National Airspace System (NAS) operations. It contains details of the physical description, geographical position, and operational characteristics and status of all components of the NAS(FAA, 2012d).

In the methodology the NFDC data is used to determine coordinates of airports, runways, fixes and waypoints for procedures in the metroplex airspace.
3.2 Methodology for TRACON flow analysis

The methodology for airport arrival flow analysis has two functions: (1) Characterize TRACON flows and (2) Assign flight tracks to flows (see Figure 8). The methodology is described in detail in the following subsections.

3.2.1 Flow Characterization

The TRACON arrival flows are defined as the flow of aircraft from the final waypoint on the Standard Terminal Arrival Route (STAR) to the runway threshold via an approach type. The flows are characterized as a combination of direction, runway and approach type. The characterization process is done using the following steps:

Step1: Identify the direction of TRACON flow

Figure 8: Methodology for Airport Arrival Flow Analysis
The location of the final waypoint on the STAR with respect to the runways determines the direction of the traffic flow. Figure 9 shows a sample STAR with its final waypoint (WP2) located south east of the airport. Therefore the cardinal direction associated with aircraft passing via WP2 is South East (SE). Similarly flows using WP1 to approach the runways would be characterized as North East (NE) flows and so on.

![Sample STAR](image)

**Figure 9: Depiction of how flows direction is determined from final waypoint on STAR**

**Step2: Identify the Approach procedure for each runway**

The next step in the characterization process is to list the approach procedures published for each runway. Based on meteorological conditions (ceiling and visibility) at the airport, aircraft use either a visual approach or an instrument approach. The instrument approaches vary based on the level of lateral and vertical guidance required. The conventional instrument approach procedure is the Instrument Landing System (ILS) approach. The more recent Performance Based Navigation (PBN) approaches are Area
Navigation (RNAV) GPS approach and RNAV Required Navigation Performance (RNP) approach.

The output of the characterization process is a table that lists all possible flows for runways at an airport. A sample of this is shown in Figure 10. The table is populated with Boolean values, 1 indicating “applicable” and 0 indicating “not applicable”. The total number of flows for each runway is determined by multiplying the total number of approaches available for the runway with the total number of directions from where the flows can originate.

![Figure 10: Output of the Flow Characterization Process](image)

### 3.2.2 Flow Assignment

The flow assignment process assigns each flight track to a flow. The flows are defined in terms of direction, runway and approach type. The arrival flight tracks to an airport (filtered from the NOP data) are high fidelity surveillance track data that originate 30-90 NM miles from the airport and terminate at the runway threshold.
The tracks are first assigned to a runway based on the final two track hits (each point of the 4D trajectory is referred to as a radar track hit). The tracks are then assigned a cardinal direction based on direction of approach. Finally, each track corresponding to a runway and an approach direction is assigned an approach type based on its proximity to published approach procedures for that runway. The detail of the algorithm for flow assignment is as follows:

**Step1: Filter out arrival tracks from rest of the data.**

The NOP data has track information for the whole TRACON. Before tracks are assigned to flows, the arrivals tracks are filtered out. This is done using the following logic:

a. Sort each track by time (descending order).

b. Get the first and last hit for each track.

c. Determine the top left and bottom right corner of the airport, by adding and subtracting 0.05 degrees from the coordinates of the airport. This will be the boundary of the airport.

   d. If the first hit is within the airport boundary then assign the flight track as a departure, else assign flight track as an arrival

**Step2: Assign runway to each arrival track.**

The algorithm for assigning a track to a runway is as follows,

a. Sort the arrival track by time (descending order).

b. Get the last two hits of the arrival track, call it the sub-track.

c. Calculate the distance from each runway’s centerline for each sub-track
d. Calculate the heading, and compare it to each runway’s alignment for sub-track.

e. Assign the sub-track to the runway with the minimum distance and difference in heading.

**Step3: Assign Direction**

Flight tracks are assigned direction based on the STAR they use to approach the runway. The algorithm for assigning track to a direction is as follows:

a. Assign each STAR a cardinal direction based on its location with respect to the airport

b. Define suitable rectangle boundaries for each STAR to capture all aircraft tracks using the STAR.

c. Determine if the track passes through the rectangle defined for the STAR.

d. Assign each track the cardinal direction associated with the STAR whose rectangle boundary it passes through.

**Step4: Assign Approach procedure type**

The tracks are assigned to an approach type based on its lateral and vertical proximity to the fixes/waypoints along the approach. The algorithm for assigning track to an approach type is as follows

a. Get all the arrival tracks for a given runway

b. Get the coordinates and the minimum altitude threshold for the waypoints of the approach procedure for the runway
c. Check the lateral and vertical proximity of the track to the approach procedure at the waypoints along the approach procedure.

d. Assign the track the approach procedure if it is within the vertical and lateral proximity thresholds.

3.3 Holding Pattern Analysis

Holding patterns are racetrack patterns based on a holding fix along the STAR (see Figure 11). They are used for delaying arriving aircraft that cannot land due to poor weather, runway unavailability or due to metroplex flow conflicts.

A key difference in the holding pattern analysis and the arrival flow analysis is the scope of the analysis. Instead of performing the track data analysis in the TRACON, the
track data analysis is done for each holding boundary i.e. the rectangular boundary defined around the published holding procedure to capture tracks in holding pattern. The methodology for holding pattern analysis is shown in Figure 12.

The algorithm for the holding pattern analysis is as follows:

a. Analyze each STAR in the terminal area and define suitable rectangular boundaries around the published holding patterns.

b. Filter out tracks that fall within the rectangular boundaries.

c. Compute the cumulative turn angle for each filtered sub-track in the rectangular boundary.

d. Determine the holding tracks by filtering out sub-tracks with cumulative turn angle greater than 360 degrees.
e. Compute the time in holding and fuel burn for each holding track as described in section 3.4.1.

3.4 Performance Metrics

The performance metrics that can be derived from the flight track data are track distance (nautical mile), track time (minute) and track fuel burn (kilogram).

For TRACON flows the metrics are measured from the final STAR waypoint to the runway threshold. The metrics are computed for each flight track in a given flow. The performances of the flows are reported in terms of mean and standard deviation of the performance metric.

For the holding patterns the performances metrics are reported in terms of frequency of holding pattern occurrence (number of holding patterns per 100 arrivals) and the mean and standard deviation of the holding pattern performance metric.

The overview of the methodology for computing performance metrics for TRACON flows and holding patterns is shown in Figure 13. The details of computing track distance (NM) and track time (minute) are discussed in section 3.4.1 and the details for computing the fuel burn is discussed in section 3.4.2.
3.4.1 Track distance and time
The algorithm for estimating the track distance and track time for TRACON arrival flows is as follows:

a. Sort arrival track for each flow by time (descending order).

b. Designate a Start Point by defining a beam (line perpendicular to flow direction of each flow) across each of the final STAR waypoint to mark the start of the TRACON arrival flow (see Figure 27 and Figure 28).

c. The track time is the difference in the 4D track’s time at the Start point and the time at the runway threshold
d. Compute the track distance at each time step from the Start Point to the runway threshold. (NOP arrival track terminate at the runway threshold).

e. Track distance is the cumulative distance from the Start point to the point at the runway threshold.

In case of holding patterns the track distance and time are the total distance/time in holding and are computed using the first and last 4D point of the holding track.

3.4.2 Track Fuel Burn
Aircraft fuel burn rate is higher in the terminal area due to level offs and change of aircraft configuration from clean to dirty. This fuel burn model captures these two aspects of terminal arrival flows by taking into consideration the energy state (kinetic – true airspeed and potential – altitude) of the aircraft at each position report of the flight trajectory. The inputs required to compute fuel burn are, the 4D trajectory, the wind magnitude and direction, and the aircraft mass estimate, thrust and drag coefficient. The details of computing the fuel burn, true airspeed, thrust and drag are described in the following sub sections.

3.4.2.1 Thrust Specific Fuel Burn
The model computes total fuel burn for a 4D trajectory by summing up the fuel burn at each time step $i$ (see Equation 1). The fuel burn at each time step is computed as a product of the thrust and thrust specific fuel consumption (see Equation 2). The expression for thrust specific fuel consumption for jets and turboprops is shown in Equation 3 and Equation 4 respectively (Euro Control, 2012b). The thrust is estimated using the Total-Energy model, which equates the rate of work done by forces acting on
the aircraft, to the rate of change of potential and kinetic energy (see Equation 5) (Euro Control, 2012b). By rearranging the total energy model, the equation of thrust is obtained (see Equation 6).

Equation 1: Total fuel burn for a flight track
\[ F = \sum_i f_i \times (t_i - t_{i-1}) \]

Equation 2: Fuel burn rate at each time step
\[ f_i = \eta_{engine} \times T_i \]

Equation 3: Thrust specific fuel consumption for jets
\[ \eta_{i, jet} = C_{f1} \times \left( 1 + \frac{TAS_i}{C_{f2}} \right) \]

Equation 4: Thrust specific fuel consumption for turboprops
\[ \eta_{i, turboprop} = C_{f1} \times (1 - \frac{TAS_i}{C_{f2}}) \times \left( \frac{TAS_i \times 1.94}{1000} \right) \]

Equation 5: Total-energy model
\[ (T_i - D_i) \times TAS_i = m_i \times g \times \frac{dh_i}{dt} + m_i \times TAS_i \times \frac{dTAS_i}{dt} \]

Equation 6: Expression for thrusts
\[ T_i = D_i + \frac{m_i \times g \times \frac{dh_i}{dt}}{TAS_i} + m_i \times \frac{dTAS_i}{dt} \]

Where,

- \( F \) is the total fuel burn for a 4D trajectory in kg.
- \( f_i \) is the fuel burn rate in kg/min.
- \( t_i, t_{i-1} \) are the timestamps for positions \( i \) and \( i - 1 \).
- \( \eta_{engine} \) is the thrust specific fuel consumption in kg/(min*kN).
- \( T_i \) is the thrust in kN.
- \( D_i \) is the drag in kN.
$C_{f1}$ is the first thrust specific fuel consumption coefficients for an aircraft type in kg/(min*kN) for jets and kg/(min*knots*kN) for turbo jets

$C_{f2}$ is the second thrust specific fuel consumption coefficient for an aircraft type in m/s.

$TAS_i$ is the true airspeed of the aircraft in m/s.

$dh_i$ is the change in altitude $= h_i - h_{i-1}$ in m

$dTAS_i$ is the change in true airspeed $= TAS_i - TAS_{i-1}$ in m/s

$dt$ is the time step increment $= t_i - t_{i-1}$ in s

$m_i$ is the mass of the aircraft in kg.

$g$ is acceleration due to gravity $= 9.81 \text{ m/s}^2$.

### 3.4.2.2 Initial Mass of the Aircraft and the Total Fuel Burn Sensitivity

The terminal area fuel burn is estimated for each aircraft track from the final waypoint on STAR to the runway threshold. The mass of the aircraft at start of the flight track (the final waypoint on STAR) is estimated using the following equation:

**Equation 7: Initial mass of the aircraft**

$$m_{initial} = \frac{(OEW + MPW) + MLW}{2}$$

Where,

$OEW$ is the operating empty weight for a given aircraft type in kg

$MPW$ is the maximum payload weight for a given aircraft type in kg

$MLW$ is the maximum landing weight for a given aircraft type.

The mass of the aircraft at the time of landing can range from the operating empty weight (OEW) and the maximum landing weight (MLW). In addition the weight of the cargo and passengers has to be taken into account as it is not included in the OEW as
specified by the manufacturer. The sum of the operating empty weight and the maximum payload weight is the lower bound for the mass of the aircraft in the terminal airspace.

The maximum landing weight is the upper bound estimate for the mass of the aircraft in the terminal airspace. The sensitivity of the total fuel burn in the terminal airspace to the initial mass of the aircraft is analyzed by estimating the fuel burn for the lower and upper bounds.

In this analysis the initial mass (the time at which the aircraft track is at the final waypoint on STAR) of the aircraft is estimated as the mean of the lower and the upper bound (see Equation 7 ) for each aircraft type. For subsequent time steps the mass of aircraft is reduced by the amount of fuel burnt in the previous time step as shown

Equation 8.

\begin{equation}
m_i = m_{i-1} - f_{i-1}
\end{equation}

3.4.2.3 True Airspeed

The time step between position reports in the NOP data for the most part vary from four seconds to a minute. In this analysis the 4D trajectories are consolidated such that the time step is at least thirty seconds. This is done to reduce noise in the velocity profile. In addition a differential equation forward filter is used to further smoothen the velocity profile(Jamet, 2011). The true airspeed is computed at each time step based on the ground speed and the wind speed (Oaks & Ryan, 2010). The true airspeed is given by,

\begin{equation}
TAS_i = \frac{GS_i \times \sin \theta_i}{GS_i \times \cos \theta_i} - \frac{WS_i \times \sin \phi_i}{WS_i \times \cos \phi_i}
\end{equation}

Where,
$GS_i$ is the ground speed in m/s.

$\theta_i$ is the aircraft bearing with respect to the north in radian.

$WS_i$ is the wind speed in m/s.

$\phi_i$ is the wind bearing with respect to the north in radian.

The ground speed and the aircraft bearing are computed using the following equations:

**Equation 10: Ground Speed**

$$GS_i = \frac{R \times c_i}{t_i - t_{i-1}}$$

**Equation 11: Central Angle between two coordinates**

$$c_i = 2 \times \text{atan2}(\sqrt{b}, \sqrt{(1 - b)})$$

**Equation 12: Coordinates intercept**

$$b = \sin^2 \left( \frac{\varphi_i - \varphi_{i-1}}{2} \right) + \cos(\varphi_{i-1}) \cos(\varphi_i) \sin^2 \left( \frac{\lambda_i - \lambda_{i-1}}{2} \right)$$

**Equation 13: Aircraft bearing with respect to the North**

$$\theta_i = \text{atan2} \left( \sin(\lambda_i - \lambda_{i-1}) \cos(\varphi_i), \cos(\varphi_{i-1}) \sin(\varphi_i) \right)$$

$$\quad - \sin(\varphi_{i-1}) \cos(\varphi_i) \cos(\lambda_i - \lambda_{i-1})$$

Where,

R is the radius of the earth = 6378100m.

$c_i$ is the haversine central angle between two coordinates ($\varphi_{i-1}, \lambda_{i-1}$) and ($\varphi_i, \lambda_i$).

$\varphi_i, \varphi_{i-1}$ are the latitude for positions $i$ and $i - 1$.

$\lambda_i, \lambda_{i-1}$ are the longitude for positions $i$ and $i - 1$.

$t, t_{i-1}$ are the timestamps for position $i$ and $i - 1$s.
The wind speed and wind bearing reported in the ASPM data are measured at ten meters from the surface. The wind speeds increase with altitude and are estimated using the power law wind profile equation (Panofsky & Dutton, 1984).

\[ WS_i = z_g \left( \frac{h_i}{h_g} \right)^\alpha \]

Where,

- \( z_g \) is the velocity of the wind at height \( h_g = 10 \text{m} \), in m/s.
- \( h_i \) is the height of the aircraft above ground in m.
- \( \alpha \) is the Hellman exponent = 0.3 for human inhabited areas.

### 3.4.2.4 Drag Computation

The drag force on the aircraft is computed using the following equations (Euro Control, 2012b):

\[ D_i = \frac{C_D \times \rho_i \times TAS_i^2 \times S}{2} \]

\[ \rho_i = \frac{p_i \times M}{R \times T} \]

\[ p_i = p_0 \left( 1 - \frac{L \times h_i}{T_0} \right) \]

\[ T = T_0 - L \times h_i \]

Where,

- \( D_i \) is drag in kN.
\( C_D \) is the coefficient of drag.

\( \rho_l \) is the density of the aircraft in kg/m\(^3\).

\( h'_l \) is the altitude of the aircraft above sea level in m.

\( S \) is the wing reference area in m\(^2\).

\( p_0 \) is the sea level atmospheric pressure = 101.325kPa.

\( p_l \) is the pressure at altitude \( h'_l \) in kPa.

\( L \) is the temperature lapse rate = 0.0065K/m.

\( T_0 \) is the sea level standard temperature = 288.15K.

\( M \) is the molar mass of dry air = 0.0289644 kg/mol.

\( R \) is the universal gas constant = 8.31477 J/(mol.K).

\( T \) is the absolute temperate in K.

The coefficient of drag in Equation 15 is a function of the coefficient of lift and the configuration of the aircraft. For terminal arrival flows, an aircraft is assumed to be in clean, approach or landing configuration at each time step based on the true airspeed and the altitude of the aircraft. The criteria assumed for selecting the configuration of the aircraft are shown in Table 8. The flight trajectories for arrival flows in the TRACON are all below 8000 feet. The minimum velocity (Vmin) for each configuration is 1.3 times the stall speed provided in the BADA’s Operations Performance File (OPF) for each aircraft type.
Table 8: Criteria for Aircraft Configuration

<table>
<thead>
<tr>
<th>Altitude (feet above ground level)</th>
<th>Velocity Threshold</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;1000ft &amp; &lt;=8000</td>
<td>TAS&gt;=VminCruise</td>
<td>Clean</td>
</tr>
<tr>
<td>&gt;1000ft &amp; &lt;=8000</td>
<td>VminApproach&lt;=TAS&lt;VminCruise</td>
<td>Approach</td>
</tr>
<tr>
<td>&lt;=1000ft</td>
<td>None</td>
<td>Landing</td>
</tr>
</tbody>
</table>

The coefficient of drag for clean, approach and landing configuration is given by Equation 19, Equation 20 and Equation 21 (Euro Control, 2012b). The coefficient of lift is given by Equation 22 (Euro Control, 2012b).

**Equation 19: Coefficient of drag in cruise configuration**

\[
C_D = C_{D0,CR} + C_{D2,CR} \times C_L^2
\]

**Equation 20: Coefficient of drag in approach configuration**

\[
C_D = C_{D0,AP} + C_{D2,AP} \times C_L^2
\]

**Equation 21: Coefficient of drag in landing configuration**

\[
C_D = C_{D0,LD} + C_{D0,LDG} + C_{D2,LD} \times C_L^2
\]

**Equation 22: Coefficient of lift**

\[
C_L = \frac{2 \times m \times g}{\rho_i \times TAS_i^2 \times S \times \cos \psi}
\]

Where,

- \(C_L\) is the coefficient of lift.
- \(C_{D0,CR}\), \(C_{D0,AP}\), \(C_{D0,LD}\) are the parasitic drag coefficient for cruise, approach and landing configuration.
- \(C_{D2,CR}\), \(C_{D2,AP}\), \(C_{D2,LD}\) are the induced drag coefficient for cruise, approach and landing configuration.
- \(C_{D0,LDG}\) is the parasitic drag coefficient of the landing gear.
- \(\psi\) is bank angle, assumed to be zero in this analysis.
3.5 **Methodology for benefits analysis of metroplex flow de-confliction**

Metroplex flow conflicts occur when low visibility and certain wind (magnitude and direction) constrain metroplex airports runway configurations such that arrivals or departure flows of one airport interfere with arrival or departure flows of the neighboring airport. The metroplex flow conflicts can be identified by performing a metroplex capacity gap analysis (Donaldson & Hansman, 2011). The capacity gap analysis involves analyzing capacity for various operating configuration in the metroplex i.e. runway configuration at each airport in the metroplex. The configurations that have a dip in capacity are further analyzed to identify flows likely constraining the airspace capacity.

An alternate approach to identify conflicting flows is to research the literature or to interview subject matter experts (tower manager and controllers).

Metroplex flow conflicts result in sharing of common airspace in the metroplex by flows from two adjacent airports. This is overcome by ground holding for departures and airborne holdings for arrivals at the airports in the metroplex. The ground holdings for departures result in departure delays and may result in cancelled flights. The airborne holding for arrivals results in en-route delays. The benefits of de-confliction are the reduction in: (1) additional departure delays (2) cancelled flights and (3) airborne holdings that occur due to flow conflict. The de-confliction using RNP approach has further benefits in fuel burn savings for arrivals from using RNP approaches that have a shorter and more efficient approach compared to conventional ILS approach. The fuel burn savings for arrival flows from the new PBN approach procedure (e.g. RNP approach) is described in section 3.6.
This section describes a methodology for estimating the cost of delays and cancelled flights for departures and airborne holdings for arrivals. The costs are computed in terms of the Airlines Direct Operating Costs (ADOC), which takes into account the cost of flight deck crew, fuel, maintenance, equipment charge and other miscellaneous charges. This dissertation focuses on airline’s cost/potential savings rather than system-wide cost/potential savings, as airline make equipage decision based on their own individual savings.

Figure 14: Methodology for estimating the benefits of Metroplex Flow De-confliction

### 3.5.1 Estimation of Cost of Ground Holding

Metroplex flow conflict results in ground holding for the departure flows. This results in additional departure delays and can result in additional cancelled flights. The
additional departure delays and cancelled flights due to metroplex flow conflict are computed by comparing the delays and cancellation statistics using historic ASPM airport and flight data for flights during periods of flow conflict with a suitable baseline. The baseline period selected represents similar operational condition at the airport (ceiling and visibility). For instance, a suitable baseline for metroplex flow conflicts occurring during IMC can be other IMC periods with no flow conflicts.

The algorithm for estimating the cost of excess departure delays and cancelled flights due to metroplex conflict is as follows:

**Step1: Identify the flow conflict and the no-flow conflict (baseline) periods**

a. Identify set of time periods (i.e., start and end times from fields 2 to 5 in ASPM airport table) of flow conflict for a given year using ASPM airport data. This is done by analyzing the runway configuration (field 76 in ASPM airport table) at the airports and identifying time bins when the runways associated with the flow conflict are in use. These time bins are called the conflict periods.

\[
C_y: \{tc_1, tc_2, tc_3 \ldots \}
\]

Where,

\(C_y\) is the set of all conflict periods in a given year \(y\)

\(tc_1, tc_2, tc_3 \ldots\) are the flow conflict periods in a given year with each period defined by a start and end time.

b. Identify set of time periods (i.e., start and end times from fields 2 to 5 in ASPM airport table) of no flow conflict (baseline) for a given year using
ASPM airport data to. This is done by analyzing the runway configuration (field 76 in ASPM airport table) at the airports and identifying time bins which have similar meteorological conditions (field 70 in ASPM airport table) and use the runways not associated with the flow conflict. Call these the baseline periods

Equation 24: Set of time periods of no flow conflict (baseline) for a given year

\[ NC_y: \{tn_{c1}, tn_{c2}, tn_{c3} \ldots \} \]

Where,

\( NC_y \) is the set of all no-flow conflict periods in a given year \( y = \{y1,y2,\ldots\} \)

\( tn_{c1}, tn_{c2}, tn_{c3} \ldots \) are the no-flow conflict periods in a given year with each period defined by a start and end time (fields 2 to 5 in ASPM airport table).

Step 2: Compute excess delays (\( D_{dep} \)) and cancelled flights (\( \Delta Cancelled \)) due to flow conflict

a. Estimate the total schedule flights for the flow conflict (\( C_y \)) and no-flow conflict (\( NC_y \)) time periods, using the ASPM flight data and BTS Airline on-time performance data. ASPM does not have information on cancelled flights and BTS has cancellation information for only domestic flights. The total number of scheduled flights for a given year (for \( C_y \) and \( NC_y \)) is estimated by summing the operational flight count and cancellation count for each time period in the ASPM flight data table and the BTS on-time performance table respectively.

Equation 25: Total scheduled flights in a year for flow conflict or no-flow conflict time periods

\[ F_{sch_T} = (\#\ ASPM\ flights)_T + (\#\ Cancelled\ BTS)_T \]
Where,

\( F_{sch_T} \) is the total scheduled flights in a year for the flow conflict \((T = C_y)\) or the no-flow conflict \((T = NC_y)\) time periods

b. Compute the percentage of scheduled flights delayed, cancelled and the average delay per scheduled flight for the flow conflict \((C_y)\) and no-flow conflict \((NC_y)\) time periods.

**Equation 26: Percentage of scheduled flights cancelled**

\[
P_{can_T} = \frac{\# \text{ Cancelled BTS}_T}{F_{sch_T}}
\]

**Equation 27: Percentage of scheduled flights delayed**

\[
P_{del_T} = \frac{\# \text{ ASPM flight delayed } > 15\text{min}}{F_{sch_T}}
\]

**Equation 28: Average delay per scheduled flight**

\[
Avg_{del_T} = \frac{\text{Total}_{del_T}}{F_{sch_T}}
\]

\[\text{Total}_{del_T} = \sum_T \text{ASPM flight delayed } > 15\text{min}\]

Where,

\( P_{can_T} \) is the percentage of scheduled flights cancelled for the flow conflict \((T = C_y)\) or the no-flow conflict \((T = NC_y)\) time periods.

\( P_{del_T} \) is the percentage of scheduled flights delayed for the flow conflict \((T = C_y)\) or the no-flow conflict \((T = NC_y)\) time periods.

\( Avg_{del_T} \) is the average delay per scheduled flight for the flow conflict \((T = C_y)\) or the no-flow conflict \((T = NC_y)\) time periods.
Total_del_T is the total delay for the flow conflict (T = C_y) or the no-flow conflict
(T = NC_y) time periods computed using the ASPM flight data (field 54 in ASPM flight
table).

c. If the average delay (Avg_del_T) and percentage cancelled flights (P_can_T)
for flow conflict (T = C_y) time period is greater than no-flow conflict
(T = NC_y) time periods, compute excess delays (Ddep) and cancelled flights
(ΔCancelled) due to flow conflict using the following equations:

\[ D_{dep} = Total_{del_{T=C_y}} - \left(F_{sch_{T=C_y}} * P_{del_{T=NC_y}}\right) * Avg_{del_{T=NC_y}} \]

\[ ΔCancelled = F_{sch_{T=C_y}} * (P_{can_{T=C_y}} - P_{can_{T=NC_y}}) \]

Where,

\[ \left(F_{sch_{T=C_y}} * P_{del_{T=NC_y}}\right) * Avg_{del_{T=NC_y}} \] is the total flight delay for flow conflict
time period (T = C_y) if percentage flight delayed and the average delay per flight is same
as no-flow conflict time periods (as a result of flow de-confliction).

\[ (P_{can_{T=C_y}} - P_{can_{T=NC_y}}) \] is the difference in scheduled flights cancelled during the
flow conflict (T = C_y) and the no-flow conflict (T = NC_y) time periods.

**Step3: Compute total cost of excess departures delays (D_{dep}) and cancelled
flights (ΔCancelled) due to flow conflict**

The metroplex flow conflict between departure flows at one airport and arrival
flows at the neighboring airport can prevent departures as aircraft taxi out to the runway
threshold, resulting in departure queues at the runway threshold. The Airline’s Direct
Operating Cost (ADOC) for additional departure delays due to metroplex flow conflict are accounted as taxi-out delay costs. They are computed using the following equations:

**Equation 31: Total ADOC due to addition departure delays**

\[ T_{ADOC_{TO}} = ADOC_{TO} \times D_{dep}. \]

**Equation 32: ADOC for taxi out delay**

\[ ADOC_{TO} = WADOC \times A_{TO} \]

**Equation 33: ADOC weighted for fleet mix**

\[ WADOC = \sum A_{type} \times ADOC_{AC_{type}} \]

Where,

- \( ADOC_{AC_{type}} \) is the ADOC per block hour for a given class of aircraft in $/hour (FAA, 2005b; pg D-8).
- \( A_{type} \) is the fraction/percentage of aircraft of a given class in the fleet mix.
- \( WADOC \) is the weighted ADOC based on the fleet mix in $/hour.
- \( A_{TO} \) is the adjustment factor for ADOC for the taxi out phase = 0.78 (FAA, 2005b; pg D-9).
- \( ADOC_{TO} \) is the ADOC per block hour for taxi out phase of the flight in $/hour.
- \( T_{ADOC_{TO}} \) is the Total ADOC due to taxi out delays in $.
- \( D_{dep} \) is the Total additional departure delays due to metroplex flow conflict in hours (computed step2 of the algorithm).

The cost of a cancelled flight to an airline is estimated to be $4977 per cancellation (FAA, 2012g; pg 14). The total cost of cancellation due to metroplex flow conflict is:

**Equation 34: Cost of Flight Cancellation**

\[ Cost_{cancel} = $4977 \times \Delta Cancelled \]
3.5.2  Holding Patterns Delays due to Metroplex Flow Conflict

The metroplex flow conflict can prevent arrivals from approaching the airport for landing, resulting in airborne holding at pre-defined fixes along the STAR. The Airlines Direct Operating Cost (ADOC) for airborne holding due to metroplex flow conflict is accounted as en-route delay costs.

The total en route delay due to holding pattern as a result of the metroplex flow conflict can be estimated using NOP data, provided NOP track data is available for the all conflict periods. NOP track data is a larger data set and access to it is limited compared to ASPM data. In case NOP track data is not available for all the conflict periods, the sample NOP track data for the conflict days is used along with the ASPM flight data to estimate the total en-route delay due to holding pattern as a result of the metroplex flow conflict.

Not all holding patterns are due to the metroplex flow conflict. It is necessary to accurately account for holding patterns due to metroplex flow conflict. The algorithm for estimating cost of en route holding due to metroplex flow conflict is as follows:

**Step1: Compute total delay due to airborne holding as a result of metroplex flow conflict** (\(D_{\text{holding}}\))

a. Collect NOP data to perform holding pattern analysis for the conflict periods identified in Step1 of section 3.5.1

b. Perform holding pattern analysis (see section 3.3) using NOP track data.

c. Identify holding patterns as a result of flow conflict with a neighboring arrival or departure flow.

i. Lookup the start time of each holding pattern using the track data
ii. Lookup using the track data the start time of the other flow involved in the flow conflict. In case of departure flow get the start of departure time. In case of arrival flow get the start time track in the TRACON.

iii. Create time bins (15 minute) with start time of the conflicting flow events e.g. arrival and departure flows, causing the flow conflict.

iv. Identify time bins that have occurrence of both the conflicting flow events. Call these the conflict bins.

d. If NOP data is available for all the conflict periods in a given year, compute total delay due to airborne holding as results of metroplex flow conflict by summing up the holding times for holding patterns in the conflict bins and GOTO step2. Else,

e. Compute the frequency of holding patterns using the number of aircraft in holding and the total number of arrivals in each conflict bin i.e. holding patterns per 100 arrivals.

f. Compute the total count of holding patterns due to the metroplex flow conflict as product of the frequency of the holding pattern and the total arrivals during the conflict period (computed from the ASPM flight data).

g. Compute the total delays due to holding patterns as product of the total count of holding patterns and the mean holding time.

**Step2: Compute cost of holding patterns due to metroplex flow conflict**

\( T_{ADOCEr} \)
The Airlines Direct Operating Cost (ADOC) for airborne holding due to metroplex flow conflict is accounted as en-route delay costs. They are computed using the following equations:

Equation 35: Total ADOC due to en route holding delays

\[ T_{ADOC_{ER}} = ADOC_{ER} \times D_{holding}. \]

Equation 36: ADOC for En route delay

\[ ADOC_{ER} = WADOC \times A_{ER}. \]

Equation 37: ADOC weighted for fleet mix

\[ WADOC = \sum AC_{type} \times ADOC_{AC_{type}}. \]

Where,

- \( ADOC_{AC_{type}} \) is the ADOC per block hour for a given class of aircraft in \$/hour (FAA, 2005b; pg D-8).
- \( AC_{type} \) is the fraction/percentage of aircraft of a given class in the fleet mix.
- \( WADOC \) is the weighted ADOC based on the fleet mix in \$/hour.
- \( A_{ER} \) is the adjustment factor for ADOC for the en route phase = 1.25 (FAA, 2005b; pg D-9).
- \( ADOC_{ER} \) is the ADOC per block hour in the en route phase of the flight in \$/hour.
- \( T_{ADOC_{ER}} \) is the Total ADOC due to en route holding delays in $.
- \( D_{holding} \) is the Total delays due to holding patterns as a result of metroplex flow conflict in hours (computed in the step1 of the algorithm).

3.6 Methodology for Benefits Analysis of PBN approach procedures at an airport

The new PBN approach capability enable precise curved path approaches (e.g., RNP 0.3 w/ RF leg) in the terminal airspace. These new approach procedures are
designed to eliminate trombone vectors in the base leg of the approach and make the approach from the final waypoint on STAR to runway threshold shorter on average compared to conventional approach procedures. This capability has two potential benefits at an airport in the metroplex:

a. The shorter approach results in fuel burn savings in the terminal airspace compared to the conventional approaches. Therefore, there is potential to design and enable new efficient procedures to all runways at the airport, not just the ones required to de-conflict the metroplex airspace.

b. The more precise PBN approach path makes the operations at an airport in a metroplex independent of the neighboring airport. This allows the use of runway configurations that are more optimal in terms of performance of terminal area flows, compared to the historic configurations that are constrained on operations at the neighboring airport.

This section describes a methodology that captures the above two benefits to estimate the total potential benefits of the new PBN approaches to airlines at an airport. An overview of the methodology is shown Figure 15.
3.6.1 Engineering new PBN flows

The approach described in this section to engineer new PBN flows (e.g. RNP approach flows) to runways at an airport relies on the availability of existing PBN flows. The flight tracks of existing PBN flows are reflected and rotated (see Figure 16) to get new PBN flows for other runways at the airport that do not have published PBN approach procedures, but could potentially benefit from them. The new flows are generated either by rotation or reflection and rotation, depending on the location of the arrival fix (final waypoint on STAR) with respect to the runway.
The rotation and reflection of existing flight tracks is done using the following equations:

Equation 38: Formula for reflection of flight track

\[ Ref_i(v) = 2 \frac{v \cdot l}{l \cdot l} * l - v \]

Where,

\( Ref_i(v) \) is the vector representing the reflected flight track coordinate

\( v \) is the flight track co-ordinate vector that needs to be reflected.

\( l \) is the vector representing the center line of the runway about which the flight track co-ordinate is reflected.

\( v \cdot l \) and \( l \cdot l \) are the dot product of the respective vectors.
Equation 39: Formula for rotation of flight track
\[
\begin{bmatrix}
  x' \\
  y'
\end{bmatrix} =
\begin{bmatrix}
  \cos \theta & -\sin \theta \\
  \sin \theta & \cos \theta
\end{bmatrix}
\begin{bmatrix}
  x \\
  y
\end{bmatrix}
\]

Where,

\(x, y\) are the flight track co-ordinate vectors with respect the point about which the vectors need to be rotated

\(x', y'\) are the rotated flight track co-ordinate vectors

\(\theta\) is the angle of rotation (i.e., angular difference between the runways).

3.6.2 Optimal Runway Configuration

In current practice the runway configuration is determined based only on the wind direction and other tower considerations. An alternate approach is to select the most optimal runway configuration from a set of feasible configurations, by taking into account the direction of traffic intensity and the fuel burn performance of individual flows in the terminal. The algorithm for determining the optimal runway configuration is as follows:

a. For a given wind magnitude and direction compute the cross wind and head wind component for each runway using the following equation:

\[
\text{Equation 40: Formula for crosswind} \quad CW = \sin(A) \cdot WS
\]

\[
\text{Equation 41: Formula for headwind} \quad HW = \cos(A) \cdot WS
\]

Where,

\(WS\) is the magnitude of the wind in knots

\(CW\) is the magnitude of the crosswind in knots
$HW$ is the magnitude of the headwind in knots

$A$ is the difference in wind and runway bearing in radian.

b. Select a set of feasible runways or runway configurations based on the cross wind and headwind thresholds and the meteorological conditions. For a runway configuration to be feasible the cross wind component should not be greater than 20 knots and the headwind component should not be less than zero. Negative headwind component means the runway has a tailwind. Also, for IMC only runway configurations that support precision or precision-like approaches are selected.

c. Compute the weighted average fuel burn per flight for a given runway configuration and approach type while taking into account traffic intensity from each direction.

Equation 42: Average fuel burn per flight for a given runway and approach type

$$f_{y',t} = \sum_{t=1}^{M} W_{y,t} \times f_y$$

Where,

$f_{y',t}$ is the average fuel burn per flight for a given runway and approach type.

$W_{y,t}$ is the weight of the arrival flows (percentage of aircrafts arriving in each flow) $y$ at time period $t$ and $\sum_{y,t=n} W_{y,t} = 1$ (i.e., the weight of arrival flows for a given time period $t$ sum up to 1). These weights are used to allocate the total arrival at the airport to individual flows. These are estimated by performing TRACON flow analysis using NOP track data (see section 3.2) for all possible runway configurations and
approach types which are a function of the meteorological conditions (visibility, wind magnitude and direction) at the airport.

\( f_y \) is the average fuel per aircraft for TRACON flow \( y \) in kg/min. The fuel burn statistics for TRACON flows are computed using the methodology in section 3.4.2.

d. Rank the runway configurations based on the fuel burn performance and select the runway configuration with lowest weighted average fuel burn as the optimal runway configuration.

e. Repeat the process for each time bin in the ASPM airport table.

3.6.3 **Total Annual Terminal Flow Fuel burn**

The model presented in this section estimates the annual fuel-burn in the terminal airspace for arrivals at an airport using historic ASPM runway and flight data, and the flow fuel-burn statistics computed using NOP track data. The total annual fuel burn for aircraft in the terminal airspace is calculated using the following equations:

Equation 43: Total annual fuel burn in the terminal airspace for arrivals at an airport

\[
F = \sum_{d=1}^{N} \sum_{t=1}^{M} A_{t,d} \cdot W_{y,t} \cdot f_y
\]

Where,

- \( F \) is the total annual fuel burn for aircraft in the terminal airspace in kg
- \( d \) is the number of days considered in the year
- \( t \) is the number of time periods/bins in a day (i.e., 15 min time bins to 1 hour time bins).
$A_{t,d}$ is the total number of arrivals for given day $d$ and time period/bin $t$. This is computed from the ASPM flight table by counting the number of arrivals in each time bin for a given day. The time bins can be hourly or 15 minutes long.

### 3.6.3.1 The total potential benefits of the new PBN approach to airlines at an airport

The algorithm for estimating the total potential benefits of the new PBN approach to airlines at an airport is as follows:

a. Engineer new RNP flows for runway that currently do not have the new PBN procedures published by using existing RNP flows to (see section 3.6.1)

b. Compute fuel burn performance metrics for the new flows and existing flows (see sections 3.2 and 3.4)

c. Estimate the optimal runway configuration for existing flows and potential future flows for a given year for each 15 minute bin in the ASPM airport table (see section 3.6.2).

d. Estimate the total annual fuel burn for actual historic runway configuration and existing flows (see section 3.6.3) and call it the baseline scenario.

e. Repeat the process for alternate scenarios. The alternate scenarios are various combinations of runway configurations (actual and optimal) and flows (existing and future).

f. Compute the total potential benefits of the new PBN approach to airlines at an airport as the difference in the total annual fuel burn $F$ for the baseline scenario and various alternatives.
3.7 Methodology for Estimating Airline Return on Investment

The airline ROI on equipage is estimated using the Net Present Value method shown below:

\[
NPV(i, N) = \sum_{t=0}^{N} \frac{R_t}{(1 + i)^t}
\]

Where,

\(i\) is the discount rate.

\(N\) is the total number of periods in years.

\(R_t\) is the net cash flow (i.e., cash inflow-cash outflow) at time \(t\)

The cash inflow per year is the savings from new PBN approach estimated using the methodology described in sections 3.5.2 and 3.6. The cash outflow is the initial airline investment in equipage which includes cost of equipment, training and certification. The assumptions made by the model are:

a. Benefits are accrued only after 100% of fleet is equipped
b. Cash outflow is the Initial Cost of Equipage when \(t=0\)
c. Cash outflow is zero for \(t>0\)
d. Cash Inflow is the benefits from new equipage per year
e. \(N\) equals 20 years.

The NPV model is also used to estimate the time to a positive ROI or Break Even Time (i.e. the smallest value of \(t\) for which the NPV is greater than zero).
3.8 Summary of the method of implementation

This methodology is demonstrated in a case-study of the benefits of the introduction of a Required Navigation Performance (RNP) approach procedure for air traffic arrival flows in the Chicago Terminal Radar Approach Control (TRACON). The methodology is implemented using GAWK (Daniel, 2010) which is an interpreted programming language designed for text processing and typically used as a data extraction and reporting tool. It is a standard feature of most Unix-like operating systems. A total of 3031 lines of code were written to implement the various modules and algorithms of the methodology. The results described in the next chapter are based off of processing a total of 43 days of NOP track data from year 2010, 2011 and 2012, and 6 years of ASPM airport and flight data from years 2007 to 2012. A total of 1 gigabyte (GB) of NOP track data and 2GB of ASPM data were processed.
CHAPTER 4: CHICAGO METROPLEX CASE STUDY

This chapter describes a case-study of the benefits of Chicago metroplex de-confliction by flow modification using new navigational capabilities. At Chicago metroplex Required Navigation Performance 0.3 (RNP) approach with Radius to Fix (RF) leg has been introduced to runway 13C at MDW to spatially de-conflict the arrival flows to 13C at MDW and departure flows from 22L at ORD (see section 4.1.1 for details). The successful de-confliction of the Chicago metroplex relies on collaboration and simultaneous equipage (RNP approach capability) by airlines at MDW and must be financially viable.

The adoption of RNP approach by airlines has been slow, primarily due to: (a) issues with estimating the Return-on-Investment (ROI) and (b) the “free rider” issue, i.e., the allocation of benefits to parties that choose not to equip but gain benefits when their competition equips. The fundamental research questions related to these issues are:

1. Does airline equipping with RNP approach capability offer a competitive advantage? (section 4.2)
2. Would airline investment in RNP approach capability yield an acceptable Return on Investment (ROI)? (section 4.5)
3. Are there opportunities to improve the ROI? (section 4.4)
4. What portfolio of incentives/strategies exists for achieving airline equipage? (section 5.2)

This case study uses high fidelity surveillance track data coupled with aerodynamic models and weather data to quantify the performance of MDW terminal area air traffic flows to estimate the potential benefits and financial feasibility of the new technology to airlines at MDW. The case study also estimates the allocation of benefits to ORD and MDW from the de-confliction of the metroplex to address the free rider issue.

The overview of the methodology (described in chapter 3) for benefits of RNP approach at Chicago metroplex is shown in Figure 17. The methodology has six functions.

Figure 17: Overview of the methodology for benefits analysis of de-confliction of Chicago metroplex using RNP approach to 13C.
The summary of the overall methodology is as follows:

a. Chicago metroplex de-confliction analysis (functions 2, 3, 4) estimates the total Airline Direct Operating Cost (ADOC) of airborne holding at MDW and departure delays at ORD from the flow conflict between ILS arrivals to runway 13C at MDW and departures from 22L at ORD. The ADOC at MDW and ORD are the annual potential cost savings from elimination of holding patterns for 13C arrivals at MDW and queues for 22L departures at ORD as a result of metroplex de-confliction from using RNP approach to 13C at MDW.

b. Arrival flow analysis at MDW using NOP track data (functions 1 and 3) estimates the performance of the new RNP approach flows to runway 13C in comparison to the conventional approach flows.

c. MDW RNP benefits analysis (function 5) estimates the total potential benefits of using RNP approach procedures to all possible runways and using the optimal runway configuration at MDW.

d. Net Present Value (NPV) analysis (function 6) estimates the ROI of RNP approach for Southwest Airlines.

The Chicago metroplex is chosen for the following reasons:

a. Chicago metroplex is one of the two metroplexes (the other being New York) identified as a candidate for flow de-confliction using RNP approach with RF leg (FAA, 2012h). The new RNP approach to runway 13C at Midway International Airport (MDW) is published and ready for use (FAA, 2012h). At
New York, the new RNP approach procedure is in its testing phase and not yet published for commercial use.

b. The major carrier at MDW (Southwest Airline) is investing $175M in equipping with RNP approach capability (Martin, 2009).

c. Southwest Airlines uses RNP approach procedure at MDW. Analysis of track data for year 2011 shows, on days when 13C is used at MDW during IMC, 9% of the total arrivals use RNP approach.

d. The availability of actual RNP tracks provides an opportunity to estimate, while taking into consideration the variance in terminal flight tracks, its true performance and benefits in comparison to the conventional approaches (ILS and Visual).

This chapter is organized as follows: section 4.1 describes the flow conflict at Chicago metroplex and an overview of the RNP benefits analysis; section 4.2 describes the potential cost saving from elimination of holding patterns for 13C arrivals at MDW and queues for 22L departures at ORD as a result of metroplex de-confliction from using RNP approach to 13C at MDW; section 4.3 describes the arrival flow analysis at MDW and performance of RNP approach in comparison to conventional approach; section 4.4 describes the total potential benefits of RNP approach at MDW from using RNP approaches to other runways, in addition to existing approach to 13C and the optimal runway configuration; and section 4.5 computes the ROI of RNP approach for Southwest Airlines.
4.1 Chicago Metroplex Flow Conflict Analysis
With 3055 operations per day on an average in year 2012, Chicago metroplex is the second largest metroplex in the U.S in terms of traffic volume (ASPM 2012). It has two airports, the Chicago O'Hare International Airport (ORD) and the Chicago Midway International Airport (MDW) within thirteen nautical miles (NM) of each other (see Figure 18).

![Diagram showing Chicago TRACON, ORD and MDW are 13NM and share common terminal airspace.](image)

Figure 18: Chicago TRACON, ORD and MDW are 13NM and share common terminal airspace.

4.1.1 Flow Conflict at Chicago Metroplex
To avoid cross wind landings, when winds are greater than 20 knots and from southeast, the arrivals to MDW must use 13C. When Instrument Meteorological Condition (IMC) exist (i.e. cloud ceiling less than 1,000 feet above ground level or
visibility less than 3 statute miles) these arrivals must use Instrument Landing System (ILS) to runway 13C. The turn on the base leg to the final leg of the ILS approach to 13C can occur 10.1 NM from the runway threshold and is 3NM from end of runway 22L at ORD (see Figure 19).

Figure 19: Flow Conflict at Chicago Metroplex between ORD 22L departures and MDW 13C arrivals, when winds are greater than 20 knots from southeast in IMC

This results in a flow conflict in the shared airspace due to the lack of vertical separation between departures from 22L at ORD and arrivals to 13C at MDW. An analysis of track data shows that arrivals to 13C at MDW are on an average at an altitude of 2800 feet when in the shared airspace. The departure from 22L at ORD using the
shared airspace cannot always climb to an altitude of 3800 feet or more (1000 feet more), required to guarantee safe separation.

The tactical time-based sharing employed by the TRACON enables the use of the common airspace by alternating between departures at ORD and arrivals at MDW. This results in ground holding for departures from 22L at ORD and airborne holding for MDW arrivals to 13C. The ground holdings for departures result in departure delays and in some circumstances may contribute to cancelled flights. The airborne holding for arrivals results in en-route delays.

4.1.2 Chicago Flow Conflict Frequency
An analysis of ASPM data for years 2007 to 2012 shows MDW experiences IMC on an average 13% of the time per year (see Figure 20). Further, runway 13C at MDW is used on an average 12% of the time during IMC (see Figure 21).

![Figure 20: Meteorological Conditions at MDW shows MDW is IMC on an average 13%](image)
A potential flow conflict can occur on an average 1.6% of the time per year when runway 13C is in use during IMC. This amounts to on an average 17 IMC days per year, with the average duration of IMC lasting on an average 5.54 hours per day, as shown in Figure 22.
4.1.3 Chicago Metroplex flow de-confliction using RNP approach
The new RNP approach with radius to fix leg to runway 13C cuts the corner on
the final leg of the approach adding sufficient distance (7NM) to maintain safe vertical
separation between the departure flows from 22L at ORD and arrival flows to 13C at
MDW. This allows arrivals to MDW without interfering with departures from runway
22L at ORD. Figure 23 shows sample RNP approach tracks to runway 13C at MDW and
their relative position to departure from runway 22L at ORD.

Figure 23: De-confliction of flows using RNP approach creates 7NM lateral separation to allow arrivals to MDW
without interfering with departures from runway 22L at ORD.
4.1.4 Overall Approach to Chicago De-confliction Analysis

The successful de-confliction of the Chicago metroplex flows relies on achieving complete equipage for airlines operating at MDW. While the RNP approach procedure has been published and is ready for use, analysis of track data for year 2011 shows, on days when 13C is used at MDW during IMC, 9% of the total arrivals use RNP approach. Therefore, it is important to quantify the benefits and the ROI of RNP approach at MDW from an airlines perspective. The primary benefits of this technology to individual airlines at MDW are cost savings from:

a. Shorter track distance in the terminal airspace compared to conventional instrument approach procedures

b. Elimination of airborne holdings that would otherwise occur due to the metroplex flow conflict.

This chapter uses the methodology described in chapter 3 to quantify the above two benefits at MDW using surveillance NOP track data. In addition, the benefits of elimination of departures queue at runway 22L and the ROI of RNP approach to the majority carrier at MDW (Southwest Airline) have also been estimated. The summary of the overall approach is as follows:

a. Chicago metroplex de-confliction analysis (section 4.2) estimates the total Airline Direct Operating Cost (ADOC) of airborne holding at MDW and departure delays at ORD from the flow conflict between ILS arrivals to runway 13C at MDW and departures from 22L at ORD. The ADOC at MDW and ORD are the annual potential cost savings from elimination of holding
patterns for 13C arrivals at MDW and queues for 22L departures at ORD as a result of metroplex de-confliction from using RNP approach to 13C at MDW.

b. Arrival flow analysis at MDW using NOP track data (section 4.3) estimates the performance of the new RNP approach flows to runway 13C in comparison to the conventional approach flows.

c. MDW RNP benefits analysis (section 4.4) estimates the total potential benefits of using RNP approach procedures to all possible runways and using the optimal runway configuration at MDW.

d. Net Present Value (NPV) analysis (section 4.5) estimates the ROI of RNP approach for Southwest Airlines.

4.2 Benefits of RNP Approach to 13C at MDW to the Chicago Metroplex

The RNP approach to 13C at MDW de-conflict flows between the ILS arrivals to runway 13C at MDW and departures from runway 22L at ORD. The flow conflict at Chicago metroplex is overcome through tactical time based sharing of the common airspace by alternating between departures at ORD and arrival at MDW. This results in ground holding for departures from runway 22L at ORD when arrivals using ILS to runway 13C at MDW are in progress and airborne holding for MDW arrivals to 13C when departures from 22L at ORD are in progress. The ground holdings for departures result in departure delays and cancelled flights. The airborne holdings for arrivals result in en-route delays.

This section computes total Airline Direct Operating Cost (ADOC) of airborne holding at MDW and departure delays at ORD from the flow conflict between ILS
arrivals to runway 13C at MDW and departures from 22L at ORD. The ADOC at MDW and ORD are the annual potential cost savings from elimination of holding patterns for 13C arrivals at MDW and queues for 22L departures at ORD as a result of metroplex de-confliction from using RNP approach to 13C at MDW.

4.2.1 Holding pattern analysis
The holding pattern analysis is conducted using NOP track data and the methodology is described in section 3.3. Boundaries are defined around waypoints with published holding pattern procedures. The total cumulative turn angle of flight track is computed for tracks within the defined boundaries. Tracks with cumulative turn angle of 360 degrees or more are filtered out at holding patterns. The holding pattern tracks and the boundaries defined to capture the holding patterns are shown in Figure 24.

Figure 24: Holding patterns for 13C arrivals detected along the STARs at MDW
Using the algorithm in the step 1 of section 3.5.2, the holding patterns for ILS arrival flow to runway 13C at MDW due to conflict with departures from 22L at ORD are detected. The duration of the conflict period along with the count of arrivals at MDW, departures from ORD, holding patterns and the frequency in terms of holdings per 100 arrivals are shown in Table 9. For the NOP data analyzed, there were a total of 811 ILS arrivals to 13C at MDW and 83 holding patterns during periods of flow conflict. There were on average 10.23 holdings per 100 arrivals.

<table>
<thead>
<tr>
<th>Date (yyyymmdd)</th>
<th>Duration of flow conflict (Hrs)</th>
<th>13C Arrivals</th>
<th>22L Departures</th>
<th>Holding Count</th>
<th>Holding per 100 arrivals</th>
</tr>
</thead>
<tbody>
<tr>
<td>20111214</td>
<td>13.7</td>
<td>292</td>
<td>169</td>
<td>28</td>
<td>10</td>
</tr>
<tr>
<td>20110426</td>
<td>3.7</td>
<td>95</td>
<td>32</td>
<td>25</td>
<td>26</td>
</tr>
<tr>
<td>20110615</td>
<td>2.3</td>
<td>48</td>
<td>26</td>
<td>8</td>
<td>17</td>
</tr>
<tr>
<td>20110223</td>
<td>2.9</td>
<td>46</td>
<td>47</td>
<td>7</td>
<td>15</td>
</tr>
<tr>
<td>20101122</td>
<td>1.0</td>
<td>13</td>
<td>21</td>
<td>7</td>
<td>54</td>
</tr>
<tr>
<td>20110620</td>
<td>1.1</td>
<td>31</td>
<td>78</td>
<td>5</td>
<td>16</td>
</tr>
<tr>
<td>20111126</td>
<td>5.3</td>
<td>110</td>
<td>40</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>20100123</td>
<td>13.7</td>
<td>176</td>
<td>43</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>20120122</td>
<td>13.1</td>
<td>251</td>
<td>49</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20110117</td>
<td>7.7</td>
<td>151</td>
<td>34</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20120213</td>
<td>1.3</td>
<td>24</td>
<td>22</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20101211</td>
<td>7.3</td>
<td>100</td>
<td>22</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20100124</td>
<td>2.2</td>
<td>23</td>
<td>19</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20110124</td>
<td>3.2</td>
<td>57</td>
<td>7</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

The mean and standard deviation of holding pattern’s duration, track distance and fuel burn is shown in Table 10. These are estimated for all aircraft types and for B73’s.
The total annual cost of holding pattern for 13C ILS arrivals at MDW is estimated based on the holding pattern statistics (Table 10) and frequency of holding patterns (Table 9). The analysis is done using the methodology in step 2 of section 3.5.2.

The number of days and duration when the Chicago metroplex had conflicting runway configuration (runway 13C in the arrival configuration at MDW and runway 22L in the departure configuration at ORD) during IMC, the corresponding totals for the number of arrival at 13C at MDW, holding count estimates, fuel burn, en route delay and airline direct operating cost due to the en route delay are shown in Table 11 for years 2007 to 2012.

### Table 10: Holding patterns statistics for holding duration, track distance and fuel burn for the fleet mix at MDW and for B73’s

<table>
<thead>
<tr>
<th>Aircraft Type</th>
<th>Track Count</th>
<th>Holding Duration (min)</th>
<th>Holding Track Distance (NM)</th>
<th>Holding Fuel burn (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
</tr>
<tr>
<td>all</td>
<td>83</td>
<td>18.37</td>
<td>9.08</td>
<td>79.75</td>
</tr>
<tr>
<td>B73</td>
<td>42</td>
<td>16.59</td>
<td>7.90</td>
<td>72.38</td>
</tr>
</tbody>
</table>

### Table 11: Cost of Holding due to flow conflict per year for 13C arrivals

<table>
<thead>
<tr>
<th>Year</th>
<th>Conflict Days per Year</th>
<th>Conflict Duration per Year</th>
<th>Total 13C Arrivals per Year</th>
<th>Holding Count per Year</th>
<th>Total Fuel burn (gallons)</th>
<th>Total Time in Holding (min)</th>
<th>Airline Direct Operating Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>8</td>
<td>2.81</td>
<td>391</td>
<td>40</td>
<td>4517.2</td>
<td>680.0</td>
<td>26618.7</td>
</tr>
<tr>
<td>2008</td>
<td>15</td>
<td>3.63</td>
<td>913</td>
<td>93</td>
<td>10547.8</td>
<td>1587.8</td>
<td>62155.7</td>
</tr>
<tr>
<td>2009</td>
<td>7</td>
<td>2.25</td>
<td>267</td>
<td>27</td>
<td>3084.6</td>
<td>464.3</td>
<td>18177.0</td>
</tr>
<tr>
<td></td>
<td>2010</td>
<td>2011</td>
<td>2012</td>
<td>Average</td>
<td>Std Dev</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------</td>
<td>------</td>
<td>------</td>
<td>------</td>
<td>---------</td>
<td>---------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Year</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>16</td>
<td>12</td>
<td>11</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>%</td>
<td>3.05</td>
<td>2.48</td>
<td>4.52</td>
<td>3.19</td>
<td>0.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flows</td>
<td>424</td>
<td>633</td>
<td>921</td>
<td>592</td>
<td>278</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Delays</td>
<td>43</td>
<td>65</td>
<td>94</td>
<td>61</td>
<td>28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td>4898.4</td>
<td>7313.0</td>
<td>10640.3</td>
<td>6833.6</td>
<td>3215.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Delay</td>
<td>737.4</td>
<td>1100.9</td>
<td>1601.7</td>
<td>1028.7</td>
<td>484.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td>28865.3</td>
<td>43093.7</td>
<td>62700.3</td>
<td>40268.4</td>
<td>18945.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The results indicate that on average there are 61 aircraft that are kept in holding per year as a result of flow conflict between 13C ILS arrivals at MDW and 22L departure at ORD. This results in fuel burn of 6,833 gallon per year on average with a standard deviation of 3,215 and delay of 1,028 minute per year on average with a standard deviation of 484. The average airline direct operating cost (ADOC) due en route delays is $40,268 per year with a standard deviation of 18,945. The ADOC is estimated using Equation 35, Equation 36 and Equation 37.

4.2.2 Departure Delay Analysis

The flow conflict at Chicago metroplex (between departures from 22L at ORD and ILS arrivals to 13C at MDW) results in the reduction of the arrival and departure capacity at ORD. This results in arrival and departure delays and can contribute to cancelled flights at ORD.

This section estimates the excess departure delays and cancellations and their associated costs as a lower bound for the additional cost of metroplex flow conflict to airlines operating at ORD. The excess departure delays and cancelled flights are estimated as the difference in the departures delays and cancelled flights at ORD for flow conflict and no-flow conflict periods. The flow conflict periods are during IMC when MDW is configured to use runway 13C as one of its arrival runways and ORD is
configured to use runway 22L as one of its departure runways. The no-flow conflict periods are during IMC when MDW is not configured to use 13C as one of its arrival runways. The excess departure delays and cancelled flights thus estimated will show the impact of 13C arrivals on ORD departures during IMC.

The number of days and duration when the Chicago metroplex has conflicting runway configuration (runway 13C in the arrival configuration at MDW and runway 22L in the departure configuration at ORD) during IMC and the corresponding statistics for the number of departures, number of cancelled flights, number of delayed flights, percentage delayed and cancelled flights, total delays, average and standard deviation of delay per flight and average airport departure rate (ADR) are shown in Table 12 for year 2007 to 2012. The same set of statistics for periods with no metroplex flow conflict is shown in Table 13.

Table 12: Departure delay and cancellation statistics at ORD during flow conflict periods

<table>
<thead>
<tr>
<th>Year</th>
<th>Days</th>
<th>Avg Duration (Hrs)</th>
<th>Flight Flow Count</th>
<th>Cancelled Flights</th>
<th>Delayed Flights</th>
<th>% Delayed</th>
<th>% Cancelled</th>
<th>Total Delay (min)</th>
<th>Avg Delay per flight (min)</th>
<th>SD Delay per flight</th>
<th>Avg ADR per 15 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>8</td>
<td>2.61</td>
<td>1441</td>
<td>218</td>
<td>1235</td>
<td>74.44244</td>
<td>13.14</td>
<td>82405</td>
<td>57.19</td>
<td>65.69</td>
<td>18.84</td>
</tr>
<tr>
<td>2008</td>
<td>15</td>
<td>3.63</td>
<td>3561</td>
<td>179</td>
<td>2685</td>
<td>71.79144</td>
<td>4.79</td>
<td>139349</td>
<td>39.13</td>
<td>52.13</td>
<td>16.94</td>
</tr>
<tr>
<td>2009</td>
<td>7</td>
<td>2.25</td>
<td>382</td>
<td>76</td>
<td>515</td>
<td>53.20248</td>
<td>7.85</td>
<td>30579</td>
<td>34.28</td>
<td>57.41</td>
<td>17.90</td>
</tr>
<tr>
<td>2010</td>
<td>10</td>
<td>3.05</td>
<td>1843</td>
<td>130</td>
<td>1186</td>
<td>60.11151</td>
<td>6.59</td>
<td>56044</td>
<td>30.41</td>
<td>44.38</td>
<td>18.48</td>
</tr>
<tr>
<td>2011</td>
<td>16</td>
<td>2.48</td>
<td>2384</td>
<td>115</td>
<td>1333</td>
<td>53.32</td>
<td>4.64</td>
<td>69305</td>
<td>29.07</td>
<td>47.23</td>
<td>19.04</td>
</tr>
<tr>
<td>2012</td>
<td>12</td>
<td>4.52</td>
<td>3215</td>
<td>119</td>
<td>2014</td>
<td>60.40792</td>
<td>3.57</td>
<td>92745</td>
<td>28.85</td>
<td>49.58</td>
<td>19.17</td>
</tr>
<tr>
<td>Average</td>
<td>11</td>
<td>3.19</td>
<td>2223</td>
<td>140</td>
<td>1495</td>
<td>63.27</td>
<td>5.91</td>
<td>78405</td>
<td>35.27</td>
<td>NA</td>
<td>18.36</td>
</tr>
<tr>
<td>Std Dev</td>
<td>3</td>
<td>1</td>
<td>942</td>
<td>46</td>
<td>687</td>
<td>8</td>
<td>3</td>
<td>33680</td>
<td>52.44</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>
The results indicate that during the flow conflict periods there are on average 2,362 scheduled departures per year at ORD, with 63.25% delayed and 5.91% cancelled flights. The average delay per flight on average is 35.27 minutes with standard deviation 52.44.

During periods of no flow conflict there are on average 26,746 scheduled departures per year at ORD, with 46.62% delayed and 4.73% cancelled flights. The average departure delay per flight on average is 24.37 minutes with standard deviation 46.70.

The flow conflict at Chicago metroplex results in 16.63% additional delayed flights and 1.18% additional cancelled flights. The average additional departure delay per flights is 11.35 minutes.

The de-confliction of the airspace by introduction of RNP approach to runway 13C at MDW could potentially result in savings of 51,563 minutes of excess total delays and 28 cancelled flights per year for departures at ORD. This amounts to $1.33M in
additional airline direct operating cost (ADOC) at the rate of $1386 per hour for ground delays (taxi-out) at ORD (computed using Equation 31, Equation 32, Equation 33) and $4977 per cancellation (FAA, 2012i).

4.2.3 Summary of Benefit of PBN Approach Procedure at Chicago Metroplex
   This section presents the benefits to Chicago metroplex from de-confliction of flows by airspace redesign using RNP approach to runway 13C at MDW.

   The flow conflict between 13C ILS arrivals at MDW and 22L departures at ORD in the Chicago metroplex occur on an average 1.6% of the time per year. The introduction of the RNP approach to 13C at MDW to de-conflict the traffic flow for these periods is estimated to reduce the direct airline operating cost per year on an average by $.04M at MDW and $1.33M at ORD.

   The magnitude of the benefits of de-confliction for the operator expected (airlines at MDW) to equip is small and the asymmetry in benefits between competing operators (airlines at MDW and ORD) in neighboring airports is large (1:33 in favor of ORD departures). As a result, there is no competitive advantage for MDW airlines in equipping due to the free rider issue. However, the successful de-confliction of Chicago metroplex relies on achieving complete equipage (RNP approach capability) for airlines operating at MDW.

4.3 Arrival Flow Analysis at MDW

4.3.1 Flow Characterization
   The flows are characterized by specifying a direction, runway and arrival approach procedure. This is done by studying the runway configuration and published arrival procedure for the airport.
At MDW there are ten runways, as shown in Figure 25. Of these, runway 13C, 31C and 4R have ILS. Runway 13C has an RNP approach as well. In IMC, the arrivals into MDW are restricted (depending on the wind conditions) to one of the three ILS runways.

![MDW runway configuration](image)

**Figure 25:** MDW runway configuration (Source: airnav.com), runways 13C, 31C and 22L have ILS, and only runway 13C has RNP 0.3 w/ RF leg approach (2011)

For arrivals into MDW there are three STARs one from the west and two from the east. The two STARs (one RNAV and one conventional) from the east terminate at Chicago Heights VORTAC (CGT) and the STAR from the west terminates at Joliet VORTAC (JOT) (Figure 2). These two waypoints feed traffic into the terminal area at MDW.
Figure 26: Location of Final waypoint on STAR w.r.t the airport (MDW).

The location of the final waypoint on the STAR with respect to the runways determines the direction from which the traffic flows. These combined with the runway and arrival approach procedure characterize various TRACON flows. For instance, at MDW flights arriving from JOT for an ILS approach to runway 13C are assigned to “W 13C ILS” flow. Similarly “E 13C RNP” flow will consist of flights arriving from the CGT (east waypoint) to runway 13C for an RNP approach.

A total of 28 flows are possible at MDW based on the characterization process described above. A summary of the counting process is shown in Table 14.
Table 14: Total Possible flows at MDW by matching the final STAR waypoint with the approach type and runway

<table>
<thead>
<tr>
<th>Rwy</th>
<th>Approach</th>
<th>Direction</th>
<th>Total</th>
<th>Flows</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Visual</td>
<td>ILS</td>
<td>RNP</td>
<td></td>
</tr>
<tr>
<td>13C</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>13L</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>13R</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>4R</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>4L</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>31C</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>31L</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>31R</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>22L</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>22R</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td></td>
<td></td>
<td>28</td>
</tr>
</tbody>
</table>

4.3.2 Flow Assignment Results

Forty three days of NOP track data for Chicago TRACON (C90) are analyzed. The days are selected from the years 2010, 2011 and 2012 to cover various meteorological conditions and runway configurations at MDW. After filtering out general aviation flights a total of 11,275 tracks are processed. A total of 438 tracks are filtered out as incomplete tracks or go-arounds.

Runways 13R/31L are excluded from the assignment process because they are too short for commercial flight landings (FAA, 2005a) and too close to runways 13C/31C making it difficult to accurately assign them flight tracks.

The flight count obtained from the track data for the remaining 24 flows are shown in Table 15. The flow track count indicates that runways 13C, 31C, 4R and 22L are the four major runways at MDW. The 16 flows associated with these runways are highlighted in Table 15. This analysis will focus on these 16 flows.
Table 15: Flow Assignment results for MDW from track data. Runways 13C, 31C, 4R and 22L are the major runways used.

<table>
<thead>
<tr>
<th>Sl.no</th>
<th>Direction</th>
<th>Runway</th>
<th>Approach</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>E</td>
<td>13C</td>
<td>ILS</td>
<td>798</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td>RNP</td>
<td>87</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td>Visual</td>
<td>1026</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>13L</td>
<td>Visual</td>
<td>8</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>22L</td>
<td>Visual</td>
<td>840</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>22R</td>
<td>Visual</td>
<td>70</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>31C</td>
<td>ILS</td>
<td>1467</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
<td>Visual</td>
<td>345</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>31R</td>
<td>Visual</td>
<td>5</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>4L</td>
<td>Visual</td>
<td>48</td>
</tr>
<tr>
<td>11</td>
<td></td>
<td>4R</td>
<td>ILS</td>
<td>390</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td></td>
<td>Visual</td>
<td>1181</td>
</tr>
<tr>
<td>13</td>
<td>W</td>
<td>13C</td>
<td>ILS</td>
<td>568</td>
</tr>
<tr>
<td>14</td>
<td></td>
<td></td>
<td>RNP</td>
<td>151</td>
</tr>
<tr>
<td>15</td>
<td></td>
<td></td>
<td>Visual</td>
<td>857</td>
</tr>
<tr>
<td>16</td>
<td></td>
<td>13L</td>
<td>Visual</td>
<td>9</td>
</tr>
<tr>
<td>17</td>
<td></td>
<td>22L</td>
<td>Visual</td>
<td>650</td>
</tr>
<tr>
<td>18</td>
<td></td>
<td>22R</td>
<td>Visual</td>
<td>56</td>
</tr>
<tr>
<td>19</td>
<td></td>
<td>31C</td>
<td>ILS</td>
<td>387</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td></td>
<td>Visual</td>
<td>987</td>
</tr>
<tr>
<td>21</td>
<td></td>
<td>31R</td>
<td>Visual</td>
<td>2</td>
</tr>
<tr>
<td>22</td>
<td></td>
<td>4L</td>
<td>Visual</td>
<td>50</td>
</tr>
<tr>
<td>23</td>
<td></td>
<td>4R</td>
<td>ILS</td>
<td>729</td>
</tr>
<tr>
<td>24</td>
<td></td>
<td></td>
<td>Visual</td>
<td>564</td>
</tr>
</tbody>
</table>

The major flows (in terms of the flow track count) from the east and the west are the ILS, RNP and Visual approaches on to runway 13C, the ILS and Visual approaches on to runway 4R and 31C and the Visual approaches on to runway 22L. A sample of these flows along with the legend is shown in Figure 7 and Figure 8.
Figure 27: Sample of the eight major flows from the east at MDW

Figure 28: Sample of the eight major flows from the west at MDW
4.3.3 Flow Performance Statistics

This section describes the performance of TRACON flows in terms of track distance (NM), time (min) and fuel burn (kg) in the terminal airspace. The performance metrics are measured from the abeam (see Figure 27 and Figure 28) on the final waypoint to STAR to the runway threshold.

The analysis is conducted using National Offload Program (NOP) data for 43 days selected to provide data for the 16 flows at MDW. After filtering out general aviation flight a total 11,275 tracks are processed. A total of 438 tracks are filtered out as incomplete tracks or go-arounds.

The performance metrics are computed for runways 13C, 31C, 22L and 4R for:

1. Individual flows from the east and the west
2. Approach type (ILS, Visual or RNP); by combining flows from east and west for an approach type
3. All flows (approach type and direction) combined for a given runway.

The runways are ranked (from lowest to highest) based on the track distance, track time and fuel burn statistics.

4.3.3.1 Track Time and Distance Statistics

The ranking of runways, from best to worse, based on individual flows from the east is shown in Table 16. The flows are ranked based on mean track distance and mean track time of each flow.

From the east the ILS and Visual approach on to runway 31C are the shortest as this is a straight-in approach. This is followed by visual approach on to runways 22L, 4R, and 13C, the ILS approach on to 4R, RNP approach on to 13C and finally ILS approach
on to 13C. For flows from the east, the ILS to 13C has the longest track distance and time.

Table 16: Ranking of runways by mean Track Time for flows from the East (lowest to highest)

<table>
<thead>
<tr>
<th>Dir/Runway/Approach</th>
<th>Count</th>
<th>Track Time (min)</th>
<th>Distance (NM)</th>
<th># of Turns in the Terminal Airspace</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
</tr>
<tr>
<td>E 31C ILS</td>
<td>1467</td>
<td>5.90</td>
<td>0.69</td>
<td>16.56</td>
</tr>
<tr>
<td>E 31C Visual</td>
<td>345</td>
<td>6.12</td>
<td>0.80</td>
<td>16.77</td>
</tr>
<tr>
<td>E 22L Visual</td>
<td>840</td>
<td>6.71</td>
<td>0.83</td>
<td>20.39</td>
</tr>
<tr>
<td>E 4R Visual</td>
<td>1181</td>
<td>8.84</td>
<td>1.77</td>
<td>28.74</td>
</tr>
<tr>
<td>E 13C Visual</td>
<td>1026</td>
<td>9.62</td>
<td>1.59</td>
<td>32.58</td>
</tr>
<tr>
<td>E 4R ILS</td>
<td>390</td>
<td>10.92</td>
<td>2.58</td>
<td>33.59</td>
</tr>
<tr>
<td>E 13C RNP</td>
<td>87</td>
<td>13.40</td>
<td>1.88</td>
<td>45.31</td>
</tr>
<tr>
<td>E 13C ILS</td>
<td>798</td>
<td>14.37</td>
<td>2.21</td>
<td>48.20</td>
</tr>
</tbody>
</table>

It should be noted that despite the accuracy of the RNP approach procedure, the variance of the RNP flow from the east to runway 13C is almost as high as the corresponding ILS approach. The variance in RNP approach flow occurs on the downwind and turn-to-base, while the variance on the ILS approach occurs by “tromboning” on the downwind, base leg and the turn to final. This phenomenon is illustrated in Figure 29.
Figure 29: Comparison of ILS and RNP approach flow from the East to runway 13C. The variance in the RNP approach flows is induced in the base leg for safe merging and spacing.

The ranking of runways, from best to worse, based on individual flows from the west is shown in Table 17. For flows from the west, the ILS and visual approach on to runway 4R are the shortest followed by, RNP, visual and ILS on to 13C, visual approach on to 31C, visual approach on to 22L and ILS on to 31C.

Table 17: Ranking of runways by mean Track Time for flows from the West (lowest to highest)

<table>
<thead>
<tr>
<th>Dir/Runway/Approach</th>
<th>Count</th>
<th>Track Time (min)</th>
<th>Track Distance (NM)</th>
<th># of Turns in the Terminal Airspace</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
</tr>
<tr>
<td>W 4R ILS</td>
<td>729</td>
<td>8.58</td>
<td>0.89</td>
<td>28.94</td>
</tr>
<tr>
<td>W 4R Visual</td>
<td>564</td>
<td>9.07</td>
<td>1.27</td>
<td>29.34</td>
</tr>
<tr>
<td>W 13C RNP</td>
<td>151</td>
<td>9.47</td>
<td>0.67</td>
<td>32.67</td>
</tr>
<tr>
<td>W 13C Visual</td>
<td>857</td>
<td>9.65</td>
<td>1.11</td>
<td>33.59</td>
</tr>
<tr>
<td>W 13C ILS</td>
<td>568</td>
<td>10.63</td>
<td>1.01</td>
<td>36.22</td>
</tr>
<tr>
<td>W 31C Visual</td>
<td>987</td>
<td>11.91</td>
<td>1.94</td>
<td>42.90</td>
</tr>
<tr>
<td>W 22L Visual</td>
<td>650</td>
<td>12.39</td>
<td>2.07</td>
<td>46.16</td>
</tr>
<tr>
<td>W 31C ILS</td>
<td>387</td>
<td>13.77</td>
<td>2.39</td>
<td>47.44</td>
</tr>
</tbody>
</table>
The variance in flow increases with the total distance and time in the terminal area and the number of turns made. For instance, consider flows on to runway 13C from east and west. The 13C flows from the east are longer and make two turns before the final approach; whereas, the 13C flows from the west are direct and make one turn before the final approach. As a result, flows to runway 13C from the west are efficient and have lower variance compared to the flows from the East (Figure 30).

The x-axis is the track distance and the y-axis is the normalized frequency. The vertical line marks the mean of the distribution. For flows to runway 13C from the east, the track distance distribution about the mean is wide spread and has a fat tail. This is caused by the vectoring in the terminal. For flows to runway 13C from the west, the track distance distribution about the mean is tight, especially for the RNP flow.

The flows from east and west consolidated and ranked by approach type are shown in Table 18. The first three rows show track time and track distance statistics for
the ILS approach, followed by RNP approach to runway 13C, and visual approaches to the major four runways 4R, 31C, 22L and 13C at MDW. Runway 22L does on have an ILS approach and only runway 13C has a RNP approach.

Table 18: Runways/Approach type ranked by Mean Track Time (lowest to highest) for arrivals from the east and the west combined.

<table>
<thead>
<tr>
<th>Runway/Approach</th>
<th>Count</th>
<th>Track Time (min)</th>
<th>Track Distance (NM)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>4R ILS</td>
<td>1119</td>
<td>9.75</td>
<td>2.26</td>
</tr>
<tr>
<td>31C ILS</td>
<td>1854</td>
<td>9.83</td>
<td>4.31</td>
</tr>
<tr>
<td>13C ILS</td>
<td>1366</td>
<td>12.50</td>
<td>2.54</td>
</tr>
<tr>
<td>13C RNP</td>
<td>238</td>
<td>11.44</td>
<td>2.42</td>
</tr>
<tr>
<td>4R Visual</td>
<td>1745</td>
<td>8.95</td>
<td>1.54</td>
</tr>
<tr>
<td>31C Visual</td>
<td>1332</td>
<td>9.02</td>
<td>3.25</td>
</tr>
<tr>
<td>22L Visual</td>
<td>1490</td>
<td>9.55</td>
<td>3.25</td>
</tr>
<tr>
<td>13C Visual</td>
<td>1883</td>
<td>9.64</td>
<td>1.37</td>
</tr>
</tbody>
</table>

For ILS approaches the flow statistics for 4R and 31C are nearly the same, followed by 13C. For visual approaches 4R is the shortest, followed by 31C, 22L and 13C. The RNP approach on to 13C is on an average shorter than the corresponding ILS approach by 1.06 minute in terms of time and 3.22NM in terms of distance. The RNP approach to 13C is on average 8% shorter track time and track distance than the ILS approach to 13C.

The visual approaches are shorter than the corresponding ILS approaches by 11% for 4R, 15% for 31C, and 23% for 13C.
The visual approach on to 13C is shorter than the RNP approach by 1.8 minute in terms of time and 5.91 NM in terms of distance.

The overall ranking for runways is shown irrespective of direction of flow or type of approach is shown in Table 19. On the whole, flows to runway 4R have the lowest mean track distance (30.15 NM) and track time (9.35 minute) followed by 31C (30.92 NM and 9.42 minute), 22L (33.27 NM and 9.55 minute, and 13C (38.10 NM and 11.19 minute).

Table 19: Runways ranked by mean Track Time (lowest to highest)

<table>
<thead>
<tr>
<th>Rwy</th>
<th>Count</th>
<th>Track Time (min)</th>
<th>Track Distance (NM)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean  SD</td>
<td>Mean SD</td>
</tr>
<tr>
<td>4R</td>
<td>2864</td>
<td>9.35  1.97</td>
<td>30.15  4.14</td>
</tr>
<tr>
<td>31C</td>
<td>3186</td>
<td>9.42  3.84</td>
<td>30.92  14.86</td>
</tr>
<tr>
<td>22L</td>
<td>1490</td>
<td>9.55  3.25</td>
<td>33.27  13.43</td>
</tr>
<tr>
<td>13C</td>
<td>3487</td>
<td>11.19 2.48</td>
<td>38.10  7.23</td>
</tr>
</tbody>
</table>

4.3.3.2 Fuel Burn Performance Statistics

At MDW there are 98 aircraft types (jets and turbo props). The list of aircraft types in each category is shown in Figure 31. The narrow body aircrafts account of 76% of the flights into MDW, followed by business jets (15%), regional jets (5%) and turbo props (4%). The most dominant aircraft type, the Boeing 73’s (B73’s), accounts for 72% of the flights at MDW.
4.3.3.2.1 Fuel Burn Performance Statistics by Flow

At MDW all arrival flows except for the RNP approach on to 13C have a fleet mix shown in Figure 31. The RNP approach on to 13C, first published in 2011 is used on a limited basis by Southwest airlines, whose fleet consists of Boeing 737’s. Analysis of track data for year 2011 shows on days when 13C is used at MDW during IMC nine percent of the Southwest arrivals use RNP approach.

This section describes fuel burn performance statistics for flows from the east and west for all aircraft types as shown in Table 20 and Table 21. Also, to show the benefits of the RNP approach, the fuel burn performance of B73’s are also computed and shown in Table 22 and Table 23.

The tables also show track-time, level-time statistics and the mean level-time to track-time ratio. The track time is the total time taken by the flight from the final
waypoint on the STAR to the runway threshold. The level time is the total level off time from the final waypoint on the STAR to the runway threshold, (i.e. when the change is the vertical profile is less than 100 feet per minute). The flows are ranked (from least to most) based on the average fuel burn per flight.

From the east, the ILS and Visual approaches on to runway 31C (100.48 kg and 100.72 kg) have the lowest average fuel burn per flight, followed by the visual approaches on to runways 22L, 4R and 13C (140.20 kg, 189.14 kg and 206.28 kg) and the ILS approach on to runway 4R (279 kg) and runway 13C (336.5 kg) (Table 20).

From the west, ILS and visual approaches on to runway 4R (160.66 kg and 162.12 kg) have the lowest fuel burn per flight, followed by the visual and ILS approaches on to runway 13C (181.19 kg and 215.68 kg), visual approaches on to runway 31C and 22L (249.9 kg and 275.32 kg) and the ILS approach on to runway 31C (313.4 kg) (Table 21).

<table>
<thead>
<tr>
<th>Flow</th>
<th>Track Count</th>
<th>Fuel Burn (kg/flight)</th>
<th>Track time (min)</th>
<th>Level Time (min)</th>
<th>% Level</th>
<th># of Turns in the Terminal Airspace</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dir/Rwy/Procedure</td>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
</tr>
<tr>
<td>E 31C Visual</td>
<td>345</td>
<td>100.48</td>
<td>47.00</td>
<td>6.12</td>
<td>0.80</td>
<td>0.42</td>
</tr>
<tr>
<td>E 31C ILS</td>
<td>1467</td>
<td>100.72</td>
<td>45.77</td>
<td>5.90</td>
<td>0.69</td>
<td>0.43</td>
</tr>
<tr>
<td>E 22L Visual</td>
<td>840</td>
<td>140.20</td>
<td>59.21</td>
<td>6.71</td>
<td>0.83</td>
<td>0.42</td>
</tr>
<tr>
<td>E 4R Visual</td>
<td>1181</td>
<td>189.14</td>
<td>101.82</td>
<td>8.84</td>
<td>1.77</td>
<td>2.25</td>
</tr>
<tr>
<td>E 13C Visual</td>
<td>1026</td>
<td>206.28</td>
<td>100.74</td>
<td>9.62</td>
<td>1.59</td>
<td>1.89</td>
</tr>
<tr>
<td>E 4R ILS</td>
<td>390</td>
<td>279.00</td>
<td>161.18</td>
<td>10.92</td>
<td>2.58</td>
<td>3.50</td>
</tr>
<tr>
<td>E 13C ILS</td>
<td>798</td>
<td>336.50</td>
<td>164.49</td>
<td>14.37</td>
<td>2.21</td>
<td>6.40</td>
</tr>
</tbody>
</table>

Table 20: Fuel burn, Track time and Level time Statistics for flows from the east, for all aircrafts, ranked by fuel burn

From the west, ILS and visual approaches on to runway 4R (160.66 kg and 162.12 kg) have the lowest fuel burn per flight, followed by the visual and ILS approaches on to runway 13C (181.19 kg and 215.68 kg), visual approaches on to runway 31C and 22L (249.9 kg and 275.32 kg) and the ILS approach on to runway 31C (313.4 kg) (Table 21).
Table 21: Fuel burn, Track time and Level time Statistics for flows from the west, for all aircrafts, ranked by fuel burn

<table>
<thead>
<tr>
<th>Flow</th>
<th>Count</th>
<th>Fuel Burn (kg)</th>
<th>Track time (min)</th>
<th>Level Time (min)</th>
<th>% Level</th>
<th># of Turns in the Terminal Airspace</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>W 4R Visual</td>
<td>564</td>
<td>160.66</td>
<td>62.52</td>
<td>9.07</td>
<td>1.35</td>
<td>1.41 1.58</td>
</tr>
<tr>
<td>W 4R ILS</td>
<td>729</td>
<td>162.12</td>
<td>54.50</td>
<td>8.57</td>
<td>0.92</td>
<td>1.26 1.12</td>
</tr>
<tr>
<td>W 13C Visual</td>
<td>861</td>
<td>181.19</td>
<td>75.03</td>
<td>9.63</td>
<td>1.11</td>
<td>1.10 1.14</td>
</tr>
<tr>
<td>W 13C ILS</td>
<td>568</td>
<td>215.68</td>
<td>86.33</td>
<td>10.61</td>
<td>1.03</td>
<td>2.51 1.64</td>
</tr>
<tr>
<td>W 31C Visual</td>
<td>987</td>
<td>249.90</td>
<td>113.66</td>
<td>11.89</td>
<td>1.97</td>
<td>3.45 2.02</td>
</tr>
<tr>
<td>W 22L Visual</td>
<td>650</td>
<td>275.32</td>
<td>109.19</td>
<td>12.37</td>
<td>2.11</td>
<td>3.24 1.95</td>
</tr>
<tr>
<td>W 31C ILS</td>
<td>387</td>
<td>313.40</td>
<td>142.85</td>
<td>13.75</td>
<td>2.42</td>
<td>4.68 2.47</td>
</tr>
</tbody>
</table>

When tower managers select a runway configuration in no wind conditions, 13C is the most equitable runway with the 14% difference in fuel burn for VFR flights from the east and the west, followed by 4R (18%), 22L (96%) and 31C (148%). The same is true during IMC, 13C (56%) is the most equitable runway followed by 4R (72%) and 31C (211%).

Operational efficiency is maximized when the arrival flow crosses the final waypoint on the STAR and flies a straight course to the runway. The ILS and visual approaches from the east on to runway 31C and from the west on to 4R have a straight approach from the final way point on the STAR. The fuel burn performances of these flows are the best when compared to other flows from the same direction.

The fuel burn performance of RNP approach flows for B73’s aircraft type is compared to the performance of other flows in Table 22 and Table 23. The RNP approach on to runway 13C ranks second last among flows from the east and third from
the top among flows from the west. It also burns on average 41-52 kg less fuel per flight per approach compared to the corresponding ILS approach and 0-114 kg more fuel per flight per approach compared to the corresponding visual approach. For RNP approach to runway 13C from the east, the vectors (for safe merging and spacing) in the base leg (before the start of the approach procedure) result in level off and higher fuel burn rate.

Table 22: Fuel burn, Track time and Level time Statistics for flows from the east, for B73’s, ranked by fuel burn

<table>
<thead>
<tr>
<th>Flow</th>
<th>Track Count</th>
<th>Fuel Burn (kg) Mean</th>
<th>SD</th>
<th>Track time (min) Mean</th>
<th>SD</th>
<th>Level Time (min) Mean</th>
<th>SD</th>
<th>% Level</th>
<th># of Turns in the Terminal Airspace</th>
</tr>
</thead>
<tbody>
<tr>
<td>E 31C ILS</td>
<td>961</td>
<td>119.49</td>
<td>39.59</td>
<td>5.92</td>
<td>0.72</td>
<td>0.41</td>
<td>0.77</td>
<td>6.91</td>
<td>Straight-In</td>
</tr>
<tr>
<td>E 31C Visual</td>
<td>215</td>
<td>121.03</td>
<td>39.68</td>
<td>6.14</td>
<td>0.91</td>
<td>0.43</td>
<td>0.93</td>
<td>7.03</td>
<td>Straight-In</td>
</tr>
<tr>
<td>E 22L Visual</td>
<td>606</td>
<td>158.09</td>
<td>48.35</td>
<td>6.69</td>
<td>0.80</td>
<td>0.39</td>
<td>0.64</td>
<td>5.76</td>
<td>One turn</td>
</tr>
<tr>
<td>E 4R Visual</td>
<td>842</td>
<td>216.36</td>
<td>95.36</td>
<td>8.72</td>
<td>1.81</td>
<td>2.11</td>
<td>1.72</td>
<td>24.16</td>
<td>One turn</td>
</tr>
<tr>
<td>E 13C Visual</td>
<td>673</td>
<td>248.06</td>
<td>78.27</td>
<td>9.59</td>
<td>1.60</td>
<td>1.84</td>
<td>1.31</td>
<td>19.22</td>
<td>Two turns</td>
</tr>
<tr>
<td>E 4R ILS</td>
<td>285</td>
<td>328.15</td>
<td>149.86</td>
<td>10.94</td>
<td>2.61</td>
<td>3.52</td>
<td>2.40</td>
<td>32.20</td>
<td>Two turns</td>
</tr>
<tr>
<td>E 13C RNP</td>
<td>87</td>
<td>362.26</td>
<td>91.46</td>
<td>13.32</td>
<td>2.08</td>
<td>4.69</td>
<td>1.96</td>
<td>35.21</td>
<td>Two turns</td>
</tr>
<tr>
<td>E 13C ILS</td>
<td>520</td>
<td>414.67</td>
<td>121.84</td>
<td>14.30</td>
<td>2.14</td>
<td>6.38</td>
<td>2.49</td>
<td>44.62</td>
<td>Two Turns</td>
</tr>
</tbody>
</table>

Table 23: Fuel burn, Track time and Level time Statistics for flows from the west, for B73’s, ranked by fuel burn

<table>
<thead>
<tr>
<th>Flow</th>
<th>Track Count</th>
<th>Fuel Burn (kg) Mean</th>
<th>SD</th>
<th>Track time (min) Mean</th>
<th>SD</th>
<th>Level Time (min) Mean</th>
<th>SD</th>
<th>% Level</th>
<th># of Turns in the Terminal Airspace</th>
</tr>
</thead>
<tbody>
<tr>
<td>W 4R ILS</td>
<td>548</td>
<td>178.17</td>
<td>42.04</td>
<td>8.51</td>
<td>0.88</td>
<td>1.23</td>
<td>1.06</td>
<td>14.49</td>
<td>Straight-In</td>
</tr>
<tr>
<td>W 4R Visual</td>
<td>423</td>
<td>178.40</td>
<td>54.16</td>
<td>8.95</td>
<td>1.17</td>
<td>1.22</td>
<td>1.40</td>
<td>13.68</td>
<td>Straight-In</td>
</tr>
<tr>
<td>W 13C RNP</td>
<td>144</td>
<td>206.31</td>
<td>46.70</td>
<td>9.44</td>
<td>0.83</td>
<td>1.25</td>
<td>1.06</td>
<td>13.28</td>
<td>One turn</td>
</tr>
<tr>
<td>W 13C Visual</td>
<td>615</td>
<td>206.47</td>
<td>56.89</td>
<td>9.59</td>
<td>1.11</td>
<td>1.02</td>
<td>1.10</td>
<td>10.68</td>
<td>One turn</td>
</tr>
<tr>
<td>W 13C ILS</td>
<td>416</td>
<td>247.56</td>
<td>64.54</td>
<td>10.57</td>
<td>0.96</td>
<td>2.44</td>
<td>1.61</td>
<td>23.11</td>
<td>Two turns</td>
</tr>
<tr>
<td>W 31C Visual</td>
<td>734</td>
<td>286.98</td>
<td>95.86</td>
<td>11.82</td>
<td>1.91</td>
<td>3.35</td>
<td>1.93</td>
<td>28.36</td>
<td>One turn</td>
</tr>
<tr>
<td>W 22L Visual</td>
<td>495</td>
<td>306.80</td>
<td>90.87</td>
<td>12.37</td>
<td>2.04</td>
<td>3.19</td>
<td>1.90</td>
<td>25.79</td>
<td>Two turns</td>
</tr>
<tr>
<td>W 31C ILS</td>
<td>295</td>
<td>355.2</td>
<td>122.9</td>
<td>13.63</td>
<td>2.4</td>
<td>4.535</td>
<td>2.5</td>
<td>33.27</td>
<td>Two Turns</td>
</tr>
</tbody>
</table>
4.3.3.2.2 Fuel Burn Performance Statistics by Approach Type

The fuel burn performance for flows from the east and west are consolidated (assuming equal weights for traffic from the east and the west) to get fuel burn per flight for each runway and approach. These are ranked based on the average fuel burn per flight, as shown in Table 24 (fleet mix) and Table 25 (only B737s). Runway 22L does not have an ILS approach and only runway 13C has a RNP approach (see Table 25).

For the fleet mix at MDW the ranking of runways for ILS approach is 31C (207.06 kg) followed by 4R (+6.5%) and 13C (+33%). For visual approach the ranking is 4R (174.9 kg) followed by 31C (+.1%), 13C (+11%), and 22L (+19%).

The fuel burn for visual approaches on to runways 31C, 4R and 13C is less than the corresponding ILS approach by 15%, 20% and 30% respectively.

<table>
<thead>
<tr>
<th>Runway/Approach</th>
<th>Track Count</th>
<th>Fuel Burn (kg/flight)</th>
<th>Track time (min)</th>
<th>Level Time (min)</th>
<th>% Level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>31C ILS</td>
<td>1854</td>
<td>207.06</td>
<td>150.20</td>
<td>9.83</td>
<td>4.31</td>
</tr>
<tr>
<td>4R ILS</td>
<td>1119</td>
<td>220.56</td>
<td>133.75</td>
<td>9.75</td>
<td>2.27</td>
</tr>
<tr>
<td>13C ILS</td>
<td>1366</td>
<td>276.09</td>
<td>144.58</td>
<td>12.49</td>
<td>2.55</td>
</tr>
<tr>
<td>4R Visual</td>
<td>1745</td>
<td>174.90</td>
<td>85.68</td>
<td>8.95</td>
<td>1.58</td>
</tr>
<tr>
<td>31C Visual</td>
<td>1332</td>
<td>175.19</td>
<td>114.65</td>
<td>9.01</td>
<td>3.25</td>
</tr>
<tr>
<td>13C Visual</td>
<td>1887</td>
<td>193.74</td>
<td>89.70</td>
<td>9.62</td>
<td>1.37</td>
</tr>
<tr>
<td>22L Visual</td>
<td>1490</td>
<td>207.76</td>
<td>110.81</td>
<td>9.54</td>
<td>3.25</td>
</tr>
</tbody>
</table>

Table 24: Fuel burn, Track time, Level Time Statistics for all aircrafts at MDW, by approach type, ranked by fuel burn
For B737s, the RNP approach on to 13C requires an average of 14% less fuel than the ILS approach on to 13C. At $3/gallon, this is equivalent to on average savings of $47 per flight per approach. The visual approach to 13C burns on average 20% less fuel than the corresponding RNP approach (see Table 25).

### Table 25: Fuel burn, Track time, Level Time Statistics for B73’s at MDW, by approach type, ranked by fuel burn

<table>
<thead>
<tr>
<th>Runway/Approach</th>
<th>Track Count</th>
<th>Fuel Burn (kg/flight) Mean</th>
<th>SD</th>
<th>Track time (min) Mean</th>
<th>SD</th>
<th>Level Time (min) Mean</th>
<th>SD</th>
<th>% Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>31C ILS</td>
<td>1256</td>
<td>237.36</td>
<td>149.08</td>
<td>9.78</td>
<td>4.24</td>
<td>2.47</td>
<td>2.76</td>
<td>25.29</td>
</tr>
<tr>
<td>4R ILS</td>
<td>833</td>
<td>253.16</td>
<td>133.18</td>
<td>9.72</td>
<td>2.30</td>
<td>2.38</td>
<td>2.18</td>
<td>24.45</td>
</tr>
<tr>
<td>13C ILS</td>
<td>936</td>
<td>331.12</td>
<td>128.40</td>
<td>12.44</td>
<td>2.50</td>
<td>4.41</td>
<td>2.88</td>
<td>35.48</td>
</tr>
<tr>
<td>13C RNP</td>
<td>231</td>
<td>284.28</td>
<td>106.55</td>
<td>11.38</td>
<td>2.50</td>
<td>2.97</td>
<td>2.33</td>
<td>26.12</td>
</tr>
<tr>
<td>4R Visual</td>
<td>1265</td>
<td>197.38</td>
<td>79.84</td>
<td>8.83</td>
<td>1.53</td>
<td>1.67</td>
<td>1.63</td>
<td>18.85</td>
</tr>
<tr>
<td>31C Visual</td>
<td>949</td>
<td>204.00</td>
<td>110.76</td>
<td>8.98</td>
<td>3.21</td>
<td>1.89</td>
<td>2.10</td>
<td>21.07</td>
</tr>
<tr>
<td>13C Visual</td>
<td>1288</td>
<td>227.27</td>
<td>71.51</td>
<td>9.59</td>
<td>1.38</td>
<td>1.43</td>
<td>1.28</td>
<td>14.95</td>
</tr>
<tr>
<td>22L Visual</td>
<td>1101</td>
<td>232.4</td>
<td>104.1</td>
<td>9.529</td>
<td>3.2</td>
<td>1.787</td>
<td>2</td>
<td>18.76</td>
</tr>
</tbody>
</table>

#### 4.3.3.2.3 Fuel Burn Performance Statistics by runway

The overall ranking for runways based on the fuel burn, irrespective of direction of flow or type of approach is shown Table 26. In general, the overall ranking of the runways in terms of fuel burn performance is 31C (+3%), 4R (+3%), 22L (+8.4%) and 13C (+29%).
Table 26: Fuel burn, Track time, Level Time Statistics for all aircrafts at MDW, by runway, ranked by fuel burn

<table>
<thead>
<tr>
<th>Runway</th>
<th>Track Count</th>
<th>Fuel Burn (kg/flight)</th>
<th>Track time (min)</th>
<th>Level Time (min)</th>
<th>% Level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean  SD</td>
<td>Mean  SD</td>
<td>Mean  SD</td>
<td></td>
</tr>
<tr>
<td>31C</td>
<td>3186</td>
<td>191.12 134.56</td>
<td>9.42 3.84</td>
<td>2.24 2.52</td>
<td>23.84</td>
</tr>
<tr>
<td>4R</td>
<td>2864</td>
<td>197.73 114.62</td>
<td>9.35 1.99</td>
<td>2.11 1.99</td>
<td>22.52</td>
</tr>
<tr>
<td>22L</td>
<td>1490</td>
<td>207.76 110.81</td>
<td>9.54 3.25</td>
<td>1.83 2.03</td>
<td>19.14</td>
</tr>
<tr>
<td>13C</td>
<td>3487</td>
<td>250.94 123.27</td>
<td>11.16 2.51</td>
<td>2.98 2.56</td>
<td>26.69</td>
</tr>
</tbody>
</table>

4.3.3.2.4 Fuel burn Level vs. Non Level

For each trajectory the fuel burn model takes into account the energy state (i.e., kinetic – true air speed, and potential – altitude) of the aircraft at each position report. The model estimates the fuel burn rate in level segments and non-level segments while taking into consideration the configuration of the aircraft (clean, or dirty). This is illustrated in Figure 32, where two trajectories for a B737 to runway 13C from the east are shown. The lateral and the vertical profile are shown in plots (a) and (b), and the true airspeed and fuel burn rate are shown in plots (c) and (d). The vertical profile, the true airspeed and the fuel burn rate are shown as a function of distance to the runway threshold.
The model captures the higher fuel burn rate in the level segments compared to the non-level segments (see Figure 32, plot b and d). The model also captures increases in fuel burn as a result of switching from clean to dirty configuration. For instance, flight1 (blue) burns more fuel as it switches from clean to dirty sooner than flight2 (red) as shown in Figure 32 (c).

The mean and standard deviation of fuel burnt on level, descent and final approach for narrow body aircrafts at MDW is shown in Figure 33. The fuel burn on the level segments is on an average 108% more than on the descent segments and 25% more than on the final approaches.
The fuel burn for individual TRACON flows is not proportional to the track time (see Figure 34 (b)). The main factors that contribute to higher fuel burn are the percentage level segments. The influence of level segments on total fuel burn is shown in Figure 34. In the terminal airspace (i.e. from final waypoint in STAR to the runway threshold) the time in descent and final approach and the corresponding fuel burn is more or less constant, as shown by the green and red line. Any increase in the total transit time in the terminal area results in an increase in the level segments, shown by the blue line. This is because aircraft have to maintain certain altitude at the start of the base leg and there is not much altitude to lose from the final waypoint of STAR to the start of the base leg. Therefore relative position of the final waypoint in STAR to the runway threshold, and the controller induced vectors for safe merging and spacing determine the duration of the terminal flow and the associated fuel burn. Therefore, longer duration flows have a higher percentage of level segments and a non-linear increase in the total fuel burn.
In case of MDW, flows to runway 13C from the east and flows to runway 22L and 31C from the west have longer level segments and a high level time to total time ratio. The straight-in flows to runway 31C from the east and runway 4R from the west have very short level segments and a low level segment to total time ratio.

Figure 34: Influence of level segments on total fuel burn. Any increase in the total transit time in the terminal area results in an increase in the level segments as aircraft have to maintain certain altitude at the start of the base leg and there is not much altitude to lose from the final waypoint of STAR to the start of the base leg.

4.3.3.3 Summary of TRACON Arrival Flow Analysis

This section presents the estimates of track time, distance and fuel burn using the actual trajectories of the aircraft. The fuel burn model takes into consideration the energy state (kinetic – true air speed and potential - altitude) of the aircraft at each position report of the flight trajectory. The model captures the higher fuel burn rate in the level segments compared to the non-level segments. The model also captures increase in fuel burn as a result of a switch from clean to dirty configuration during the approach in the terminal airspace (i.e. from final waypoint on STAR to the runway threshold).
The mean track time, distance and fuel burn per flight are estimated for 16 major arrival flows at MDW using 43 days of NOP track data. The performance metrics are used to rank runways based on, the individual flows from east and west, the approach procedures irrespective of flow direction and the overall efficiency irrespective of approach type and flow direction.

The implications of the TRACON arrival flow analysis for MDW arrivals are as follows:

**4.3.3.3.1 Performance of RNP approach**

The RNP approach flows to 13C burns 14% less fuel than the corresponding ILS approach and 25% more fuel than the corresponding visual approach flows on an average. Therefore the benefits of RNP approach to 13C are limited to IMC days.

The variance in flight tracks in the terminal airspace, caused by controller vectoring for merging and spacing, is a function of the approach type along with the relative position and the distance of the final waypoint on the STAR to the runway threshold. Operational efficiency is maximized when the arrival flow crosses the final waypoint on the STAR and flies a straight course to the runway. TRACON flows that require turns to line-up for the final approach segment add vector complexity and result in increased track distance and track time, and more importantly increased variance in track distance and track time resulting in lost runway productivity. Without efficient merging and spacing the benefits of precise curved path RNP approach are nullified. The "vectors" between the final waypoint on the STAR and the start of the RNP approach introduce as much variation in flight tracks as the ILS flows.
4.3.3.3.2 Role of Level Segments in Approach
For narrow body aircrafts at MDW, the fuel burn rate in level flights (35 kg/min) is 108% greater than fuel burn for near-idle descent segments (15 kg/min) and 25% greater than fuel burn on the final approach segment (25 kg/min).

4.3.3.3.3 Potential for using Optimum Runway Configurations
During Visual Meteorological Conditions (VMC), assuming equal weights for arrivals from the east and west, the least average fuel burn arrival flow for VFR approach procedures is 4R (174.9 kg) followed by 31C (+1%), 13C (+11%) and 22L (+19%).
During Instrument Meteorological Conditions (IMC), assuming equal weights for arrivals from the east and west, the least average fuel burn arrival flow for ILS approach procedures is 31C (207.06 kg) followed by 4R (+6.5%) and 13C (+33%). This information combined with the wind information (magnitude and direction) can be used to select runway configurations that are optimal both in terms of wind and terminal area fuel burn.

The Optimal Runway Configuration model can be used to determine the optimal runway configuration for the tower control manager at the airports. In current practice the runway configuration is determined based only on the wind direction.

4.4 Benefits of RNP Approaches to all Runways at MDW
The analysis of benefits of RNP approaches to all runways at MDW is motivated by two factors: (1) the potential use of RNP approach to all runways and (2) the potential use of optimal runway configuration.
4.4.1 Engineering new RNP Approaches at MDW

As described in section 3.6, the new PBN approach with RF leg capability enable precise curved path approaches (e.g. RNP 0.3 w/ RF leg) in the terminal airspace. These new approach procedures are designed to eliminate trombone vectors in the base leg of the approach and make the approach from the final waypoint on STAR to runway threshold shorter on average compared to conventional approach procedures. The shorter approach result in fuel burn savings in the terminal airspace compared to the conventional approaches.

The use and the benefits of RNP approach with RF leg for an airline operating at MDW is just not limited to using RNP approach to 13C. This analysis uses the methodology describe in section 3.6.1 to reflect and rotate existing RNP tracks to runway 13C to construct RNP flows to other major runway (22L, 31C and 4R) at MDW.

Runway 22L is 90° toward the north of runway 13C. Therefore, the RNP flow to runway 22L from the east is obtained by reflecting the west RNP flow to runway 13C about the runway’s (13C) axis and rotating by 90°. Similarly the RNP flow to runway 22L from the west is obtained by reflecting the RNP flow to runway 13C from the east about the runway’s (13C) axis and rotating by 90°. The new flows to 22L are shown in Figure 35 and Figure 36.
Figure 35: Hypothesized RNP approach flows to 22L from the east, obtained from reflecting and rotating RNP flows to 13C from the west by 90 degree

Figure 36: Hypothesized RNP approach flows to 22L from the west, obtained from reflecting and rotating RNP flows to 13C from the east by 90 degree
Runway 4R is 90° toward the south of runway 13C. Therefore, the RNP flow to runway 4R from the east is obtained by rotating the west RNP flow to runway 13C by 90° (see Figure 37). The west flows to runway 4R are aligned with the runway and do not need a RF leg. It is assumed that RNP flows from the west to runway 4R have the same performance as the ILS approach in terms of fuel burn.

![Figure 37: Hypothesized RNP approach flow to runway 4R from the east, obtained from reflecting and rotating RNP flows to 13C from the west by -90 degree](image)

Runway 31C is the other side of runway 13C. Therefore, the RNP flow to runway 31C from the west is obtained by reflecting the west RNP flow to runway 13C about the runway’s (13C) axis and rotating by 180° (see Figure 38). The east flows to runway 31C are aligned with the runway and do not need a RF leg. Therefore as in case
of runway 31C, it is assumed that RNP flows from the east to runway 31C have the same performance as the ILS approach in terms of fuel burn.

![Map of runway flows](image)

**Figure 38: Hypothesized RNP flow to runway 31C from the west, obtained from reflecting and rotating RNP flows to 13C from the west by 180°**

The fuel burn performance of these new hypothesized flows are computed and included with performance statistics of the existing flows. The 4-D tracks of the existing RNP approach flows are for B73 aircraft type, as Southwest airline is the only commercial carrier that uses RNP approach at MDW. The average fuel burn per flight for each flow and its standard deviation for Boeing 73’s (B73’s) (which constitutes 72% of the fleet mix at MDW for all operations except general aviation) is shown in Figure 39.
The RNP flows at MDW only have B73’s aircraft type. The estimates for the RNP flow’s mean fuel burn per flight for the fleet mix at MDW (see Figure 31) are obtained by multiplying a factor of 0.84 to the fuel burn estimates of B73’s. This factor is determined by analyzing ILS and visual approach flow at MDW that have the complete fleet mix at MDW (see section 4.3.3.2.1).

Figure 39: Fuel burn performance (mean and standard deviation) of existing and hypothesized flows at MDW, for B73’s and the fleet mix at MDW.

The hypothesized flows are marked in Figure 39. The RNP approaches to 22L from the east and the west have a higher fuel burn per flight than corresponding visual approaches on average by +10.5% for the east and +43.5% for the west. Therefore, the hypothesized RNP approaches to runway 22L are not desirable over the conventional visual approaches.
The fuel burn performances of the hypothesized RNP approach to runway 4R from the east and the hypothesized RNP approach to runway 31C from the west are lower than the corresponding ILS and visual approach on average by -47% and -20% for 4R and -44% and -30% for 31C. These RNP approaches eliminate the trombone vectors on the base leg that are present in the corresponding ILS and visual approaches to runways 4R and 31C. Therefore, these new approaches would be preferred both in VMC and IMC.

4.4.2 Optimal Runway Configuration for MDW Arrivals
One of the implications of TRACON arrival flow analysis (see section 4.3.3.3.3) is that fuel burn performance for all terminal area arrival flows are not the same and depend on the relative position of the runway with respect of the approach direction and the type of approach. The current process of selecting runway configuration is based on wind direction and magnitude and other operational constrains like the metroplex flow conflict. For instance, at Chicago metroplex MDW avoids using ILS approach to 13C due the flow conflict with 22L departures from ORD. The de-confliction of flows at Chicago metroplex using RNP approach and the added fuel burn savings associated with the new approach provides an opportunity to assess the benefits of using optimal runway configurations that take in consideration the fuel burn performance of flows in addition to the wind magnitude and direction.

This section determines the optimal runway configuration for arrivals at MDW for given set of flows using the methodology described in section 3.6.2. For each fifteen minute periods, the set of feasible runways for the given wind (magnitude and direction) and meteorological conditions (IMC or VMC) is ranked based on the intensity of traffic.
volume from the east and west direction and the fuel burn performance of individual flows at MDW. The runway with lowest average fuel burn per flight is select as the optimal runway for the arrivals at MDW.

The terminal air traffic flows at MDW originate from the east or the west. The traffic volume from the east and the west vary throughout the day. The average fraction of traffic volume from the east for each hour of the day is shown in Figure 40. The fraction of traffic volume from the west is one minus the fraction of traffic volume from the east. The red line is the 50% mark when there are equal volumes of traffic from the east and the west. At MDW the traffic is predominantly from the east except for 1PM, 4PM, 7PM and 10PM when traffic volumes are higher from the west. From 6AM to 10 PM the fraction of traffic volume from the east at MDW ranges from 0.46 to 0.69.

Figure 40: East – West Traffic flow volume ratio at MDW by hour of the day
In this analysis the fraction of traffic volume from the east and the west are used as weights to combine the mean fuel burn performance of flows from the east and west for a given runway and approach type. The weighted fuel burn averages are then used to rank and select the runway with the best (lowest) weighted average fuel burn for a given approach type. The runway thus selected will minimize the total fuel burn in the terminal airspace.

The weighted average fuel burn per flight for various ratios for traffic volume from the east and the west, for visual, ILS and RNP flows at MDW are shown in Figure 41, Figure 42, and Figure 43. For a given runway and approach type, the “zero” on the x-axis corresponds to the mean fuel burn of the flow from the west and the “one” corresponds to mean fuel burn of the flow from the east. Each line is the mean fuel burn per flight for various levels of traffic volume from the east and the west. The range (0.46 to 0.69) of traffic volume ratio applicable at MDW is highlighted as well.

For all approach types (visual, ILS and RNP) runways 31C or 4R have the best fuel burn performance. For visual approaches, performance of runway 4R is better than 31C as long as traffic from the east is 54% or less of the total traffic volume. When the traffic from the east is greater than 54% of the total traffic runway 31C has better fuel burn performance. A similar tradeoff occurs between runways 13C and 22L, when the traffic from the east is 55% or less of the total traffic, runway 13C is more favorable than runway 22L in terms of fuel burn per flight in the terminal airspace.
At MDW only runways 13C, 31C and 4R have published ILS approach procedures. The ILS approach to runway 31C has the lowest weighted average fuel burn per flights followed by ILS approach to runways 4R and 13C (see Figure 42).
For RNP approaches runway 31C is the best with the lowest weighted average fuel burn per flight followed by runways 4R, and 13C or 22L. The performance of runway 13C is better than 22L until the traffic volume from the east is 57% or less of the total traffic volume, above which runway 22L has better fuel burn performance (see Figure 43).

![RNP approach](image)

**Figure 43: Runway ranking based on traffic volume ratio for RNP approaches**

The fuel burn performances for all the runways (by approach type) at MDW as a function of traffic level from the east and the west are shown in Figure 44. The weighted average fuel burn for RNP approaches are shown in solid line, visual approaches are shown in dashes lines and ILS approaches are shown in dash-dotted line. The legend shows the ranking of the runway by available approach type for the runway. For example, runway 31C at MDW has the best fuel burn performance for RNP approaches followed
by visual approaches and ILS approaches. At MDW, irrespective of the traffic volume from the east and the west, the RNP approach to runway 31C has the lowest (best) fuel burn performance followed by the RNP approach to runway 4R. The ILS approach to runway 13C has the highest fuel burn performance. All other approaches show trade-offs based on the level of traffic from the east and west.

Figure 44: Runway ranking based on traffic volume ratio for all flows at MDW

Using the methodology described in section 3.6.2, the optimal runway for MDW arrivals is determined based on the existing flows and the hypothesized flows. The existing flows consists of the 16 major flows identified using the TRACON flow analysis. The additional hypothesized flows are RNP approaches to runway 22L, 31C and 4R.
The runways used at MDW for arrivals, obtained from analysis of ASPM airport data for year 2007 to 2012, are shown in Figure 45. This is compared to the optimal usage as estimated by the optimal runway configuration model. The optimal usage is estimated for two sets of flows: “Optimal 1” which is based on existing 16 major flows at MDW, namely the ILS, visual and RNP approaches to 13C, the ILS and visual approaches to 31C and 4R, and visual approaches to 22L from the east and the west and “Optimal 2” which includes hypothesized RNP flows to runways 22L, 31C and 4R in addition to the 16 major flows.

![Figure 45: Runway usage at MDW, ASPM vs. optimal 1 and optimal 2.](image-url)
The analysis of ASPM data for year 2007 to 2012 shows that runways 31C, 4R, 22L and 13C are used for arrivals on average 44%, 33%, 20% and 3% of the time respectively.

The optimal runway usage (optimal 1) based on the 16 major flows and historic wind information indicate no major change in use of runways 31C and 4R for arrivals. However, the optimal runway configuration model shows that 13C is more favorable than 22L in presence of south east winds and heavier traffic from the west (more than 43% of the total traffic).

The optimal runway usage (optimal 2) based on the 16 major flows, 4 new RNP flows and historic wind information suggest an increase in usage of runway 22L(15%) over 13C (9%) and 31C (51%) over 4R(24%) compared to “optimal 1”. This is because the RNP approach to 22L has better fuel burn performance than RNP approach to 13C when traffic volumes from the east are higher than 57% of the total traffic. Also, the RNP approach to 31C is always (irrespective of the traffic volumes from the east and the west) more efficient than any of the flows to 4R; therefore, for prevailing winds from the north 31C is always more favorable than 4R.

4.4.3 Annualized Benefits of RNP Approach at MDW

Using the methodology described in section 3.6.3, the annualized fuel burn benefits of RNP approaches at MDW are estimated as the difference between the total annual terminal area fuel burn for the baseline case and the four alternatives. For each case the total fuel burn for terminal area flows is computed for the total number of arrivals at MDW per year on average.
The total arrivals at MDW from 6AM to 10PM for years 2007 to 2012 are shown in Figure 46. On average there are 96,300 total arrivals and 69,430 (72%) Southwest arrivals (SWA) per year at MDW.

![Figure 46: Total number of arrivals at MDW for years 2007 to 2012](image)

The total fuel burn per year (for IMC, VMC and total) for the baseline case and the four alternatives are shown in Table 27. For each case the table also shows the flows and runway configuration considered for the fuel burn calculations in the first two columns. The potential savings in fuel burn per year and the associated costs from using the alternative flows and runway configurations over the baseline case are shown in the last column.
Table 27: Total fuel burn per year on an average for the baseline and the four alternatives and their associated benefits for all arrivals at MDW.

<table>
<thead>
<tr>
<th>Flows</th>
<th>Runway Config</th>
<th>Fuelburn/year in gallons</th>
<th>Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>VMC</td>
<td>IMC</td>
</tr>
<tr>
<td>13C (Visual, ILS) 31C (Visual, ILS) 4R (Visual, ILS) 22L (Visual)</td>
<td>ASPM - Baseline</td>
<td>4.8E+06</td>
<td>2.9E+05</td>
</tr>
<tr>
<td>13C (Visual, ILS, RNP) 31C (Visual, ILS) 4R (Visual, ILS) 22L (Visual)</td>
<td>ASPM - A1</td>
<td>4.8E+06</td>
<td>2.9E+05</td>
</tr>
<tr>
<td></td>
<td>Optimal1 - A2</td>
<td>4.7E+06</td>
<td>2.9E+05</td>
</tr>
<tr>
<td>13C (Visual, ILS, RNP) 31C (Visual, ILS, RNP) 4R (Visual, ILS, RNP) 22L (Visual, RNP)</td>
<td>ASPM - A3</td>
<td>4.2E+06</td>
<td>2.6E+05</td>
</tr>
<tr>
<td></td>
<td>Optimal2 - A4</td>
<td>4.1E+06</td>
<td>2.6E+05</td>
</tr>
</tbody>
</table>

The baseline case estimates the total terminal area fuel burn at MDW per year on average for the ASPM runway configuration and the associated conventional flows (i.e. visual approach flows during VMC and ILS approach flows during VMC).

The alternate case A1 estimates the benefits of using RNP approach to runway 13C instead of the ILS approach. The total terminal area fuel burn at MDW per year on average is estimated for the ASPM runway configuration and the associated convectional and 13C RNP approach flows. The use of RNP approach to 13C instead of ILS approach during VMC yields a fuel burn saving of 5800 gallons of fuel per year. At $3/gallon this amounts to $17K savings per year on average for all MDW arrivals.

The alternate case A2 estimates the benefits of using the optimal runway configuration (Optimal 1 in Figure 45) instead of the runway usage as per the ASPM data and the associated flows. The alternate case A2 yields fuel burn savings of 45,000 gallons per year on average. The fuel burn savings are from the use of runway 13C which is more
favorable than 22L in presence of south east winds and heavier traffic from the west (more than 43% of the total traffic). At $3/gallon this amounts to $135K savings per year on an average for all MDW arrivals.

The alternate case A3 estimates the benefits of using ASPM runway configuration and the introduction of other RNP approaches to runways 31C, 4R and 22L. The alternate A3 yields a fuel burn savings of 660,000 gallons per year. At $3/gallon this amounts to $1.97M savings per year on an average for all MDW arrivals.

The alternate case A4 estimates the benefits of using the optimal runway configuration (Optimal 2 in Figure 45) instead of the runway usage as per the ASPM data and the associated flows. The alternate A4 yields a fuel burn savings of 890,000 gallons per year on an average. At $3/gallon this amounts to $2.67M savings per year on an average for all MDW arrivals.

The benefits of using the four alternatives over the baseline are also estimated for Southwest arrivals at MDW (see Table 28). The benefits to Southwest from using RNP approach to runway 13C under alternatives A1 and A2 are $15K and $115K per year on an average respectively. The benefits to Southwest from using RNP approach to all major runways (13C, 31C, 4R and 22L) under alternatives A3 and A4 are $1.7 M and $2.3M respectively.
Table 28: Total annual fuel burn for baseline and four alternative and their associated benefits for Southwest arrivals at MDW

<table>
<thead>
<tr>
<th>Flows</th>
<th>Runway Config</th>
<th>Fuelburn/year in gallons</th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>VMC</td>
<td>IMC</td>
<td>Total</td>
<td></td>
<td>Savings</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
<td>Gallons</td>
</tr>
<tr>
<td>13C (Visual, ILS) 31C (Visual, ILS) 4R (Visual, ILS) 22L (Visual)</td>
<td>ASPM - Baseline</td>
<td>4.1E+06</td>
<td>1.7E+05</td>
<td>6.7E+05</td>
<td>9.2E+04</td>
<td>4.3E+06</td>
<td>1.6E+05</td>
<td>NA</td>
</tr>
<tr>
<td>13C (Visual, ILS, RNP) 31C (Visual, ILS) 4R (Visual, ILS) 22L (Visual)</td>
<td>ASPM - A1</td>
<td>4.1E+06</td>
<td>1.7E+05</td>
<td>6.6E+05</td>
<td>9.0E+04</td>
<td>4.3E+06</td>
<td>1.6E+05</td>
<td>5.0E+03</td>
</tr>
<tr>
<td></td>
<td>Optimal1 - A2</td>
<td>4.1E+06</td>
<td>1.7E+05</td>
<td>6.5E+05</td>
<td>8.9E+04</td>
<td>4.3E+06</td>
<td>1.6E+05</td>
<td>3.8E+04</td>
</tr>
<tr>
<td>13C (Visual, ILS, RNP) 31C (Visual, ILS, RNP) 4R (Visual, ILS, RNP) 22L (Visual, RNP)</td>
<td>ASPM - A3</td>
<td>3.6E+06</td>
<td>1.6E+05</td>
<td>4.8E+05</td>
<td>6.5E+04</td>
<td>3.7E+06</td>
<td>1.6E+05</td>
<td>5.6E+05</td>
</tr>
<tr>
<td></td>
<td>Optimal2 - A4</td>
<td>3.5E+06</td>
<td>1.6E+05</td>
<td>4.9E+05</td>
<td>6.6E+04</td>
<td>3.5E+06</td>
<td>1.6E+05</td>
<td>7.8E+05</td>
</tr>
</tbody>
</table>

The noticeable increase in fuel burn savings for case A3 is from the use of RNP approaches to runways 31C and 4R which have better fuel burn performance than the corresponding ILS and visual approaches. For instance, assuming equal weights for traffic from the east and the west at MDW, the fuel burn savings in the terminal airspace from using RNP approach to 31C instead of the corresponding ILS and visual approach are 65.64 kg and 37.55 kg per flight on an average respectively. Similarly, the fuel burn saving in the terminal airspace from using RNP approach to 4R instead of the corresponding ILS and visual approach are 51.95 kg and 18 kg per flight on average respectively.

The use of optimal runway configuration “optimal 2” in case A4 further increases the fuel burn savings by 26%. This increase in fuel burn savings is from the increase use of runway 22L (15%) over 13C (9%) and 31C (51%) over 4R (24%), compared to optimal runway configuration “optimal 1”. During IMC the RNP approach to runway
22L has better fuel burn performance than RNP approach to runway 13C, when traffic volumes from the east are higher than 57% of the total traffic volume, As described before in section 4.4.2. Also, the RNP approach to 31C is always (irrespective of the traffic volumes from the east and the west) more efficient than any of the flows to 4R, therefore for prevailing winds from the north at MDW 31C is always more favorable than 4R.

The overall analysis shows that the new RNP approach procedures to all the major runways at MDW (13C, 31C, 4R and 22L) and their associated fuel burn savings over the convectional visual and ILS approaches enable the use of optimal runway configuration (see Figure 45, “optimal 2”). This results in a savings of 890K gallons per year on an average for all arrivals at MDW and a savings of 760K gallons per year on an average for Southwest arrivals at MDW. The fuel burn savings are from using the RNP approaches at MDW 77% of the time with fuel burn saving in the terminal airspace of 33kg per flight on an average. At $3/gallon the savings amount to $2.67M per year on an average for all arrivals and $2.3M per year on an average for Southwest arrivals at MDW.

4.4.4 Summary of Benefits of PBN Approach Procedures at MDW

The asymmetry in benefits between competing operators (airlines at MDW and ORD) in neighboring airports is large (1:33 in favor of ORD departures). In this way, there is no competitive advantage for MDW airlines in equipping due to the free rider issue. Using the methodology described in section 3.6.3, this section estimates the annualized benefits of using RNP approaches to all the major runways at MDW (13C,
4R, 22L, 31C) for the historic runway configuration (ASPM) and the optimal runway configurations (Optimal1 and Optimal 2).

In addition to reducing the additional cost due to metroplex flow conflict, RNP approach can be used to save fuel by having shorter and more efficient procedures compared to conventional approach procedures in the terminal airspace.

The methodology enabled the evaluation of the introduction of additional RNP approach procedures to major runways (13C, 31C, 4R and 22L) at MDW. This has the potential of saving on an average 660K gallon per year of fuel for arrivals at MDW. At $3/gallon this amounts to a savings of $1.97M per year.

The de-confliction of metroplex airspace makes operations at neighboring airspace independent of each other allowing scope for further improvement in terminal fuel burn efficiency by choosing optimal runway configurations.

The methodology also identifies opportunities to select optimal runway configuration at MDW based on wind magnitude/direction and fuel burn efficiency of terminal area flows. The use of optimal runway configuration for wind and fuel burn, along with additional RNP approach procedure, has the potential of saving on average 890K gallons per year of fuel for arrivals at MDW. At $3/gallon this amounts to a savings of $2.67M per year.

The analysis also estimates the benefits of using RNP approach to the majority carrier at MDW (Southwest Airlines). The use of optimal runway configuration for wind and fuel burn, along with additional RNP approach procedures to runways 13C, 31C, 4R
and 22L, has the potential of saving on an average 760K gallons per year of fuel for Southwest airlines at MDW. At $3/gallon this amounts to a savings of $2.3M per year.

4.5 Net Present Value Analysis of RNP Equipage for Southwest Airlines

This section estimates the return on investment (ROI) for Southwest Airlines using the NPV model described in section 3.7.

The Southwest Airline is investing $175M in equipping with RNP approach capability (Martin, 2009). The two financial parameters of interest to an airline are the Net Present Value (NPV) of the investment and the time it takes to obtain a positive ROI or Break Even Time (BET). The NPV analysis done to estimate these two parameters has the following assumptions:

a. Benefits are accrued only after 100% of fleet is equipped
b. Cash outflow = Initial Cost of Equipage, when time t=0
c. Cash outflow =0 for t>0
d. Cash Inflow = Benefits from new equipage per year
e. The NPV is computed for N=20 years

The RNP 0.3 approach with RF leg enabled by the precise curved path approach capability of the aircraft cuts the corner on the final approach making the final approach shorter. The shorter approach results in fuel burn savings in the terminal airspace compared to the conventional approaches. Analysis in section 4.4.3 shows that at MDW the use of RNP can result in a total potential savings of 760K gallons of fuel per year on average for Southwest Airlines. At $3/gallon this amounts to a savings of $2.3M per year.
The cash inflow of $2.3M per year does not yield a positive ROI at MDW. The NPV analysis of, the number of MDW like airports required for Southwest to break even at 5% and 10% discount rates is shown in Figure 47. The NPV curves are for savings at $3/gallon. The analysis shows that Southwest will need at least 10 more airports like MDW to break even in less than 10 years at a discount rate of 5%. With 15 more airports like MDW the breakeven is achieved in 5 years with the 20 year NPV of $276M.

![NPV Curves at $3/gallon](image)

*Figure 47: Analysis showing Break Even Time and Net Present Value for 20 years horizon for various combinations of number of MDW likes airports and discount rates.*

The sensitivity of the Break Even Time and the 20 year NPV to fuel price for 5% and 10% discount rate is shown in Table 29 and Table 30. The analysis shows an increase in fuel prices will yield more acceptable ROIs and NPVs. This is assuming the increase in
operations cost due to increase in fuel price is passed to the passengers and does not result in reduction in demand and daily operations.

Table 29: Break Even Time and 20 year NPV sensitivity to fuel price, at 5% discount rate

<table>
<thead>
<tr>
<th># Airports</th>
<th>$3</th>
<th>$4</th>
<th>$5</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>&gt;20 &amp; $-25M</td>
<td>17 &amp; $25M</td>
<td>12 &amp; $75M</td>
</tr>
<tr>
<td>10</td>
<td>10 &amp; $125M</td>
<td>7 &amp; $225M</td>
<td>6 &amp; $326M</td>
</tr>
<tr>
<td>15</td>
<td>6 &amp; $276M</td>
<td>5 &amp; $426M</td>
<td>4 &amp; $577M</td>
</tr>
</tbody>
</table>

Table 30: Break Even Time and 20 year NPV sensitivity to fuel price, at 10% discount rate

<table>
<thead>
<tr>
<th># Airports</th>
<th>$3</th>
<th>$4</th>
<th>$5</th>
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<tbody>
<tr>
<td>5</td>
<td>&gt;20 &amp; $-67M</td>
<td>&gt;20 &amp; $-31M</td>
<td>19 &amp; $4M</td>
</tr>
<tr>
<td>10</td>
<td>13 &amp; $40M</td>
<td>8 &amp; $112M</td>
<td>6 &amp; $183M</td>
</tr>
<tr>
<td>15</td>
<td>7 &amp; $148M</td>
<td>5 &amp; $255M</td>
<td>4 &amp; $363M</td>
</tr>
</tbody>
</table>

Airports where Southwest Airlines have more than 10,000 arrivals per year on an average are shown in Figure 48.
MDW is the second largest operations center for Southwest Airline after Las Vegas International Airport (LAS). Based on the current level of operation Southwest Airlines does not have 10 more airports like MDW. However, Southwest can still break even based on the total number of RNP approach operation it carries out throughout its network. Analysis shows that MDW has a total of 1.1M arrival operations per year on average throughout its network. The carrier will break even in 10 years at a discount rate of 5% if it can perform half a million RNP approaches per year throughout its network, while saving at least 33 kg of fuel per approach.

4.5.1 Summary
The Southwest Airline is investing $175M in equipping with RNP approach capability (Martin, 2009).

Analysis in section 4.4.3 shows that at MDW the use of RNP can result in a total potential savings of 760K gallons of fuel per year on average for Southwest Airlines. At
$3/gallon this amounts to a savings of $2.3M per year. These savings are estimated using the optimal runway configuration model, which models the benefits of using of RNP approach to all major runways (13C, 31C, 22L and 4R) at MDW. Based on the fuel burn performance of existing and hypothesized RNP approaches, RNP can be used at MDW 77% of the time with fuel burn savings of 33kg per flight per approach over the alternate approach procedure (ILS or visual).

Investing in RNP approach for single airport use (for de-confliction of airspace and improving terminal approach efficiency) does not yield a positive ROI at MDW.

The results from the analysis were used to estimate the ROI for investing in RNP for the major carrier (Southwest Airlines) at MDW. The results show that the RNP approach does not yield a positive ROI at MDW, and that the carrier will have to perform at least half a million RNP approaches per year throughout its network, saving at least 33 kg of fuel per approach on an average to break-even in 10 years at a discount rate of 5%.
5 CHAPTER 5: CONCLUSIONS AND FUTURE WORK

A metroplex is a collection of airports serving a metropolitan area. A key determinant of the capacity of the metroplex airspace is the extent of interaction between arrival and departure flows at the airports. In some metroplexes the geometry of the airports is such that, under certain wind and weather conditions, there exist conflicts between the flows that require excessive ground holding for departures and airborne holding for arrivals. Advances in aircraft navigation technologies have created opportunities to improve arrival flow efficiencies and de-conflict metroplex flows. However, adoption of these technologies has been slow and haphazard due to issues with estimating the true Return-on-Investment (ROI), the need for collaboration and simultaneous equipage across competing stakeholders, and the allocation of benefits to parties that choose not to equip but gain benefits when their competition equips. Together these issues have created a “modernization stalemate.”

The recent availability of high fidelity surveillance track data coupled with aerodynamic fuel burn models and airport wind and weather data create an opportunity to provide detailed analysis of metroplex traffic flows to include the real-world complexities of traffic flows and aircraft trajectories.
This dissertation describes a holistic methodology to use high fidelity surveillance track data coupled with aerodynamic models and weather data to quantify the efficiencies and costs of metroplex terminal area air traffic flows.

This methodology is intended for assessing benefits of proposed terminal airspace concepts-of-operations (e.g. metroplex de-confliction using RNP approach) and associated technologies that require simultaneous equipage and development of collaborative procedures by multiple stakeholders (airlines and ANSPs).

This chapter is organized as follows: section 5.1 describes the conclusions related to the methodology developed in this dissertation; section 5.2 describes the conclusions related to the results of the case study; section 5.3 describes the issue with achieving equipage and strategies for equipage; and section 5.4 describes the potential application of this methodology and future work.

5.1 Hybrid model for benefits analysis of PBN and metroplex de-confliction

This dissertation is motivated by the issues with the implementation of PBN approach procedures for de-confliction of metroplex airspace. The NAS modernization stalemate is due to: (a) lack of airlines confidence in the benefits of new technology and (b) free rider issue and asymmetry in distribution of benefits of the new technology. Both factors affect the implementation of PBN approach procedures for de-conflicting metroplex airspace. A review of the literature related to metroplex analysis identified the following methodological gaps:

1. The costs of metroplex flow conflict and the potential benefits associated with the de-confliction have been analyzed from a system-wide
perspective and not from an airlines perspective (Atkins, 2008; Clarke et al., 2011; Devlin et al., 2012). Any benefits analysis of operational changes that require airlines to equip should be done from an airlines perspective.

2. The benefits analysis of new PBN approach procedures has been estimated using simulated de-coupled routes (Clarke et al., 2011) or analysis of operational data (Devlin et al., 2012). The key benefits of these new approach procedures to individual airlines are fuel burn savings from shorter and more efficient flight paths in the terminal airspace. In the case of metroplex flow conflict, the airlines also benefit from elimination of holding patterns for de-confliction of terminal area flows. Therefore, fuel burn analysis using actual track data is required to account for the energy state of the aircraft and the vertical profile of the trajectory in the terminal airspace. Also a methodology to estimate for the cost of holding patterns using actual track data is required.

3. Existing analyses using surveillance track data (Dorfman et al., 2012; Enriquez, 2013; Levy, 2003; Vempati & Ramadani, 2012) have not been extended to estimating the benefits and the ROI of PBN approach procedures to individual airlines based on savings from shorter terminal area flight path and elimination of holding patterns.
This dissertation addresses these gaps by developing a holistic methodology to use high fidelity surveillance track data coupled with aerodynamic models and weather data to estimate the benefits of PBN approaches and in doing so:

1. Estimate the track distance/time, fuel burn performance of the new PBN approach procedures and compare it to conventional approach procedures.

2. Estimate the Return on Investment of the new PBN approach procedures to individual airlines.

3. Estimate the benefits of metroplex de-confliction to capture magnitude of the asymmetry and the potential for simultaneous adoption of the technology by the competing stakeholders.

5.2 Implications of the Chicago Metroplex Case Study

The methodology is demonstrated in a case-study of the benefits of the introduction of a Required Navigation Performance (RNP) approach procedure for air traffic arrival flow de-confliction at the Chicago Terminal Radar Approach Control (TRACON).

The high equipage, training and certification costs of RNP capability coupled with lack of confidence in the anticipated benefits are one reason airlines may be reluctant to invest in RNP approach capability. The results of this dissertation indicate that investing in RNP approach for single airport use (for de-confliction of airspace and improving terminal approach efficiency) does not yield a positive ROI in 20 years at MDW.

The free rider issue and the asymmetry in distribution of benefits associated with the de-confliction of airspace further prevent the airlines from making the investment.
Therefore the RNP approach capability on its own is not an attractive technology to adopt for operation in a network of airports with prevalent visual conditions. These are described in more details in the following subsections.

5.2.1 Performance of RNP approach

An arrival flow analysis at MDW was performed to compare the performance of the new RNP approach (13C) to the conventional approach procedure (ILS 13C) to assess the benefits of the new procedure to the metroplex and to individual airlines.

The RNP approach flows to 13C burns 14% less fuel than the corresponding ILS approach and 25% more fuel than the corresponding visual approach flows on average. Thus, the benefits of RNP approach to 13C are limited to IMC days.

The variance in flight tracks in the terminal airspace, due to controller vectoring for merging and spacing, is a function of the approach type along with the relative position and the distance of the final waypoint on the STAR to the runway threshold. Operational efficiency is maximized when the arrival flow crosses the final waypoint on the STAR and flies a straight course to the runway. TRACON flows that require turns to line-up for the final approach segment add vector complexity and result in increased track distance and track time, and more importantly increased variance in track distance and track time resulting in lost runway productivity.

Without efficient merging and spacing, the benefits of precise curved path RNP approach are nullified as the "vectors" between the final waypoint on the STAR and the start of the RNP approach introduce as much variation in flight tracks as the ILS flows.
5.2.2 Asymmetry in Benefits of De-confliction
The flow conflict between 13C ILS arrivals at MDW and 22L departures at ORD at Chicago metroplex occur on an average 1.6% of the time per year. The introduction of the RNP approach to 13C at MDW to de-conflict the traffic flow for these periods is estimated to reduce the direct airline operating cost per year on an average by $.04M at MDW and $1.33M at ORD.

The magnitude of the benefits of de-confliction for the operator expected (airlines at MDW) to equip is small and the asymmetry in benefits between competing operators (airlines at MDW and ORD) in neighboring airports is large (1:33 in favor of ORD departures). This results in no competitive advantage in equipping due to the free rider issue.

5.2.3 Potential for additional RNP approaches
In addition to reducing the additional cost due to metroplex flow conflict, RNP approach can be used to save fuel by having shorter and more efficient procedure compared to conventional approach procedures in the terminal airspace.

The methodology also enables the evaluation of the introduction of additional RNP approach procedures on to other runways at MDW. This has the potential of saving on average 660K gallons per year of fuel for arrivals at MDW. At $3/gallon this amounts to a savings of $1.97M per year.

5.2.4 Potential for choosing better runway configuration
The de-confliction of metroplex airspace makes operations at neighboring airspace independent of each other, providing scope for choosing optimal runway configurations for improving terminal area fuel burn efficiency.
The analysis also identifies an opportunity to select optimal runway configuration at MDW based on wind magnitude/direction and fuel burn efficiency. The use of optimal runway configuration for wind and fuel burn, along with additional RNP approach procedure has the potential of saving on an average 890K gallons per year of fuel for arrivals at MDW. At $3/gallon this amounts to a savings of $2.67M per year.

5.2.5 **ROI for individual airlines**

Investing in RNP approach for single airport use (for de-confliction of airspace and improving terminal approach efficiency) does not yield a positive ROI at MDW for Southwest Airlines.

The results from the analysis are used to estimate the ROI for investing in RNP for the major carrier (Southwest Airlines) at MDW. The results show that the RNP approach does not yield a positive ROI at MDW for Southwest Airlines. The carrier will have to perform at least half a million RNP approaches per year throughout its network and save at least 33 kg of fuel per approach on average to break-even in 10 years at a discount rate of 5%.

5.3 **Strategies for equipage**

To enable the RNP approach the air navigation service providers (ANSPs) must design and approve RNP approaches, develop ATC procedures and train air traffic controllers. In addition, airlines must equip with RNP equipment, train the crew and receive certification to fly the procedure. The adoption of RNP approaches by airlines has been slow, primarily due to: (a) issues with estimating the Return-on-Investment (ROI) and (b) the “free rider” issue, (i.e., the allocation of benefits to parties that choose not to
equip but gain benefits when their competition equips). This section describes various strategies for achieving RNP approach equipage.

5.3.1 Market-based Approach

The market-based approach relies on the inherent benefits of a technology to sell itself and achieve the desired equipage.

In the case of metroplex flow de-confliction and RNP approach capability, there are three major issues that negate the benefits of the RNP approach: (a) the terminal area vectoring for merging and spacing required to ensure safe separations, (b) limited potential use of the approach capability (i.e. limited to IMC days as fuel burn performance of visual approaches are better than RNP approaches in most cases) and (c) the free rider issue (i.e. the asymmetric benefits to the competition serving the market).

These issues and the high costs of equipage result in low ROI for the airlines making investment in RNP approach undesirable.

At Chicago metroplex south-east winds during IMC require the use of ILS on 13C for MDW arrivals. The ILS approach to 13C at MDW conflicts with departures from 22L at ORD. This flow conflict occurs on an average 1.6% of the time per year. The introduction of the RNP approach to 13C at MDW to de-conflict the traffic flow for these periods is estimated to reduce the direct airline operating cost per year on average by $0.04M at MDW and $1.33M at ORD (an asymmetry of 1:33 in favor of airlines at ORD). Also the "vectors" (due to merging and spacing) between the final waypoint on the STAR and the start of the RNP approach introduce as much variation in flight tracks as the ILS flows. These factors negate the benefits of RNP approach. Therefore, the RNP approach
capability on its own is not an attractive technology to adopt for operations at airports with prevalent Visual Meteorological Conditions (VMC).

**5.3.2 Operational Incentives**

Programs like Best Equipped Best Serve (BEBS) are being developed to provide operational incentives in the form of priority arrival slots to equipped operator during traffic flow management initiatives (TMIs) (AhmadBeygi et al., 2013). The proposed TMI identifies periods (on flow conflict days) when equipage-based priority can be applied. During these time periods, referred to as exclusionary periods, the metroplex flows are de-conflicted by only allowing equipped aircraft at the airports. This allows metroplex to resume normal operations, but penalizes flights that are not equipped to fly the procedure required to de-conflict the metroplex.

The implementation of such TMIs will need new decision support tools and the associated training for the controller to manage the duration of the program and allocation of slots based on the level of equipage (AhmadBeygi et al., 2013).

The use of such TMIs at Chicago metroplex will results in normal operations at ORD during the exclusionary periods at the expense of airlines operating at MDW. The investment in equipage by airlines at MDW (necessary for the de-confliction) will not yield significant savings in delays as arrival demand at MDW is well below the capacity. In addition, the limited access will create equity issues for non-equipped operators resulting from excess delay allocation. This will increase overall NAS delays due to network wide delay propagation as a result of large delays for some flights. For instance,
15 minute delays for four flights can be more easily absorbed by the network than 1 hour delay for a single flight

5.3.3 Financial Incentives
In cases of market failure, a theoretical case can be made to provide financial incentives to airspace system users to equip (Post et al., 2011). In case of RNP, the benefits of the operational changes while disproportionate, not only benefit the equipped operator but also other operations and the system as a whole. This asymmetry in distribution of benefits causes the market failure. In such cases, financial incentives can be provided to defray the cost of avionics. The financial incentives can use public funds or use a tax pool that would tax every stakeholder proportional to the benefits accrued from the operational change. This will require accurate estimates of benefits to individual stakeholders which can be done using this methodology.

5.3.4 Mandate
An alternative, in the interest of modernization, would be a government mandate to equip with RNP approach capability. Mandating equipage for RNP will solve the free rider issue and ensure modernization of the NAS that is required to meet the future demand necessary for the growth of the nation.

In the past, equipage for NAS modernization for improving capacity or safety has been achieved through FAA mandates. These include:

a. **VHF Radio Transceivers**: Mandated in 1961, requiring two-way radio communications using Very High Frequency (VHF) for conducting flight operations on and around all controlled airports throughout the country
The VHF radio provided higher bandwidth and voice clarity. Higher bandwidth meant availability of more number of channels, which boosted airspace capacity.

b. **Transponders**: Mandated in 1978, requiring all aircraft operating in Terminal Radar Service Areas (TRSAs) and Terminal Control Areas (TCAs) to have transponders to report identity (Mode A) and altitude (Mode C) installed by July 1981 (FAA, 2012b).


d. **Wind Shear**: Mandated in 1988, requiring all turbine-powered airliners seating 30 passengers or more carry equipment to warn pilots when they encounter low-altitude wind shear and provide them with information needed to escape safely (FAA, 2012b).

e. **Reduced Vertical Separation Minima (RVSM)**: The mandate required all aircraft and flight crews operating in domestic airspace between flight level (FL) 290 to 410 to be RVSM compliant as of January 20, 2005 (FAA, 2012g). RVSM increased capacity of airspace by reduction of vertical separation requirement to 1000 feet from a previous requirement of 2000 feet for flight level (FL) 290 to 410.

From the perspective of metroplex flow de-confliction, mandating equipage is inefficient as all aircraft do not need to equip. Also, the overall cost to equip is higher than the additional airline operating cost due to metroplex flow conflict by orders of
The additional airline operating cost due to flow conflict at Chicago and New York are $4.5M and $3M (Devlin et al., 2012); whereas, the cost to airlines to equip with RNP approach capability is in the hundreds of million ($175M for Southwest Airlines).

The air navigation service providers (ANSPs) must design and approve RNP approaches to all possible runways at all major airports and train air traffic controllers. The lack of RNP approaches will restrict the use and the potential benefits of the approach capability. For example, this analysis shows investing in RNP approach for single airport use (for de-confliction of airspace and improving terminal approach efficiency) does not yield a positive ROI at MDW for Southwest Airlines. The carrier will have to perform at least half a million RNP approaches per year throughout its network and save at least 33 kg of fuel per approach on average to break-even in 10 years at a discount rate of 5%. Also, at Chicago metroplex the airlines at ORD will not have any direct benefits from equipping unless new procedures are put in place to make use of the capability. Therefore, before a mandate to equip for RNP approaches is made, the following key issues need to be addressed:

a. The air navigation service providers (ANSPs) must design and approve RNP approaches to all possible runways at all major airports for airlines to use.

b. The ANSPs must upgrade the surveillance systems and train air traffic controllers to smoothly merge and space aircraft at the start of the RNP approach.
5.4 Future Work and Application
The methodology described in the dissertation can be applied to other metroplexes to estimate the benefits of de-confliction of flows using new PBN approach procedures. In addition, this dissertation presents several opportunities for continued work in the form of methodological improvements and potential applications.

5.4.1 Methodological Improvements
The key methodological improvements are:

a. Include airline’s entire networks (all airports) to accurately estimate the potential benefits of the new PBN approach to individual airlines.

b. Minimize the setup time to run the model by automating the TRACON flow analysis. This will require automated extraction of coordinates of STAR and approach procedures from NFDC database and use of clustering algorithms (Enriquez, 2013; Levy, 2003) to assign tracks to flows.

5.4.2 Analysis tool
The development of the capability to conduct benefits assessment of new concepts-of-operations and technologies using surveillance track data coupled with aerodynamic fuel burn models significantly improves the accuracy and reliability of benefits assessments. The methodology presented in this dissertation can be used to develop an analysis tool that can be used by policy decision-makers and investors (airlines) to better understand where the costs and benefits are accrued.
5.4.3  **Optimal Runway Configuration**

The Optimal Runway Configuration model built as a part of the methodology can be used in determining the optimal runway configuration for the tower control manager at the airports. In current practice the runway configuration is determined based only on the wind direction. An alternate approach is to select the most optimal runway configuration from a set of feasible configurations, by taking into account the direction of air traffic and the fuel burn performance of individual flows in the terminal. The results of the dissertation show that there is potential for further fuel saving using this approach.
APPENDIX A: GAWK CODE FOR CHICAGO METROPLEX ANALYSIS

A1. Instructions to run the Code

The following code is run using unix/linux terminal or an emulator (e.g., Cygwin). The instructions to run the code are as follows:

1. Copy the input files, the scripts and the user-defined functions to a directory.
2. Change directory in the terminal to the one containing the files.
3. Run code by typing ./script_run_main.gawk \ in the unix/linux terminal.

A2. List of Input Files

The code requires the setup and input data files provided below:

File name: NOP_filelist.dat
# This contains names of all the NOP track data files that need to be processed. The NOP track data files should in the same directory as all the other files.
NOP_20110118_JobID316090
NOP_20110124_JobID316091
NOP_20110125_JobID316092
NOP_20110126_JobID316093
NOP_20110127_JobID316094
NOP_20110322_JobID316095
NOP_20110323_JobID316096
NOP_20110610_JobID316097
NOP_20110611_JobID316098

File name: airport_info.dat
# airport lat lon arr_color dep_color elev(\ feet)
MDW 41.7859722 -87.7524167 red blue 620
ORD 41.9816486 -87.9066714 green pink 672

File name: runway_info.dat
# airport lat lon arr_color dep_color rwy1 rwy2 lat1 lon1 lat2 lon2 color_arr_rwy1 color_dep_rwy1 color_arr_rwy2 color_dep_rwy2
MDW 41.7859722 -87.7524167 red blue 13C 31C 41.791573 -87.761067 41.779240 -87.743738 red crimson firebrick darkred
MDW 41.7859722 -87.7524167 red blue 4R 22L 41.791960 -87.759317 41.791996 -87.743056 pink hotpink deeppink mediumvioletred
MDW 41.7859722 -87.7524167 red blue 4L 22R 41.782336 -87.747300 coral orangered tomato orange
MDW 41.7859722 -87.7524167 red blue 13L 31R 41.788068 -87.758803 mediumspringgreen green
darkolivegreen
ORD 41.9816486 -87.9066714 green pink 10 27L 41.983900 -87.890551 lightgreen
yellowgreen
darkgreen
ORD 41.9816486 -87.9066714 green pink 9R 27L 42.002832 -87.899084 darkturquoise cadetblue steelblue
lightsteelblue

File name: flow_direction.dat
# Airport Arrival/Dep Direction lat1(upperleft) lon1(upperleft) lat2(lowerright) lon2(lowerright)
MDW Atracks E 41.72663605364218 -87.06180839663364 41.22663605364218 -86.76180839663364
MDW Atracks W 41.65792541789417 -87.5715184784265 41.32349630243619 -88.28656624524224

File name: flow_info_all.dat
# Airport Arr(Tracks)_Dep(DTracks) Direction Runway Procedure Fix1 Fix1_radius(NM) Vertical
MDW Atracks E 13C ILS HEBKU 4.5 0
MDW Atracks E 13C RNP GIKLE 5 0
# MDW Atracks E 13C RNP JUPIR 1.5 2000
# MDW Atracks E 13C Visual 0
MDW Atracks W 13C ILS HEBKU 4.5 0
MDW Atracks W 13C RNP GIKLE 5 0
# MDW Atracks W 13C RNP JUPIR 1.5 2000
# MDW Atracks W 13C Visual 0
MDW Atracks W 31C ILS GLEAM 6 4000
MDW Atracks E 31C ILS GLEAM 2.5 4000
# MDW Atracks W 31C ILS HILLS 5 0
# MDW Atracks E 31C Visual 0
# MDW Atracks E 4R ILS TASUE 6 0
MDW Atracks E 4R ILS CADON 2.5 4000
MDW Atracks W 4R ILS CADON 2.5 4000
# MDW Atracks E 4R Visual 0

File name: MDW_fix.dat
# waypoint lat lon
OKK 40.5278 -86.058
TROLY 40.6945 -86.0542
GOTNE 40.9613 -86.048
FISSK 41.0492 -86.4328
VEECK 41.1253 -86.6192
OZZEY 41.3992 -86.9335
AZUMO 41.4578 -87.0048
HALIE 41.5161 -87.1589
CGT 41.51 -87.5715
FWA 40.9782 -85.1912
BAGEL 41.516 -85.6137
GSH 41.5252 -86.028
MEGGZ 41.5234 -86.3957
AWSUM 41.5221 -86.5732
IROCK 41.5191 -86.9052
HALIE 41.5161 -87.1589
CGT 41.51 -87.5715
LFD 42.0625 -84.7651
BAGEL 41.516 -85.6137
SPI 39.8397 -89.6777
YEARY 40.6874 -88.8643
PNT 40.8212 -88.7335
MOTIF 41.2296 -88.501
MINOK 41.4689 -88.3633
JOT 41.5464 -88.3184
MAGOO 40.0249 -90.7618
PIA 40.6801 -89.793
KORTT 40.8858 -89.3157
MOTIF 41.2296 -88.501
IRK 40.135 -92.5917
LMN 40.5967 -93.9676
RENZO 41.1358 -89.8062
BDF 41.1597 -89.5879
MOTIF 41.2296 -88.501
CVA 41.7085 -90.4833
BDF 41.1597 -89.5879
TOYUL 41.7123 -88.0704
GIKLE 41.7693 -87.9846
JUPIR 41.8263 -87.8987
NIDEE 41.8356 -87.8303
DULTA 41.8252 -87.8083
TASUE 41.6006 -87.9891
JERNU 41.6613 -87.9128
HADGI 41.7219 -87.8364
PAKLE 41.6039 -87.8323
JERNU 41.6613 -87.9128
BANER 41.6106 -87.972
CADON 41.6457 -87.9278
CITYGO 41.7117 -87.8447
OLOXE 41.7487 -87.7978
KANLE 41.846 -87.9957
HANOD 41.9065 -87.9188
EXEKE 41.8491 -87.8379
JABRI 41.8807 -87.4811
HAXOM 41.9381 -87.5621
EXARE 41.8776 -87.6391
CIDIG 41.8196 -87.7127
CGT 41.51 -87.5715
HILLS 41.6294 -87.534
GLEAM 41.6634 -87.5814
RUNTS 41.7144 -87.6529
HOBEL 41.7433 -87.6934
PANGO 41.6063 -87.6586
HAKBO 41.6667 -87.582
FANEK 41.7244 -87.6626
CENAP 41.7619 -87.7152
IDUDE 41.7387 -87.4892
HAKBO 41.6667 -87.582
HEBKO 41.9075 -87.9245
HITOB 41.8386 -87.8273
MANLI 41.9089 -87.5016
HINSN 41.7907 -87.7447

File name: goaround_holding.dat
# Airport Type(Arrival/Departures) Checkraduis
MDW Atracks 20
# ORD Atracks 20

File name: flow_measuring_fix.dat
# Airport Arrival/Dep Direction (measuring line) lat1 lon1 lat2 lon1 check_radius
MDW Atracks E CGT 41.646154 -87.410911 41.476136 -87.612629 25
MDW Atracks W JOT 41.437972 -88.192559 41.658152 -88.44957 40
This file contains the aircraft operation performance information obtained from BADA OPF files. A sample of the information is provided below. Make sure all the information as consistent with the header is enter for every aircraft type at the airport. See BADA manual and “function.badacoeficient" in section A4 for information about each field in the file.

<table>
<thead>
<tr>
<th>Type</th>
<th>Model</th>
<th>Registry</th>
<th>Distance</th>
<th>Speed</th>
<th>Mach</th>
<th>Climb</th>
<th>Cruise</th>
<th>Cruise Altitude</th>
<th>Thrust</th>
<th>Thrust Altitude</th>
</tr>
</thead>
</table>
| B739 | 0.70675 | 583.997 | 13.133 | 61936 | 0.93516 | 0.025734 | 0.033615 | 156 | 0.04685 | 0.0220897 97 116925 219 150000 Jet
| B738 | 0.70057 | 549.478 | 14.19 | 65932 | 0.92958 | 0.025452 | 0.035815 | 149 | 0.0492 | 0.0424 109 0.0689 0.0404 0.0249 107 63375 124.65
| B737 | 0.6864 | 490.188 | 10.592 | 59399 | 0.9342 | 0.023738 | 0.037669 | 143 | 0.0477 | 0.065000 Jet
| B733 | 0.78052 | 525.608 | 14.768 | 52584 | 0.99371 | 0.024958 | 0.040885 | 141 | 0.06 | Jet
| B703 | 1.15 | 565.889 | 28 | 49990 | 1 | 0.0142 | 0.062707 | 125 | 0.0284 | 0.05
| B462 | 0.75195 | 391.4 | 18.993 | 75 | 20684.5 | 78.82 22930 Turboprop
| ATP | 3.0341 | 5144444444444444 | 5.9858 | 10000000000000000 | 1.0502 | 0.02635 | 0.027511 | 99 | 0.05266 | 0.027511 83 0.07899 0.027511 0.02 75 20684.5 78.82 22930 Turboprop
| B462 | 0.75195 | 391.4 | 18.993 | -642700 | 0.98117 | 0.032922 | 0.039381 | 135 | 0.066984 | 0.039381 93 0.099876 0.039381 0.02 90.5 35000 77.3 42200 Jet
| B703 | 1.15 | 565.889 | 28.49990 | 1 | 0.0142 | 0.062707 | 125 | 0.0284 | 0.062707 96 0.0246 0.062707 0.02 96 93500 274.6 140000 Jet
| B712 | 0.62821 | 267.11 | 10.444 | 133650 | 1.0429 | 0.020945 | 0.045998 | 145 | 0.0465 | 0.0243 107 0.0588 0.041 0.0224 104 44750 90.02 52600 Jet
| B722 | 0.32166 | 60.3135 | 28.211 | 60154 | 0.92644 | 0.018415 | 0.061258 | 157 | 0.03683 | 0.061258 106 0.055245 0.061258 0.02 104 68750 157.9 86400 Jet
| B732 | 1.4232 | 1108.73 | 20.144 | 53383 | 0.99363 | 0.021609 | 0.043078 | 143 | 0.0411 | 0.0416 102 0.079 | 0.0385 0.02544 99 43950 91.09 52300 19
| B733 | 0.78052 | 525.608 | 14.768 | 52584 | 0.99371 | 0.024958 | 0.040885 | 141 | 0.0605 | 0.0414 108 0.092 | 0.0373 0.02 106 50400 91.09 62800 19
| B734 | 0.7595 | 508.95 | 14.769 | 52343 | 0.97905 | 0.025953 | 0.044644 | 152 | 0.0477 | 0.0433 115 0.0833 0.0373 0.0228 109 55310 91.09 68000 19
| B735 | 0.77318 | 454.846 | 14.733 | 52667 | 0.97946 | 0.022776 | 0.045399 | 143 | 0.0542 | 0.041 110 0.089 | 0.0383 0.015 103 49360 91.09 66080 19
| B736 | 0.63557 | 360.955 | 15.384 | 61221 | 0.96824 | 0.021696 | 0.036752 | 137 | 0.0497 | 0.0403 100 0.0721 0.0401 0.0208 99 54000 124.65 65000 Jet
| B737 | 0.68644 | 490.188 | 10.592 | 59399 | 0.9342 | 0.023738 | 0.037669 | 143 | 0.0477 | 0.0423 105 0.0653 0.0412 0.0235 103 57510 124.65 70800 Jet
| B738 | 0.70057 | 549.478 | 14.19 | 65932 | 0.92958 | 0.025452 | 0.035815 | 149 | 0.0492 | 0.0424 109 0.0689 0.0404 0.0249 107 63375 124.65 78300 Jet
| B739 | 0.70675 | 583.997 | 13.133 | 61936 | 0.95361 | 0.028574 | 0.03615 | 156 | 0.04685 | 0.037283 118 0.080202 | 0.034566 0.0211 69866 124.85 813919 Jet

174
File name: MDW_wind_info.dat
This file contains information (see header) extracted from the ASPM airport table for years 2006 to 2012. In addition the date time information is converted to unix timestamp. A sample of the file is shown below. Make sure all the field are present.

# LOCID YYYYMM DAYNUM HR_LOCAL QTR TIMESTAMP(UNIX) MC CEILING VISIBLE TEMP WND ANGL WND SPEED RUNWAY
MDW 200601 1 0 1 1136095200 V 120 8 - 210 5 31C31L31R|22L31C31L31R
MDW 200601 1 0 2 1136096100 V 120 8 - 210 5 31C31L31R|22L31C31L31R
MDW 200601 1 0 3 1136097000 V 120 8 - 210 5 31C31L31R|22L31C31L31R
MDW 200601 1 0 4 1136097900 V 120 8 - 210 5 31C31L31R|22L31C31L31R
MDW 200601 1 1 1 1136098800 V 120 8 - 210 4 31C31L31R|22L31C31L31R
MDW 200601 1 1 2 1136099700 V 120 8 - 210 4 31C31L31R|22L31C31L31R
MDW 200601 1 1 3 1136100600 V 120 8 - 210 4 31C31L31R|22L31C31L31R
MDW 200601 1 1 4 1136101500 V 120 8 - 200 7 31C31L31R|22L31C31L31R
MDW 200601 1 2 1 1136102400 V 120 8 - 200 7 31C31L31R|22L31C31L31R
MDW 200601 1 2 2 1136103300 V 120 8 - 200 7 31C31L31R|22L31C31L31R

File name: aircraft_cat.dat
This file contains aircraft categories at MDW. A sample of the file is shown below. This can derived from the NOP data being processed. The aircraft are classified as turboprops, business jet (small, medium, large), regional jets (medium, small), B73’s and narrow body based on their MTOW.

# Actype Engine Count MTOW Category
B737 Jet 5785 70080 B737s
B738 Jet 15 78300 B737s
B733 Jet 1526 62800 B737s
B735 Jet 328 60680 B737s
B732 Jet 1 52300 B737s
B734 Jet 2 68000 B737s
B738 Jet 15 78300 narrow_body
A320 Jet 30 77000 narrow_body
B721 Jet 1 77000 narrow_body
MD90 Jet 9 77000 narrow_body
B737 Jet 5785 70080 narrow_body
A319 Jet 297 70000 narrow_body

File name: flow_colors_2.dat
# direction runway approach color
E 13C ILS red
E 13C RNP magenta
E 13C Visual pink
# E 13L SA
E 22L Visual orange
# E 22R Visual 64 15.111 22.47 18.6924 1.59441
E 31C ILS blue
E 31C Visual violet
# E 4L SA 35 23.6128 39.851 31.543 4.54613
E 4R ILS yellow
E 4R Visual green
W 13C ILS red
W 13C RNP magenta
W 13C Visual pink
# W 13L Visual 6 31.034 97.834 44.0956 26.4114
W 22L Visual orange
# W 22R Visual 62 36.295 78.4852 48.9974 7.92077
W 31C ILS blue
W 31C Visual yellow
# W 31R Visual 1 41.7532 41.7532 41.7532 0
# W 4L Visual 34 25.6115 39.2291 30.2807 2.73918
W 4R ILS green
W 4R Visual lime
File name: rnp_gen_info.dat
This file contains the criteria for reflecting and rotating 13C RNP tracks to get RNP tracks for 22L, 31C and 4R at MDW.
# airport direction1  runway1 direction2 runway2 rotate(0,1) reflect
MDW E 4R W 13C RNP 1 0
MDW E 22L W 13C RNP 1 1
MDW W 22L E 13C RNP 1 1
MDW W 31C W 13C RNP 1 1

File name: MDW_flight_data_2007_2012.TAB
This the ASPM flight table (tab separated) for MDW from year 2007 to 2012. The can be downloaded from the FAA ASPM website.

File name: MDW_star_holding_fix.dat
This file contains the coordinates for boundaries to capture holding patterns on the arrival STARs for MDW.
# direction holding fixes coordinates
# W MINOK
W MOTIF -88.31906309616981 41.27655670829328 -88.45340850652383 40.9712032958472 -88.77191894379681 41.03584907437446 -88.62588191894508 41.35448425806798
# W PNT
# W PIA
# W BDF
E OZZEY -86.84127460957141 41.14297499358587 -87.13463422302871 41.36712527344572 -87.0060399870756 41.74145373742799 -86.72558787251218 41.25764817533518
E FISSK -86.48080818382738 41.1979152102979 -86.05732347451041 41.09936272533439 -86.16326659945729 40.8433443177345 -86.59425723283579 40.94508811340405
E HALIE -87.42489454004537 41.57038497020047 -87.1422507845394 41.56647298242147 -87.13370082771226 41.42736351560021 -87.4334148456261 41.425452145423
E IROCK -86.99004519299315 41.50828170749523 -86.99059307454925 41.65809435393067 -86.5916684322361 41.65976256473662 -86.59209867470884 41.51051470725858
E GSH -85.49007757056091 41.65951969124372 -85.49679772117916 41.32506632044909 -86.2257425653612 41.32597546754238 -86.2090567269282 41.67198864319884

File name: MDW_2007_2012_arr_rwy
This file combine ASPM airport and flight table to get the count of flight from each direction to each runway.
# LOCID YYYYMM DAYNUM HR_LOCAL QTR TimeStamp MC CEILING VISIBLE TEMP WND_ANGL WND_SPED
RUNWAY Traffic_east Traffic_west Ratio Arrival_Rwy
MDW 200701 17 2 1167657300 1013 9 38 260 11 31C31L31R|22L31C31L31R 10 0 0.662356 31C
MDW 200701 18 1 1167660000 1015 10 39 270 10 31C31L31R|22L31C31L31R 2 1 0.646597 31C
MDW 200701 18 2 1167660900 1015 10 39 270 10 31C31L31R|22L31C31L31R 2 1 0.646597 31C
MDW 200701 18 3 1167661800 1015 10 39 270 10 31C31L31R|22L31C31L31R 4 3 0.646597 31C
MDW 200701 18 4 1167662700 1015 10 39 290 13 31C31L31R|22L31C31L31R 2 2 0.646597 31C
MDW 200701 19 1 1167663600 1015 10 39 290 13 31C31L31R|22L31C31L31R 3 2 0.6 31C
MDW 200701 19 2 1167664500 1015 10 39 290 13 31C31L31R|22L31C31L31R 4 2 0.6 31C
MDW 200701 19 3 1167665400 1015 10 39 290 13 31C31L31R|22L31C31L31R 3 1 0.6 31C
MDW 200701 19 4 1167666300 019 10 40 310 10 31C31L31R|22L31C31L31R 2 2 0.6 31C

File name: ORD_ASPM_airport.txt (tab separated)
ASPM airport table for ORD for years 2007 to 2012.

File name: ORD_flight_data_2007_2012.TAB (tab separated)
ASPM flight table for ORD for years 2007 to 2012.
A3. **Gawk scripts**

The scripts for the analysis are provided below. Each script needs to be saved (as the file name provided) in the same directory as the other files.

**File name: script_run_main.gawk**

```plaintext
# This script runs all the other scripts
infile="NOP_filelist.dat"

# run script_process_tracks_2.gawk
gawk '{if($1!="#") print $0} $infile > temp_input
gawk '{execute="/script_process_tracks_2.gawk "$1; print execute; system(execute)}' temp_input

# run script_compute_NOP_stats.gawk
gawk 'BEGIN{execute="/script_compute_NOP_stats.gawk"; print execute; system(execute)}'

# run script_plot_tracks_by_flow0.gawk
gawk 'BEGIN{execute="/script_plot_tracks_by_flow0.gawk"; print execute; system(execute)}'

# run script_get_new_rnp_approach0.gawk
gawk 'BEGIN{execute="/script_get_new_rnp_approach0.gawk"; print execute; system(execute)}'

# run script_get_fb_all_flows.gawk
gawk 'BEGIN{execute="/script_get_fb_all_flows.gawk"; print execute; system(execute)}'

# run script_MDW_annual_fb0.gawk
gawk 'BEGIN{execute="/script_MDW_annual_fb0.gawk"; print execute; system(execute)}'

# run script_get_holding_patterns.gawk
gawk 'BEGIN{execute="/script_get_holding_patterns.gawk"; print execute; system(execute)}'

# run script_metroplex_benefits.gawk
gawk 'BEGIN{execute="/script_metroplex_benefits.gawk"; print execute; system(execute)}'
```

**File name: script_MDW_annual_fb0.gawk**

```plaintext
# This script estimate the annual fuel burn for MDW arrivals
# Input files
# Input1 ASPM runway and wind info
rwy_windy_info="MDW wind info.dat"
# Input2 ASPM flight info
flight_info="MDW_flight_data_2007_2012.TAB"
# Input3 valid ac types
actypes="aircraft_cat.dat"
# NOP data
nopflight="NOP_data_all_good_2"
# Year range
year_start="2007"
```
year_end="2012"
# Time range
time_start=7
time_end=22
# Fuel burn flow
MDW_fb_flow="MDW_all_flows_mean_fb"
# runways
r1="13C"
r2="31C"
r3="22L"
r4="4R"

# basic process repeat flag
# Change this to zero if the basic data process does not have to be repeated
firstrun=1
if [ $firstrun -eq 1 ] then

# Process flight information and get flight count every 15 min
# make actype tab separated
sed 's/ /\t/g' $actypes > temp_actypes
gawk -v year_start=$year_start -v year_end=$year_end 'BEGIN{x=99} {if($1!=x){if(FNR!=1){if(count==2) print hr,y1/(y1+y2); x=$1; count=1; y1=$3; hr=$1} else{count++; y2=$3}} END{if(count==2) print hr,y1/(y1+y2)}' $flight_info | sort -k1,1n -k2,2n -k3,3n -k4,4n > temp_flightcount

# Get the hourly east west traffic ratio
TZ=UTC gawk -v zone=-6 '{if($1!="#"){mnth=strftime("%m",$13); hr=strftime("%H",$13); qtr=int(strftime("%M",$13)/15)+1; if(mnth>=3 && mnth<11){hr=hr+zone-1} else{hr=hr+zone}; if(hr<0){hr=hr+24}; arr[hr" ",$23]++}} END{for(no in arr) print no, arr[no]}' $nopflight | sort -k1,1n -k2,2n > temp_tratio_1

# Combine wind info with traffic and traffic ratio information for every qtr
awk '{if($15~/^0/){$15=0}}1' $MDW_fb_flow | gawk '(NR==FNR){arr[$1" ",$2" ",$3" ",$4]=$5" ",$6; next} ($2" ",$3" ",$4" ",$5 in arr){print $0, arr[$2" ",$3" ",$4" ",$5]}' MDW_flightcount $rwy_wind_info | awk '{if($15~/^0/){$15=0}}1' temp_tratio_1 | awk '{print $0}' temp_qtr_info1 | awk '{print $0, arr[$2" ",$3" ",$4]}' $MDW_east_west_ratio > temp_qtr_info2

# Filter out periods before 7AM and after 10PM
gawk -v time_start=$time_start -v time_end=$time_end '(if($4-7<=time_start && $4<=time_end) print $0)' temp_qtr_info2 > temp_qtr_info3

# Create proxy approach for RNP approach on to 31C and 4R from the east and west respectively
  # E 31C ILS = E 31 RNP
  # W 4R ILS = W 4R RNP
gawk '{if($1="E" && $2="31C" && $3="ILS") || ($1="W" && $2="4R" && $3="ILS")}{print $0}!' MDW_fb_flow | awk '{if($3="RNP")1; $3="MDW_fb_flow"}1' temp_MDW_fb_flow_1 | sort -k1,1n -k2,2n -k3,3n -k4,4n > temp_MDW_fb_flow_2

gawk '{if($2 "S3"-"S3" && $5<="S3") {s0=0; s1=0; s2=0; s3=0; s4=0; s5=0} else{print x,fbi,fbs,791}'} temp_MDW_fb_flow_2 > temp_MDW_fb_flow_3

# print average fuel burn per runway per approach for various values of east west ratio
(0 to 1)
# Get the actual runway for each 15 min bin

gawk -v r1=$1 -v r2=$2 -v r3=$3 -v r4=$4 '{if($13~/^"$r1"/){print $0,r1} else{if($13~/^"$r2"/){print $0,r2} else{if($13~/^"$r3"/){print $0,r3} else{if($13~/'"$r4"'/){print $0,r4} else{print $0,"NA"}}}}}' temp_qtr_info3 > temp_qtr_info4

# Output MDW arrival runway config

cp temp_qtr_info4 MDW_$year_start"_"$year_end"_"arr_rwy

# Get average fuel burn per flight for actual and optimal runway configuration
# print out three cases of flows
# case1: only Visual and ILS, case2: case1 plus 13C RNP, case3: all flows

gawk 'BEGIN{print 1; print 2; print 3}' > temp_flowcases

# For all aircrafts get actual and optimal runway configuration

gawk -v infile="temp_qtr_info4" -v fb_flow="temp_MDW_fb_flow_3" '{execute="time ./script_get_fb_15min_actual_config.gawk "$1" "infile" "fb_flow; print execute; system(execute)"'} temp_flowcases

# The output of the above script is temp_qtr_info4 with additional information

# Compute total number of flight and fuel burn for each case
# flight count field for All flights is $14 and for SWA is $15

# Also fuel burn for B737 is more than all fleet mix by 1.19

gawk -v fcf=14 -v factor=1.19 '{if($fcf!=0){year=substr($2,1,4); if($18!=999){fltcnt[year]+=0; firing[year]+=factor; a1[year]+=factor; a2[year]+=factor; a3[year]+=factor; a4[year]+=factor} else{fltcnt[year]+=0; firing[year]+=factor; a1[year]+=factor; a2[year]+=factor; a3[year]+=factor; a4[year]+=factor}}}' temp_flight_count_fb_by_year1

gawk -f function.mean -f function.std -f function.avgfb_allcases temp_flight_count_fb_by_year1 > temp_flight_count_fb_by_year1_swa

# Compute average fuelburn per year

gawk -f function.mean -f function.std -f function.avgfb_allcases temp_flight_count_fb_by_year1_swa > temp_flight_count_fb_by_year2_swa

# Get actual and optimal runway config

gawk 'actual[17]+; opt1[21]+; opt2[26]+ END{for(no in actual){print no, actual[no], opt1[no], opt2[no]}}' temp_qtr_info4 | sort -k1,1 > MDW_runway_config1

# Get IMC VMC for each year

gawk '{arr[substr($2,1,4)+"$7"]++} END{for(no in arr){print no, arr[no]}'} temp_qtr_info4 | sort -k1,1 > temp_MDW_MC

else

gawk 'BEGIN(y="do nothing")'

# The output of the above script is temp_qtr_info4 with additional information
Compute total number of flight and fuel burn for each case
flights count field for All flights is $14 and for SWA is $15
Also fuel burn for B737 is more than all fleet mix by 1.19

Compute total fuelburn per year for all year

```
gawk -v fcf=14 -v factor=1 '{if($fcf!=0){year=substr($2,1,4); if($18!=999){fltcnt[year"$7"]=fct; base[year"$7"]=$(18*$fcf)*factor; a1[year"$7"]=$(20*$fcf)*factor; a2[year"$7"]=$(23*$fcf)*factor; a3[year"$7"]=$(25*$fcf)*factor; a4[year"$7"]=$(28*$fcf)*factor;}}' temp_qtr_info4 | sort -k1,1n -k2,2n > temp_flight_count_fb_by_year1
```

Compute average fuelburn per year

```
gawk -f function.mean -f function.std -f function.avgfb_allcases temp_flight_count_fb_by_year1 > temp_flight_count_fb_by_year2
```

Compute total fuelburn per year for all year

```
gawk -v fcf=15 -v factor=1.19 '{if($fcf!=0){year=substr($2,1,4); if($18!=999){fltcnt[year"$7"]=fct; base[year"$7"]=$(18*$fcf)*factor; a1[year"$7"]=$(20*$fcf)*factor; a2[year"$7"]=$(23*$fcf)*factor; a3[year"$7"]=$(25*$fcf)*factor; a4[year"$7"]=$(28*$fcf)*factor;}}' temp_qtr_info4 | sort -k1,1n -k2,2n > temp_flight_count_fb_by_year1_swa
```

# Get actual and optimal runway config
```
gawk '{actual[$17]++; opt1[$21]++; opt2[$26]++} END{for(no in actual){print no, actual[no], opt1[no], opt2[no]}}' temp_qtr_info4 | sort -k1,1 > MDW_runway_config1
```

# Get IMC VMC for each year
```
gawk '{arr[substr($2,1,4)"$7"]++} END{for(no in arr) print no, arr[no]}' temp_qtr_info4 | sort -k1,1n > temp_MDW_MC
```

File name: script_assign_airport.gawk

# This script filters out noise and assign track to the airport of interest
# This also separates arrival from departure
infile1=$1
airport=$2
lat=$3
lon=$4
color1=$5
color2=$6
input1=$infile1"_first_last"
input2=$infile1"_all_filtered"

out1=$infile1"$airport"_AD"
out2=$infile1"$airport"_Ltracks"
out3=$out2".kml"
out4=$infile1"$airport"_Dtracks"
out5=$out4".kml"

# Assign airport, arrival departure information to each flight
```
gawk -v airport=$airport -v lat=$lat -v lon=$lon -v alt=2000 -v span=.05 -f function.assignairports $input1 > temp_AD
```

# Separate arrival track from departure tracks
```
gawk "([NR==FNR]){if($NF=="A"){$1 in arr}next} ($1 in arr){print $0,arr[$1]}" temp_AD
```
```
gawk "([NR==FNR]){if($NF=="D"){$1 in arr}next} ($1 in arr){print $0,arr[$1]}" temp_AD
```

# Print output files
# airport flights
cp temp_AD $out1

# Arrival track information
cp temp_A_tracks $out2
# kml file for arrival tracks
if [ -s $out2 ]
    then
gawk -v filename=$out1 -v linecolor=$color1 -f function.getcolor -f function.kmlfile_1 $out2 > $out3
fi

# Departure track information
cp temp_D_tracks $out4
# kml file for arrival tracks
if [ -s $out4 ]
    then
gawk -v filename=$out1 -v linecolor=$color2 -f function.getcolor -f function.kmlfile_1 $out4 > $out5
fi

File name: script_assign_flow_direction.gawk
# This script assigns direction to each track
# Input
infile1=$1
recno=$2
airport=$3
type=$4
direction=$5
lat1=$6
lon1=$7
lat2=$8
lon2=$9
# Step1 Get input file
if [ $recno -eq 1 ]
    then
    input1=$infile1"_"$airport"_"$type
    input2=$infile1"_"$airport"_"$type"rwy"
    rm temp_assignedids
else
    input1="temp_remainingtracks"
    input2=$infile1"_"$airport"_"$type"rwy"
fi
if [ $recno -ne 0 ]
    then
    # Get id of track inside the box
    gawk -v lat1=$lat1 -v lon1=$lon1 -v lat2=$lat2 -v lon2=$lon2 '($7<lat1 && $7>lat2 && $8>lon1 && $8<lon2) print $1' $input1 | sort -u > temp_validid
    # Print out remaining track
    gawk '(NR==FNR){arr[$1];next} !($1 in arr){print $0}' temp_validid $input1 > temp_dummy
    cp temp_dummy temp_remainingtracks
    # Assign valid id the flow direction
    gawk -v direction=$direction '($1 in arr){print $1,direction} !($1 in arr){print $0,direction}'' $input2 >> temp_assignedids
else
    out1=$infile1"_"$airport"_"$type"rwy_dir"
    cp temp_assignedids $out1
fi

File name: script_assign_flow_direction0.gawk
# This script executes the script_assign_flow_direction.gawk
# Input
infile1=$1
### type airport is the airport of interest type is Arrival tracks (Atracks) or Departure tracks (Dtracks)

gawk -v airport=$airport -v type=$type '{if($1==airport && $2==type){i++;print i,$0}}
END{print 0,airport,type}'

## Assign flow direction

gawk -v infile1=$infile1 '{execute="time ./script_assign_flow_direction.gawk "infile1" "$0; print execute; system(execute)"; temp_flowdirection}

### File name: script_assign_flow_procedure.gawk

This script assigns flow procedure to each track

# e.g. ILS RNP or visual approach

## This script assigns direction to each track

**Input**

- `infile1` = $1
- `recno` = $2
- `airport` = $3
- `type` = $4
- `runway` = $5
- `procedure` = $6
- `fix` = $7
- `check_radius` = $8
- `vertical` = $9
- `fix_lat` = $10
- `fix_lon` = $11

**# Step1 Get input file**

if [ $recno -eq 1 ]
then
    input1="$infile1" "$airport" "$type"
    input2="$infile1" "$airport" "$type" rwy_dir_pro
fi

**# rm temp_assignedids**

**# filter out tracks for the current runway and direction**

gawk -v runway=$runway -v direction=$direction '{if($21==runway && $22==direction) print $1,$21,$22}' $input2 > temp_ids_runway_direction
gawk '(NR==FNR){arr[$1];next} ($1 in arr){print $0}' temp_ids_runway_direction $input1a > temp_track_runway_direction

input1="temp_track_runway_direction"
else
    input1="temp_remainingtracks"
    input2="$infile1" "$airport" "$type" rwy_dir_pro
fi

**# body of the code where each track is assigned to a procedure**

if [ $recno -ne 0 ]
then
    **# Get id of track around each fix**
    **# Debug test print**

    gawk -v fix_lat=$fix_lat -v fix_lon=$fix_lon -v check_radius=$check_radius -f function.distfromfix1 -f function.gcd_haversine_2 $input1 | sort -u > temp_test
    gawk -v vertical=$vertical -v fix_lat=$fix_lat -v fix_lon=$fix_lon -v check_radius=$check_radius -v procedure=$procedure -v runway=$runway -v scale=0.2 -f function.distfromfix1 -f function.bearing -f function.absvalue -f function.radian -f function.degrees -f function.gcd_haversine_2 -f function.dist_point_line_2 -f function.getcartesian_2 $input1 | sort -u > temp_validid
    **# Print out remaining track**

    gawk '(NR==FNR){arr[$1];next} !($1 in arr){print $0}' temp_validid $input1 > temp_dummy
    cp temp_dummy temp_remainingtracks
```bash
# Assign valid id the flow direction

gawk -v procedure="$procedure" 'NR==FNR{arr[$1]; next} ($1 in arr){$23=procedure}1'
temp_validid $input2 > temp_assignedids
cp temp_assignedids $input2
else
# If there are no ILS approach then copy the input1 file to temp_remainingtracks
cp $input1 temp_dummy2
cp temp_dummy2 temp_remainingtracks
fi

gawk -v direction=$direction 'NR==FNR{arr[$1]; next} ($1 in arr){print $0,direction}'
temp_validid $input2 >> temp_assignedids
else
##out1=$infile1"_"$airport"_"$type"rwy_dir_pro"
##cp temp_assignedids $out1
# Assign Visual approach to track that have not been assigned ILS or RNP
gawk -v runway=$runway -v direction=$direction '{if($21==runway && $22==direction) print $1,$23}'
$input2 > temp_ids_procedure
gawk '{if($2==1) print $0}' temp_ids_procedure > temp_ids_notassigned
if [ -s temp_ids_notassigned ]
then
gawk -v procedure="Visual" 'NR==FNR{arr[$1]; next} ($1 in arr){$23=procedure}1'
temp_ids_notassigned $input2 > temp_assignedids
cp temp_assignedids $input2
fi
fi

File name: script_assign_flow_procedure0.gawk
# This script executes script_assign_flow_procedure.gawk
#
# Input
# infilie=$1
# recno=$2
# airport=$3
# type=$4
# direction=$5
# runway=$6
# flowinfo=$7

if [ $recno -eq 1 ]
then
# Create a file to record the procedure for each track
gawk '{print $0,1}' $infile1"_"$airport"_"$type"rwy_dir_pro" $infile1"_"$airport"_"$type"rwy_dir_pro" temp_basefile

## Assign flow direction
gawk -v airport=$airport -v type=$type -v runway=$runway -v direction=$direction '{if($1==airport & $2==type & $3==direction & $4==runway){i++;print i,$0}} END{print 0,airport,type,direction,runway}' $flowinfo > temp_flowinfo

File name: script_assign_runway.gawk
# This script assign each track to a runway
#
# arr=$1
# infilie=$2
# runwayinfo=$3
# airport=$4
# lat=$5
```
lon=$6

# Step 1: Get the first two track points in case of departures and last two in case of arrivals for each flight
if [ $arr -eq 1 ]
then
    input1=$infile1 "$airport" Atracks
    out1=$infile1 "$airport" Atracksrwy
    awk '{if($1!=x){x=$1; if(FNR!=1){print arr[i-1],arr[i]}; i=1; delete arr; arr[i]=$0} else{i++; arr[i]=$0}} END{print arr[i-1],arr[i]}' $input1 > temp_1record
else
    input1=$infile1 "$airport" Dtracks
    out1=$infile1 "$airport" Dtracksrwy
    awk '{if($1!=x){x=$1; if(FNR!=1){print arr[1],arr[2]}; i=1; delete arr; arr[i]=$0} else{i++; arr[i]=$0}} END{print arr[1],arr[2]}' $input1 > temp_1record
fi

# Filter out runway co-ordinates for airport of interest
awk -v airport=$airport '{if($1==airport) print $6,$7,$8,$9,$10,$11}' $runwayinfo > temp_runway_coordinates

# Assign runway to each track
awk -v arr=$arr -v lat=$lat -v lon=$lon "f function.getrunway_2 -f function.getcartesian
-f function.bearing -f function.degrees -f function.dist_point_line -f function.absvalue temp_runway_coordinates temp_1record > temp_runway

# Output runway assignments
cp temp_runway $out1

# print kml file
# Get the color information for each runway
# get runways
awk '{if(SNF!="NA") print SNF}' temp_runway | sort -u > temp_runway2

# get runway info
if [ $arr -eq 1 ]
then
gawk -v airport=$airport "(NR==FNR){arr[$1];next} ($6 in arr){if($1==airport) print $6,$12}" temp_runway2 $runwayinfo > temp_runwayinfo1
gawk -v airport=$airport "(NR==FNR){arr[$1];next} ($7 in arr){if($1==airport) print $7,$14}" temp_runway2 $runwayinfo > temp_runwayinfo2
cat temp_runwayinfo1 temp_runwayinfo2 > temp_runwayinfo3
else
gawk -v airport=$airport "(NR==FNR){arr[$1];next} ($6 in arr){if($1==airport) print $6,$13}" temp_runway2 $runwayinfo > temp_runwayinfo1
gawk -v airport=$airport "(NR==FNR){arr[$1];next} ($7 in arr){if($1==airport) print $7,$15}" temp_runway2 $runwayinfo > temp_runwayinfo2
cat temp_runwayinfo1 temp_runwayinfo2 > temp_runwayinfo3
fi

# print kml file
awk -v input1="temp_runway" -v input2=$input1 "execute="/script_print_kml_byrwy.gawk "input1" "input2" "$1" "$2; print execute; system(execute)" $temp_runwayinfo3

# remove temp file
rm temp*

File name: script_combine_NOP_files.gawk
# This files combines all NOP processed data
# Input
infile1=$1
recno=$2
all=$3
airport=$4
type=$5
custom=$6
if [ "MDW" == "$airport" ]
then
  if [ $custom -eq 1 ]
  then
    if [ $recno -eq 1 ]
    then
      rm NOP_data_all_good_custom
      input=$ infile1
      out1="NOP_data_all_good_custom"
    else
      if [ $recno -eq 1 ]
      then
        rm NOP_data_all
      else
        rm NOP_data_all_good
      fi
    fi
  else
    if [ $recno -eq 1 ]
    then
      if [ $all -eq 1 ]
      then
        rm NOP_data_all_custom
      else
        rm NOP_data_all_good
      fi
    fi
  fi
  if [ $all -eq 1 ]
  then
    out1="NOP_data_all"
    input=$ infile1"_"$airport"_"$type"rwy"
  else
    out1="NOP_data_all_good"
    input=$ infile1"_"$airport"_"$type"rwy_dir_pro"
  fi
fi

###if [ "MDW" == "$airport" ]
###then
  gawk -v infile1=$ infile1 '{print infile1,$0}' $ input | gawk '{if($24==1){if($22=="13L" || $22=="4L" || $22=="22L" || $22=="22R" || $22=="31R"){$24="Visual"} else{$24="SA"}}1}' >> $out1
fi

if [ "ORD" == "$airport" ]
then
  if [ $recno -eq 1 ]
  then
    rm NOP_data_all_good_ORD
  fi
  out1="NOP_data_all_good_ORD"
  input=$ infile1"_"$airport"_"$type"rwy"
  gawk -v infile1=$ infile1 '{print infile1,$0}' $input >> $out1
fi

File name: script_combine_flow_stats.gawk
# This script computes stats for combined flows
# input files
input=1
MC=2 # (values are 0-VMC, 1-IMC(ILS), 2-IMC(RNP))

infile1="NOP_"$ input"_stats"
infile2="NOP_"$ input"_stats_custom"
out1="NOP_"$ input"_stats_combined_"$MC"
# Get required records
if [ $MC -eq 0 ]
  then
cat $infile1 $infile2 | gawk '{if($1!="NA") print $0}' | gawk '{if($3=="Visual" || $3=="SA") print $0}' | sort -k2,2 > temp_infile
else
  if [ $MC -eq 1 ]
  then
cat $ infile1 $ infile2 | gawk '{if($1!="NA") print $0}' | gawk '{if($3=="ILS" || $3=="SA") print $0}' | sort -k2,2 > temp_infile
else
cat $ infile1 $ infile2 | gawk '{if($1!="NA") print $0}' | gawk '{if($3=="RNP" || $3=="SA") print $0}' | sort -k2,2 > temp_infile
fi
fi

# Get stats for each runway by combining flows.
gawk -f function.combine_flow_stats temp_infile > $out1

File name: script_combine_fuelburn_actypes.gawk
# This script combines fuel burn for all aircraft types for various flows
# Input1 aircraft types
ac_cat=$1
percentage=$2

# runways
r1=$3
r2=$4
r3=$5
r4=$6

input="NOP_fuelburn "$ac_cat"_stats"
gawk -v percentage=$percentage -v r1=$r1 -v r2=$r2 -v r3=$r3 -v r4=$r4 '{if($1!="NA" && $2~/('"$r1"'|"$r2"'|"$r3"'|"$r4")/ && $4>10) print $0,percentage}' $input >> temp_actypes3

File name: script_combine_fuelburn_actypes0.gawk
# This script combines fuel burn for all aircraft types for various flows
# This script is only for MDW arrivals
# Input1 aircraft types
actype="aircraft_cat.dat"
infile="NOP_data_all_good"

# runways
r1=$1
r2=$2
r3=$3
r4=$4

# Get percentage of flights under each aircraft category
gawk '(NR==FNR){arr[$1]=$5; next} ($2 in arr){print $2,arr[$2]}' $actype $infile > temp_actypes1
gawk '{{(arr[$2]++; count++) END{for(no in arr){print no,arr[no],arr[no]/count}' temp_actypes1 | sort -k3,3nr > temp_actypes2

# Combine files
# The output of the script is temp_actypes3
rm temp_actypes3
```bash
gawk -v r1=$r1 -v r2=$r2 -v r3=$r3 -v r4=$r4
'{execute="./script_combine_fuelburn_actypes.gawk "$1" "$3" "r1" "r2" "r3" "r4; print execute; system(execute)}" temp_actypes2

# Calculate average fuel burn per flight for each flow
sort -k1,1 -k2,2 -k3,3 temp_actypes3 | gawk '{if($1" "$2" "$3!=x){if(FNR!=1){if(count>=2){print x,flights,"NA","NA",fb,"NA"}}; x=$1" "$2" "$3; count=1; flights=0; flights+=flights+$4; fb=0; fb=fb+$7*$9} else{count++; flights=flights+$4; fb=fb+$7*$9}} END{if(count>=2){print x,flights,"NA","NA",fb,"NA"}}' temp_actypes4

File name: script_compute_NOP_stats.gawk
# This script compute stats for processed NOP data
# For MDW Arrivals
# Input
filelist="NOP_filelist.dat"
out1="NOP_MDW_Atracks_flow_stats.dat"
bada="BADA_coefficient_2.dat"
aircraft_category="aircraft_cat.dat"
# Combine all the files
# Good tracks for MDW Atracks
# The output file name is NOP_data_all_good
# Don't have the run this unless script_process_tracks_2.gawk has been modified and run
# MDW arrivals
# ORD departures
# The output file name is NOP_data_all_good_ORD
# MDW flow stats analysis
# mark track with noise that had not been filtered
# Filter out general aviation flights
# Get count of all the flows
# Compute statistics for each flow
# Track mile stats (field no 26)
# Track mile stats (field no 27)
```
# fuel burn stats (field no 30)
gawk -v fieldno=30 -v input="NOP_data_all_good_2" -v GA=0
'({execute="/script_get_min_max_mean_std.gawk "FNR" "input" "$1" "$2" "$3" "$4" "$5"
"fieldno" "GA; print execute; system(execute)"} temp_flow_counts

##sort -k1,1 -k2,2 -k3,3 temp_stats_out > NOP_tracktime_stats

# level time stats (field no 31)
gawk -v fieldno=31 -v input="NOP_data_all_good_2" -v GA=0
'({execute="/script_get_min_max_mean_std.gawk "FNR" "input" "$1" "$2" "$3" "$4" "$5"
"fieldno" "GA; print execute; system(execute)"} temp_flow_counts

##sort -k1,1 -k2,2 -k3,3 temp_stats_out > NOP_tracktime_stats

cp temp_stats_out NOP_leveltime_stats

# Get goaround stats

# Track mile stats (field no 26)
gawk -v fieldno=26 -v input="NOP_data_all_good_2" -v GA=1
'({execute="/script_get_min_max_mean_std.gawk "FNR" "input" "$1" "$2" "$3" "$4" "$5"
"fieldno" "GA; print execute; system(execute)"} temp_flow_counts

##sort -k1,1 -k2,2 -k3,3 temp_stats_out > NOP_tracktime_stats_GA


cp temp_stats_out NOP_tracktime_stats_GA

# Track mile stats (field no 27)
gawk -v fieldno=27 -v input="NOP_data_all_good_2" -v GA=1
'({execute="/script_get_min_max_mean_std.gawk "FNR" "input" "$1" "$2" "$3" "$4" "$5"
"fieldno" "GA; print execute; system(execute)"} temp_flow_counts

##sort -k1,1 -k2,2 -k3,3 temp_stats_out > NOP_tracktime_stats_GA


cp temp_stats_out NOP_tracktime_stats_GA

### Get distribution aircraft types

# Get the engine type and MTOW for each aircraft
gawk '{print $0,"NA","NA"} NOP_data_all_good > temp_engine_MTOW_1
gawk '{NR==FNR){mtow[$1]=$19;engine[$1]=$20;next} ($29 in mtow){$33=mtow[$29];$34=engine[$29]}1' temp_engine_MTOW_1 > temp_engine_MTOW_2

# Get distribution by a/ctype
gawk '{if($25=="NA") print $0} temp_engine_MTOW_2 | sort -k29,29 | gawk -f function.fb_actype -f function.min_max_mean_sd_3 -f function.mean -f function.std | sort -k4,4nr > distribution_actype

# Compute fuel burn for each aircraft category
gawk '{print $5}' $aircraft_category | sort -u > temp_ac_cat
gawk -v infile="NOP_data_all_good_2" -v actypes=$aircraft_category
'({execute="/script_compute_fuelburn_bycat.gawk "infile" "actypes" "$1; print execute; system(execute)"} temp_ac_cat

File name: script_compute_fb_new_rnp.gawk

# This script computes track distance/time and fuel burn for the new rnp tracks generated by reflection and rotation of 13C RNP tracks

# get track info for all the valid ids

# input variables
infile=$1
badadata=$2
reco=$3
airport=$4
type=$5
direction=$6
fix=$7
lat1=$8
lon1=$9
lat2=${10}
lon2=${11}
check_radius=${12}
lat0=${13}
lon0=${14}
alat=$[15]  
alon=$[16]  
elev=$[17]  
winfo=$[18]  

## Set input and output filenames
in1="tracks_"$infile1  
o1="metrics_"$infile1

if [ $recno -eq 1 ]
then
  # Create a file to record the procedure for each track
  cp $out1 temp.out
  # Two fields for track mile and track time
  # Three fields for airline name, ac type and fuel burn
  gawk '{print $0,"NA","NA","NA","NA","NA","NA","NA","NA","NA"}' temp.out > $out1
fi

# Get track info close to the airport
gawk -v fix_lat=$alat -v fix_lon=$alon -v check_radius=$check_radius -f function.distairport -f function.gcd_haversine_2 $input1 | sort -k1,1 -k2,2n > temp_validtracks1a

# Compute cumulative distance to threshold
gawk -f function.dist2thresh -f function.gcd_haversine_2 temp_validtracks1a > temp_validtracks2

# Compute distance from fix
scale=3 -f function.dist_point_line_2 -f function.getcartesian_2 -f function.absvalue $input1|sort -k1,1 -k2,2n -k3,3n > temp_validtracks3

# Get the distance from fix to threshold
function.distimefix2thresh_2 -f function.absvalue $input1|temp_validtracks3 > temp_validtracks4

# Update output file with distance and time to threshold from corner post
cp $out1 temp.out
gawk '{d2t[$1]=$2; t2t[$1]=$3; next} ($1 in d2t){$25=d2t[$1]; $26=t2t[$1]}1' temp_validtracks4 temp.out > $out1

# Fuel burn calculation
Fuel burn is a function of track mile flow and hence had to be computed for each direction

# Update airline name and ac type in the output file
if [ $recno -eq 1 ]
then
  # Get airline code and ac type for each flight
  cat $input4 | sort -u > temp_airline_ac_type
  function.distfromfix2 temp_validtracks3 temp_airline_ac_type temp.out > $out1
fi

# Get information about the 4D profile
# Get combine wind information with track data
# Get the min and max timestamp
### sort 

```bash
# Get wind information for valid timestamp range
# get the first time stamp for each flight
```
fixinfo="MDW_fix.dat"
goaaround_holding="goaround_holding.dat"
flowmeasuringfix="flow_measuring_fix.dat"
badaata="BADA_coefficient_2.dat"
windinfo="MDW_wind_info.dat"

# input file
infile1="$direction"_"$runway"_"$procedure"

out1="metrics_"$infile1

# Next few script reform track information to NOP output format (does this makes sense??)
# get the last two hits for each track
gawk '{if($1!=x){x=$1; if(FNR!=1){print arr[i-1],arr[i]}; i=1; delete arr; arr[i]=$0} else{i++; arr[i]=$0}} END{print arr[i-1],arr[i]}' $input1 > temp_1record
cp temp_1record $out1

# print the runway, direction and procedure

gawk -v runway=$runway -v direction=$direction -v procedure=$procedure '{print $0,runway,direction,procedure,"NA"}' $out1 > temp_out1
cp temp_out1 $out1

# Get lat lon the fix from where distance needs to be computed

gawk 'NR-FNR{lat[$1]=$2;lon[$1]=$3;next} ($4 in lat) {print $0, lat[$4], lon[$4]}' $fixinfo $flowmeasuringfix > temp_flowfix_0

# Get lat lon the airport to filter out track with some check radius

gawk 'NR-FNR{lat[$1]=$2;lon[$1]=$3;alt[$1]=$6;next} ($1 in lat) {print $0, lat[$1], lon[$1], alt[$1]}' $airportinfo temp_flowfix_0 > temp_flowfix

# get flow reference point for the direction

gawk -v direction=$direction -v airport=$airport '{if($1==airport && $3==direction){print $0}}' temp_flowfix > temp_flowfix2

# Compute fuel burn for all tracks

gawk -v infile1=$infile1 -v badadata=$badadata -v windinfo=$windinfo1 '{execute="time ./script_compute_fb_new_rnp.gawk "$infile1" "$badadata" "$0" "$windinfo" print execute; system(execute)}' temp_flowfix2

# This part is temp addition needs to be removed later on

cut -d" " -f 1-7,9-21 temp_validtracks7 > temp_mitre_$infile1.txt

File name: script_compute_fuelburn_bycat.gawk

# This file computes fuel burn statistics for each aircraft category
# inputs
# 1 infile=$1
# 2 actypes=$2
# 3 category=$3

# get valid actype for each category

gawk -v category=$category '{if($5==category) print $1}' $actypes > temp_valid_ac_types

# filter out valid records from the NOP filelist

gawk 'NR-FNR{arr[$1]; next} ($29 in arr){print $0}' temp_valid_ac_types $infile > temp_valid_records_1

# Compute fuel burn statistics
gawk 'if($11!="#")if($30!="NA"){print $0,$31/$27}'} temp_valid_records_1 > temp_all_good_valid_actype

# Get stats for specific fields

# flight fuel burn rate for level, non level and final approach

# Get plots for track time vs fuel burn and level time vs fuel burn

# level time track time ratio vs fuel burn

# level time track time ratio vs track time

# level time track time ratio vs level time

# level time track time ratio vs fuel burn

# level time track time ratio vs final approach time

# level time track time ratio vs final approach fuel burn

# level time track time ratio vs non-level time

---

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# level time track time ratio vs non-level fuel burn

```bash
gawk -v category="$category" -v infile="temp_all_good_valid_actype" -v timefield=37 -v fbfield=36 -v GA=0 '{execute="/script_get_time_vs_fuelburn.gawk "infile" "timefield" "fbfield" "GA" "$2" "$3" "$4" "category; print execute; system(execute)} END{execute="/script_get_time_vs_fuelburn.gawk "infile" "timefield" "fbfield" "GA" 0 all all all "category; print execute; system(execute)}' temp_flow_counts3

# Get fuel burn stats
gawk -v fieldno=30 -v input="temp_all_good_valid_actype" -v GA=0 '{execute="/script_get_min_max_mean_std.gawk "FNR" "input" "$1" "$2" "$3" "$4" "$5" "fieldno" "GA; print execute; system(execute)}' temp_flow_counts

### sort -k1,1 -k2,2 -k3,3 temp_stats_out > temp_stats_out NOP_fuelburn_stats

cp temp_stats_out NOP_fuelburn_stats

# Get Level time stats
gawk -v fieldno=31 -v input="temp_all_good_valid_actype" -v GA=0 '{execute="/script_get_min_max_mean_std.gawk "FNR" "input" "$1" "$2" "$3" "$4" "$5" "fieldno" "GA; print execute; system(execute)}' temp_flow_counts

# Get Track time stats
gawk -v fieldno=27 -v input="temp_all_good_valid_actype" -v GA=0 '{execute="/script_get_min_max_mean_std.gawk "FNR" "input" "$1" "$2" "$3" "$4" "$5" "fieldno" "GA; print execute; system(execute)}' temp_flow_counts

### sort -k1,1 -k2,2 -k3,3 temp_stats_out > temp_stats_out NOP_tracktime_stats

cp temp_stats_out NOP_tracktime_stats

File name: script_compute_stats_new_rnp.gawk

# This script computes stats for the user defined rnp approach tracks

# initialize input file
rnp_gen="rnp_gen_info.dat"
# create file list
gawk '{print "metrics_"$2"_"$3"_"$6} $rnp_gen' > temp_filelist

filelist="temp_filelist"

# combine all the files
gawk -v all=0 -v airport="MDW" -v type="Atracks" -v custom=1 '{execute="/script_combine_NOP_files.gawk "$1" "FNR" "all" "airport" "type" "custom; print execute; system(execute)}' $filelist

# Get count of all the flows
gawk -v level=3 '{if($1!="#"){$0,$31/$27,$30/$27,$32/$31,($30-$32)/($27-$31)}} END{for(no in arr) print level,no,arr[no]}' NOP_data_all_good_custom | sort -k3,3 > temp_flow_counts

# Compute statistics for each flow

# Track mile stats (field no 26)
gawk -v fieldno=26 -v input="NOP_data_all_good_custom" -v GA=0 '{execute="/script_get_min_max_mean_std.gawk "FNR" "input" "$1" "$2" "$3" "$4" "$5" "fieldno" "GA; print execute; system(execute)}' temp_flow_counts

### sort -k1,1 -k2,2 -k3,3 temp_stats_out NOP_trackmile_stats

cp temp_stats_out NOP_trackmile_stats

# Track mile stats (field no 27)
gawk -v fieldno=27 -v input="NOP_data_all_good_custom" -v GA=0 '{execute="/script_get_min_max_mean_std.gawk "FNR" "input" "$1" "$2" "$3" "$4" "$5" "fieldno" "GA; print execute; system(execute)}' temp_flow_counts

### sort -k1,1 -k2,2 -k3,3 temp_stats_out > NOP_tracktime_stats

cp temp_stats_out NOP_tracktime_stats

# This is code is only for B73's
```
File name: script_compute_track_mile_time_fuel.gawk

# This script computes the track mile and track time for each track from the fix to the runway threshold

# Input
infile1=$1
badadata=$2
recno=$3
airport=$4
type=$5
direction=$6
fix=$7
lat1=$8
lon1=$9
lat2=${10}
lon2=${11}
check_radius=${12}
lat0=${13}
lon0=${14}
alat=${15}
alon=${16}
elev=${17}
windinfo=${18}

# Set input file name
input1=$infile1"_"airport"_"type
input2=$infile1"_"airport"_"type"_rwy_dir_pro
input3=$infile1"_"airport"_"type"_GA_ids
input4=$infile1".csv"

# Set output filename
out1=$infile1"_"airport"_"type"_rwy_dir_pro

if [ $recno = 1 ];
then
# Create a file to record the procedure for each track
cp $out1 temp_out
# Two fields for track mile and track time
# Three fields for airline name, ac type and fuel burn
gawk '!{print $0,"NA","NA","NA","NA","NA","NA","NA","NA","NA"}' temp_out > $out1
fi

# Filter out relevant flight ids
# Get all flight for the given direction that have been assigned to a flow
gawk -v direction=$direction '{if($22==direction) print $1}' $input2 > temp_validids1
## Remove ids that are goarounds

```bash
if [ -s $input3 ]
then
    gawk '{NR==FNR}{arr[$1]=next} !(1 in arr){print $0}' $input3 temp_validids1 > temp_validids2
else
cp temp_validids1 temp_validids2
fi
```

## Get track info for all the valid ids

```bash
gawk '{NR==FNR}{arr[$1]=next} (1 in arr){print $0}' temp_validids2 $input1 > temp_validtracks1
```

## Get track info close to the airport

```bash
gawk -v fix_lat=$alat -v fix_lon=$alon -v check_radius=$check_radius -f function.distairport -f function.gcd_haversine_2 temp_validtracks1 | sort -k1,1 -k2,2n > temp_validtracks1a
```

## Filter out flight above 8000 ft for flows from the east and 12000ft for flows from the west

```bash
gawk -v direction=$direction '{if(direction=="E") if($9<=8000) print $0} else{if($9<=12000) print $0}' temp_validtracks1a > temp_validtracks1b
```

## Compute cumulative distance to threshold

```bash
gawk -f function.dist2thresh -f function.gcd_haversine_2 temp_validtracks1b > temp_validtracks2
```

## Compute distance from fix

```bash
gawk -v fix_lat=$lat0 -v fix_lon=$lon0 -v lat1=$lat1 -v lon1=$lon1 -v lat2=$lat2 -v lon2=$lon2 -v scale=3 -f function.dist_point_line_2 -f function.getcartesian_2 -f function.absvalue -f function.distfromfix2 temp_validtracks2 > temp_validtracks3
```

## Get the distance from fix to threshold

```bash
gawk -f function.distimefix2thresh_2 -f function.absvalue temp_validtracks3 > temp_validtracks4
```

## Update output file with distance and time to threshold from corner post

```bash
cp $out1 temp_out
gawk '{NR==FNR}{d2t[$1]=$2; t2t[$1]=$3; next} (1 in d2t){$25=d2t[$1]; $26=t2t[$1]}1' temp_validtracks4 temp_out > $out1
```

## Fuel burn calculation

Fuel burn is a function of track mile flow and hence had to be computed for each direction

## Update airline name and ac type in the output file

```bash
if [ $recno -eq 1 ]
then
    gawk -F"," '{if($4="") print $1,substr($3,1,3),$4}' $input4 | sort -u > temp_airline_ac_type
cp $out1 temp_out
gawk '{NR==FNR}{arr1[$1]=$2; arr2[$1]=$3; next} (1 in arr1){$27=arr1[$1]; $28=arr2[$1]}1' temp_airline_ac_type temp_out > $out1
fi
```

## Get information about the 4D profile

## Get combine wind information with track data

## Get the min and max timestamp

```bash
sort -k2,2n temp_validtracks3 | gawk '{if(FNR==1){first=$2}; last=$2} END{print first,last}1' > temp_timestamp_first_last
```

## Get wind information for valid timestamp range

```bash
gawk '{if(FNR==1){first=$1+15*60; last=$2+15*60} else{if(FNR==1){if($6>first){if($6<last){print $0} else{exit}}}1}}' temp_timestamp_first_last $windinfo > temp_valid_windinfo
```
# Combine wind information with track data in temp_validtracks3

gawk '{if(NR==FNR){arr1[FNR]=$6;arr2[FNR]=$11 "$12}
else{for(i=1;i<length(arr1);i++){if($2>arr1[i] && $2<=arr1[i]+15*60){print $0,arr2[i]}}}}' temp_valid_windinfo temp_validtracks3 > temp_validtracks3b

# For each time step, compute the time increment, change in altitude, distance, velocity, acceleration

gawk -v elev=$0 -f function.bearing -f function.degrees -f function.radians -f function.computeTAS -f function.absvalue temp_validtracks3b > temp_validtracks3c

cp temp_validtracks3c temp_validtracks3

# Assign ac type to each track

gawk '((NR==FNR){arr[$1]=$3; next} ($1 in arr){print $0, arr[$1]})' temp_airline_ac_type temp_validtracks5 > temp_validtracks6

# Compute fuel burn for each flight

gawk -v elev=$0 -f function.absvalue -f function.computeFuelburn1 -f function.airDensity $badadata temp_validtracks6 > temp_validtracks7

cp temp_validtracks7 temp_validtracks7_$direction

# Get fuel burn per flight for the flow and for the level and final segments
# specify start of the final as start of final approach in case of MDW it is 1700 feet

gawk -v final=1700 -f function.fuelburn_levelsegment -f function.absvalue temp_validtracks7 > temp_validtracks8

# Update output file

cp $out1 temp_out

gawk '{fb2t[$1]=$2; ls2t[$1]=$3; fbl2t[$1]=$4; fs_t[$1]=$7; fs_fb[$1]=$8; nl_t[$1]=$5; nl_fb[$1]=$6; next} ($1 in fb2t){$29=fb2t[$1]; $30=ls2t[$1]; $31=fbl2t[$1]; $32=fs_t[$1]; $33=fs_fb[$1]; $34=nl_t[$1]; $35=nl_fb[$1]}1' temp_validtracks8 temp_out > $out1

File name: script_compute_track_mile_time_fuel0.gawk

# This script executes script_compute_track_mile_time.gawk
# Input
infile=$1
flowfix=$2
badadata=$3
windinfo=$4

##if [ $recno -eq 1 ]
##then
# Create a file to record the procedure for each track
##gawk '{print $0,1,"NA","NA"} $infile"_"$airport"_"$type"rwy_dir" > $infile"_"$airport"_"$type"rwy_dir_pro"
## test
##cp $infile"_"$airport"_"$type"rwy_dir_pro" temp_basefile
##fi

## Compute track mile and track time for each flow direction

gawk -v infile=$1 -v $badadata=$badadata -v windinfo=$windinfo '{execute="time ./script_compute_track_mile_time_fuel.gawk "$infile" "$badadata" "$FNR" "$0" "$windinfo" print execute; system(execute)}' $flowfix

##gawk -v infile=$1 -v $badadata=$badadata -v windinfo=$windinfo '{execute="time ./script_compute_track_mile_time_fuel2.gawk "$infile" "$badadata" "$FNR" "$0" "$windinfo" print execute; system(execute)}' $flowfix

# File name: script_detect_goaround_holding.gawk
# This script detects go arounds and holding patterns
# Step1: Calculate bearing between two consecutive points
# Step2: Calculate change in bearing
# Step3: Add up change in bearing
# Step4: If above threshold then classify as go around or holding pattern

# Input
infile1=$1
airport=$2
type=$3
check_radius=$4
lat=$5
lon=$6

# infile
input1=${infile1}"_"$airport"_"$type
input2=${infile1}"_"$airport"_"$type"rwy_dir_pro"

# output file
out=${infile1}"_"$airport"_"$type"rwy_dir_pro"
out1=${infile1}"_"$airport"_"$type"_GA_all"
out2=${infile1}"_"$airport"_"$type"_GA_ids"
out3=${infile1}"_"$airport"_"$type"_HOL_all"
out4=${infile1}"_"$airport"_"$type"_HOL_ids"

# filter out track with valid runway assignment
awk \'{if($21!="NA")print$1}1\}' $input2 > temp_assignedids
# Get track information for all valid tracks
awk \'{if(NR==FNR){arr[$1]=;next} ($1 in arr){print $0}}1\}' temp_assignedids $input1 > temp_validtracks
# Get tracks away from the airport
awk \'{if(NR==FNR){arr[$1]="GA";next} ($1 in arr){print $0, arr[$1]}1\}' $input2 temp_turn_angle1 > $out1
# Get goaround ids
awk \'{if($1!=x){if(FNR!=1){if((turnangle1*1)>threshold || turnangle2>threshold || gacheck==1){print id,turnangle1,turnangle2,diff,gacheck}}; x=$1; alt=$9; gacheck=0} else{alt_diff=$9-alt; alt=$9; if(alt_diff>=300){gacheck=1};id=$1; turnangle1=$13; turnangle2=$14; diff=$15; rwydirpro=$16}} END{if((turnangle1*1)>threshold || gacheck==1){print id,turnangle1,turnangle2,diff,gacheck}}1\}' $out1 > $out2
# Update output file
if [-s $out2 ]
then
cp $out temp_out
awk \'{if(NR==FNR){arr[$1]="GA"; next} ($1 in arr){$24=arr[$1]}1\}' $out2 temp_out > $out
fi
# Get holding tracks
# gawk -f function.bearing -f function.absvalue -f function.goaround_holding -f function.radian -f function.degrees temp_tracks_away > $out3
# Get holding ids
# gawk -v threshold=200 '{if($1!=x){x=$1; if(FNR!=1){if(turnangle<0){turnangle=turnangle*-1}; if(turnangle>threshold){print id,turnangle}} else{id=$1; turnangle=$13}}}' $out3 > $out4

File name: script_detect_goaround_holding0.gawk
# This script executes the script_detect_goaround_holding.gawk
# Input
infile-$1
recno-$2
airport-$3
type-$4
goaround_holding-$5
airportinfo-$6

if [ $recno -eq 1 ]
then
# Create a file to record the procedure for each track
cp $infile"_"$airport"_"$type"rwy_dir_pro" temp_out
gawk '{print $0,"NA"}' temp_out > $infile"_"$airport"_"$type"rwy_dir_pro"
## test
## cp $infile"_"$airport"_"$type"rwy_dir_pro" temp_basefile
fi

## airport is the airport of interest type is Arrival tracks (Atracks) or Departure tracks (Dtracks)
gawk -v airport=$airport -v type=$type '{if($1==airport && $2==type){print $0}}' $goaround_holding > temp_goaround_holding2
## get the lat lon information of the airport of interest
gawk '(NR==FNR){lat[$1]=$2;lon[$1]=$3;next} ($1 in lat){print $0, lat[$1], lon[$1]}' $airportinfo temp_goaround_holding2 > temp_goaround_holding3
## Assign flow direction
gawk -v infile1=$infile1 '{execute="time ./script_detect_goaround_holding.gawk "infile1" "$0; print execute; system(execute)}"' temp_goaround_holding3

# File name: script_filter_holding_patterns.gawk
# This script filters holding patterns from the track data
# Input
recno-$1
runway-$2
direction-$3
fix-$4
lon1-$5
lat1-$6
lon2-$7
lat2-$8
lon3-$9
lat3-{$10}
lon4-{$11}
lat4-{$12}

# get infile
infile="tracks_"$runway"_"$direction
if [ $recno -eq 1 ]
then
rm temp_tracks_rectangle
fi

# Filter valid tracks

gawk -v lat1=$lat1 -v lon1=$lon1 -v lat2=$lat2 -v lon2=$lon2 -v lat3=$lat3 -v lon3=$lon3 -v lat4=$lat4 -v lon4=$lon4 -v scale=5 -v fix=$fix -f function.pointinrectangle

# Get coordinates for each flight type

File name: script_get_FIX_NAV_latlon.gawk
# This script processes FIX and NAV data to get lat lon info in google earth format
# STAR and APPROACH info
# Combined FIX and NAV file

cat FIX.txt NAV.txt > temp_FIX_NAV

# Get required information
## INFO start and length
# FIX
# NAME 5,30
# lat 67,14
# lon 81,14
# NAV
# NAME 5,4
# TYPE 9,20
# lat 372,14
# lon 397,14
gawk 'BEGIN{OFS="t"} {if(substr($0,1,4)="FIX1") {print substr($0,1,4),substr($0,5,5),"NONE",substr($0,67,12),substr($0,81,13)}; if(substr($0,1,4)="NAV1") {print substr($0,1,4),substr($0,5,3),substr($0,9,7),substr($0,372,12),substr($0,397,13)}}'
temp_FIX_NAV > temp_FIX_NAV_2

# Convert lat lon format
gawk 'function sumarr(arr){out=0; out=out[1]+arr[2]/60+arr[3]/3600; return out} BEGIN{FS=OFS="t"} {split($4,a1,"-"),sumarr(a1);$4=out;split($5,a1,"-"),sumarr(a1); $5=1-out}1' temp_FIX_NAV_2 > temp_FIX_NAV_3

# Get lat lon info for each fix or navaid in "MDW_STARS_approach.dat"
gawk 'BEGIN{FS=OFS="t"} (NR==FNR){arr[$2]=a1"t"$5; next} ($1 in arr){$2=arr[$1]}1' temp_FIX_NAV_3 $infile.dat > $infile

# Generate kml file
color1="brown"
color2="yellow"
gawk -v filename=$infile -v linecolor1=$color1 -v linecolor2=$color2 -f function.getcolor -f function.kmlfile_2 $infile > $infile.kml

# Get all the fixes and navaids and put them in kml format
gawk 'BEGIN{FS=OFS="t"} (NR==FNR){arr[$1]; next} ($2 in arr){print $0}1' temp_FIX_NAV_3 $infile.dat > temp_FIX_NAV_4
color1="white"
color2="purple"
gawk -v filename=$infile -v linecolor1=$color1 -v linecolor2=$color2 -f function.kmlfile_3 temp_FIX_NAV_4 > $infile_fix_nav.kml

---

File name: script_get_fb_15min_actual_config.gawk
# This script computes average fuel burn per flight given the east west flow ratio and the runway configuration
# # Input 1, flow scope
flow_scope=$1
# Input 2, ASPM data
infile=$2
# Input 3, flow fuel burn
fb_flow=$3

# Filter out flows
if [ "!$flow_scope = -eq 1"]
then
# Flow scope 1, existing visual and ILS flows
gawk 'if($2="ILS" || $2="Visual") print $1,$2,$4,$6' $fb_flow > temp_fb_flow
else
# Flow scope 2, existing visual, ISL and RNP flows
if [ "$flow_scope = -eq 2"]
then
gawk 'if($2="ILS" || $2="Visual" || $1$2="13CRNP") print $1,$2,$4,$6' $fb_flow > temp_fb_flow
else
gawk 'print $1,$2,$4,$6' $fb_flow > temp_fb_flow

200
file
file

# Print average fuel burn for each record
gawk '{if($2=="Visual"){print "V",$0} else{if($2=="ILS"){print "I",$0} else{print "I",$0; print "$V",$0)}}}' temp_fb_flow > temp_fb_flow_2

gawk -v flow_scope="$flow_scope" -f function.radian -f function.absvalue -f function.getFrwrvconfig1 temp_fb_flow_2 $infile > temp_fb_allrecords
cp temp_fb_allrecords $infile

File name: script_get_fb_all_flows.gawk
# This script brings together fuel burn for all flows
# Actual data and simulated data
# For B737s and for all jets combined.
# Print fuel burn for new rnp flows with other flows for B737s
# Inputs
fb_stats_b737_existing="NOP_fuelburn_B737s_stats"
fb_stats_b737_new="NOP_fuelburn_stats_custom"

# This script is valid for only MDWs major runways
r1="13C"
r2="31C"
r3="4R"
r4="22L"

# Print stats for all flows for B737s
gawk -v r1=$r1 -v r2=$r2 -v r3=$r3 -v r4=$r4 '{if($1!="NA" && $2~("$r1"|"$r2"|"$r3"|"$r4")) print $0 }' $fb_stats_b737_existing > temp_stats_b737s
cat $fb_stats_b737_new temp_stats_b737s | sort -k1,1 -k3,3 -k7,7 > temp_stats_b737s_2

# Compute average fuel for each flow for all jet types combined (output file temp_actypes4)
gawk -v r1=$r1 -v r2=$r2 -v r3=$r3 -v r4=$r4 'BEGIN{execute="./script_combine_fuelburn_actypes0.gawk "$r1" "$r2" "$r3" "$r4";} print system(execute)}' temp_stats_b737s_2 temp_actypes4 > temp_actypes5

# Compute percentage reduction in fuel burn
gawk '{NR==FNR}{arr[$1] "$2" "$3"=$7; next} ($1" "$2" "$3" in arr){print $0, arr[$1] "$2" "$3" -$7)/arr[$1] "$2" "$3"}}' temp_stats_b737s_2 temp_actypes4 > temp_actypes5

# Get the average fraction reduction in average fuel burn per flight per flow

gawk '{sum+=S10; count++;} END{print sum/count}' temp_actypes5 > temp_b737_all_fraction

# Get fuel burn for all flows B737 and all aircrafts combined
gawk '{if(NR==FNR){factor=$1} else{print $0,$7*(1-factor)}}' temp_b737_all_fraction temp_stats_b737s_2 > MDW_all_flows_mean_fb

File name: script_get_first_last_hit.gawk
# This script filters NOP data and get the first and last hit for each track
# infile1=$1

input1=$infile1".csv"
out1=$infile1"_all_filtered"
out2=$out1".kml"
out3=$infile1"_first_last"
# Print out required fields from the NOP data

gawk -F"," 'function round(x1){sec=substr(x1,1,2); dec=substr(x1,4,1);
  if(dec>=.5){out=sec+1} else{out=sec}; if(length(out)==2){return
  out} else{return "0"out}}
  {if(NF==11){if(substr($3,1,3)!="VFR" &
    substr($3,1,3)!="UNK") {if(substr($1,1,4)/2!=0) {if($6=""| org="NA")
      else{org=""}; if($7=""| des=""| time=""| "NA"; print
      $1,org,des,substr($11,1,length($11)-7)":"round(substr($11,length($11)-
      5,4)),"$8","$9","$10*100))}}
  $input1 > temp_all}

# Remove record with less than 10 data points

gawk '{{arr[$1]++} END{for(no in arr){if(arr[no]>=10){print no, arr[no]}}}'
temp_all > temp_valid_rec
gawk '{{(NR==FNR){{arr[$1]; next}} ($1 in arr){{print $0}}}'}
temp_valid_rec temp_all | TZ=UTC
gawk '{sec=mktime(substr($5,1,4)" "substr($5,6,2)" "substr($6,1,2)"
    "substr($6,4,2)" "substr($6,7,2))}}1'
temp_all2

# Get the first and last point of each track

gawk '{if($1!=x){x=$1; if(FNR!=1){print record, lat, lon, alt};
  record=$0} else{lat=$7; lon=$8; alt=$9} END{print record, lat, lon, alt}'
temp_all2 > temp_first_last

# output files

# output temp_all2 in kml format

cp temp_all2

# print kml file

cp kmltemp_all2

# output the first and last stamp for each track

cp temp_first_last

# remove temp files

rm temp*

---

**File name: script_get_holding_patterns.gawk**

# This script detects holding patterns and get stats on fuel burn and time on holding

# Input 1 list of flights

input1="NOP_data_all_good_2"

# Input 2 list of

input2="NOP_filelist.dat"

# Input 3 holding pattern fix info

holding_fix="MDW_star_holding_fix.dat"

# Input 4 runway, direction and aircraft type

runway="13C"

app="ILS"

direction1="E"

direction2="W"

actype="B73"

airport="MDW"

# Input 5 BADA and wind info

badadata="BADA_coefficient_2.dat"

windinfo1="MDW_wind_info.dat"

# output files

out1="tracks "$runway "$direction1

out2="tracks "$runway "$direction2

out3="tracks_holding "$runway

# Time range to considered
# Time range

time_start=7
time_end=22

# Specify the time zone to compute local time
tcurrent=-5
tzone=-6

firstrun=0

if { $firstrun -eq 1 }

then

# Get tracks for runway 13C
# change type to NA for normal tracks and GA for tracks with excess turn angle
# gawk -v runway=$runway -v type="NA" -v actype="actype" '{if($22==runway && $29~/^"actype"/){print $2,$23,$29}}' $input1 > temp_test1

# filter out valid record
# Get day with ILS approaches on to 13C (indicative of IMC)
gawk -v runway=$runway -v app=$app 'if($22==runway && $24==app){print $1}}' $input1 | sort -u > temp_validfiles
gawk '(NR==FNR){arr[$1]; next} ($1 in arr){print $0}' temp_validfiles $input1 > temp_valid_records1

gawk -v time_start=$time_start -v time_end=$time_end -v tcurrent=$tcurrent -v tzone=$tzone 'BEGIN{tdiff=tcurrent-tzone} {hr_local=strftime("%H",$13); hr_zone=hr_local-tdiff; if(hr_zone>=time_start && hr_zone<=time_end) print $2,$23,$29}'
temp_valid_records1 > temp_valid_records2

gawk '(NR==FNR){arr[$1]; next} ($2 in arr){print $0}' temp_valid_records2 temp_valid_records1 > NOP_summary_valid_records

gawk -v runway=$runway -v app=$app '{if($22==runway && $24==app){print $2,$23,$29}}' NOP_summary_valid_records > temp_test1

# remove temp_test2
rm temp_test2

# get track info for ids in temp_test1
# The output of this script in temp_test2 containing the track info
gawk -v flightids="temp_test1" 'execute="/script_print_error_tracks.gawk "$1" flightids; print execute; system(execute)}' $input2

# Copy temp_test2 to another file along with the direction information
# Printing out track from the east
# gawk -v direction='$direction1' '{execute="/script_filter_holding_patterns.gawk "$0" "$runway" "$direction1"; print execute; system(execute)}' temp_holding_fix

# Printing out track from the east
# gawk -v direction='$direction2' '{execute="/script_filter_holding_patterns.gawk "$0" "$runway" "$direction2"; print execute; system(execute)}' temp_holding_fix

# Filter out track hits and detect holding patterns that fall within the holding pattern boundary defined in MDW_star_holding_fix.dat
# out out file temp_tracks_rectangle
# gawk get list of valid holding patterns boundaries
gawk '{if($1!="#") print $0}' $holding_fix > temp_holding_fix

gawk -v runway=$runway '{execute="/script_filter_holding_patterns.gawk "$runway" "$0"; print execute; system(execute)}' temp_holding_fix

# Get the cumulative turn angle for each flight

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```bash
gawk -f function.bearing -f function.absvalue -f function.goaround_holding -f function.radians temp_tracks_rectangle > temp_turn_angle1

gawk -v threshold=360 '{if($1!=x){if(FNR!=1){if((turnangle1-1)>threshold || temp_turn_angle1>threshold) || (turnangle2>threshold) || (turnangle1>threshold || turnangle2>threshold)){print x,fix}}; x=$1; fix=$1; turnangle1=0; turnangle2=0} else{if($14="Start" && $15="Start") {turnangle1=$14; turnangle2=$15}}}' temp_turn_angle1 > temp_turn_angle2

# print out holding patterns

gawk 'NR==FNR{arr[$1 " "$2]; next} ($1 " "$1 in arr){print $0}' temp_turn_angle2 temp_turn_angle1 > $out3

# Print kml file

gawk -v out=$out3 -v color="red" 'BEGIN{execute="/script_print_kml.gawk "out" "color; print execute; system(execute)}';

gawk -v out=$out3 -v runway=$runway -v airport=$airport -v infile2="NOP_summary_valid_records" -v badadata=$badadata -v windinfo=$windinfo
'BEGIN{execute="time ./script_get_holding_stats.gawk "infile1" "badadata" "windinfo" "infile2" "runway" "airport; print execute; system(execute)}';

else
gawk 'BEGIN{y="do nothing"}';

# Compute holding stats
# time and fuel burn

gawk -v infile1=$out3 -v runway=$runway -v airport=$airport -v infile2="NOP_summary_valid_records" -v badadata=$badadata -v windinfo=$windinfo
'BEGIN{execute="time ./script_get_holding_stats.gawk "infile1" "badadata" "windinfo" "infile2" "runway" "airport; print execute; system(execute)}';

fi

File name: script_get_holding_stats.gawk
# This script computes holding stats, time in holding, fuel burn
# Input
infile=$1
badadata=$2
windinfo=$3
nop_summary=$4
runway=$5
airport=$6

# Output file names
out1=$airport "_" $runway _ holdings_metrics
out2=$airport "_" $runway _ holding_stats

# specify rwy and approach type that cause the metroplex flow conflict
rwy="13C"
app="ILS"
app2="RNP"
out3=$airport _ arr "$rwy" "$app"
out4=$airport _ holdingratio "$rwy" "$app"

# Specify the time zone to compute local time
tcurrent=-5
tzone=-6

# Compute holding pattern track distance
```
# Filter required fields, and bring the input file in the standard format for functions can be used

cut -d" " -f1-10 $infile > temp_holdingtracks1
gawk -f function.dist2thresh -f function.gcd_haversine_2 temp_holdingtracks1 > temp_validtracks2

# Distance from fix does not apply, enter a dummy field
gawk '('print $0, "NA")' temp_validtracks2 > temp_validtracks3

# Get wind information
# get the first time stamp for each flight
gawk '{if($1!=x){print $0; x=$1}}' temp_validtracks3 | sort -k2,2n > temp_validtracks3_1

# Get wind mag and direction
# compute TAS

gawk -v elev=$1 -v function.bearing -f function.degrees -f function.radians -f function.computeTAS -f function.get_track_profile_info -f function.gcd_haversine_2 temp_validtracks3b > temp_validtracks5

# Assign ac type to each track

# Compute fuel burn for each flight

gawk -v holding=1 -v elev=$1 -v function.absvalue -f function.computeFuelburn1 -f function.air_density $badadata temp_validtracks6 > temp_validtracks7

# For each aircraft in holding get the start and end time, total time, distance and fuel burnt in holding.
gawk '{if($1!=x){if(FNR!=1){print x,actype,tstart,tend,(tend-tstart)/60,tdistance,tfb}; x=$1; tstart=$2; actype=$18} else{tend=$2;tdistance=$9;tfb=$21}} END{print x,actype,tstart,tend,(tend-tstart)/60,tdistance,tfb}' temp_validtracks7 temp_validtracks7b > $out1

# Compute the mean and standard deviation for holding metrics

gawk -v actype="all" -f function.holdingstats -f function.mean -f function.std $out1 > temp_stats1
gawk -v actype="B73" -f function.holdingstats -f function.mean -f function.std $out1 > temp_stats2
cat temp_stats1 temp_stats2 | gawk 'BEGIN{print actype count mean_htime sd_htime mean_hdis sd_hdis mean_hfb sd_hfb}';(print $0)';(print $0) > $out2

# Get ratio of total arrivals on to runway 13C during IMC (ILS approach) and total number of holding patterns
# The ratio is computed per event
# Event is defined by the start and stop of a flow
# In case of MDW its the start and stop of ILS approach on to 13C

**sort** -k1,1 -k3,3n **$nop_summary** | **gawk** -v **rwy=$rwy** -v **app=$app** -v **app2=$app2**

![](https://example.com/regex1)

**Get 22L departure count for each bin that has arrival onto 13C during IMC**

**# Get list of files to get the counts from**

### **gawk** '(print $7)' **temp_arr_count1** | **sort** -u > **temp_filelist**

### **get the buffer between time windows**

**gawk** '{if($7!=x){x=$7;tend=$4;print $0,0} else{print $0,$3-tend;tend=$4}}' **temp_arr_count1** > **temp_arr_count2**

**# Sum up the arrival for each day**

**gawk** '(NR==FNR){arr[$2]=$1;next} ($1 in arr){print arr[$1],$0}' **$nop_summary** $out1 | **gawk** '{arr[substr($1,length($1)-19,8)]++} END{for(no in arr) print no, arr[no]}' > **temp_holding_day1**

### **print the holding count along with duration of each day**

**gawk** '(NR==FNR){arr[$2]=$2; next} ($1 in arr){print $0, arr[$1]}' **temp_holding_day1** $out3 > **temp_event_duration_2**

**gawk** '(NR==FNR){arr[$2]=$2; next} ($1 in arr){print $0, arr[$1]}' **temp_event_duration_3** | **gawk** 'BEGIN{print "Date Durtn_Hr 13C_Arr 22L_Dep Holding_count Holdingper100"} {if($2>1) print $0,$5*100/$3}' > **$out4**

---

**File name: script_get_min_max_mean_std.gawk**

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**This script get stats on each flow**

**Input**

recono=$1

input=$2

level=$3

direction=$4

runway=$5

procedure=$6

count=$7

fieldno=$8

GA=$9

if [ $level -eq 0 ] then

**Combine flows by approach and runway by giving equal weight to each flow**

**Get stats by approach**

**gawk** '({if($2!=$x)k++}{if(FNR!=1){m1=0;s1=0;for(i=1;i<length(arr_mean)+i++){x1=1+count[i];m1=m1+arr_mean[i]*(1/length(arr_mean))};v1=0;for(i=1;i<length(arr_sd)+i++){v1=v1+1/length(arr_sd)*(arr_mean[i]-m1)^2);v1=sqrt(v1);print "NA",runway,approach,x1,m1,s1,m1,s1}} END{m1=0;s1=0;for(i=1;i<length(arr_mean);i++){x1=1+count[i];m1=m1+arr_mean[i]*(1/length(arr_mean))};v1=0;for(i=1;i<length(arr_sd);i++){v1=v1+1/length(arr_sd)*(arr_mean[i]-m1)^2);v1=v1+1/length(arr_sd)*(arr_mean[i]-m1)^2);v1=sqrt(v1);print "NA",runway,approach,x1,m1,s1,m1,s1}} temp_stats_out > $out3

**Get stats by runway**

**gawk** '('if($2!=x)k++{if(FNR!=1){m1=0;s1=0;for(i=1;i<length(arr_mean);i++){x1=1+count[i];m1=m1+arr_mean[i]*(1/length(arr_mean))};v1=0;for(i=1;i<length(arr_sd);i++){v1=v1+1/length(arr_sd)*(arr_mean[i]-m1)^2);v1=sqrt(v1);print "NA",runway,approach,x1,m1,s1,m1,s1}} temp_stats_out > $out3

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m1=0; s1=0;
for(i=1;i<=length(arr_mean);i++){s1=s1+count[i]; m1=m1+arr_mean[i]*(1/length(arr_mean))};

v1=0; for(i=1;i<=length(arr_sd);i++){v1=v1+(1/length(arr_sd))*(arr_sd[i]^2+(arr_mean[i]-m1)^2)}; sd1=sqrt(v1);

print "NA",runway,"NA",s1,"NA","NA",m1,sd1};
x=$2; i=1; delete arr_mean; delete arr_sd; delete count; count[i]=$4; arr_mean[i]=$7; arr_sd[i]=$8; runway=$2; approach=$3} else{i++; count[i]=$4; arr_mean[i]=$7; arr_sd[i]=$8}}
END

m1^2)); s1=sqrt(v1); print "NA",runway,"NA",s1,"NA","NA",m1,sd1};

x=$2; i=1; delete arr_mean; delete arr_sd; delete count; count[i]=$4; arr_mean[i]=$7; arr_sd[i]=$8; runway=$2; approach=$3} else{i++; count[i]=$4; arr_mean[i]=$7; arr_sd[i]=$8}}

END

{m1=0; s1=0; for(i=1;i<=length(arr_mean);i++){s1=s1+count[i]; m1=m1+arr_mean[i]*(1/length(arr_mean))};

v1=0; for(i=1;i<=length(arr_sd);i++){v1=v1+(1/length(arr_sd))*(arr_sd[i]^2+(arr_mean[i]-m1)^2)}; sd1=sqrt(v1); print "NA",runway,"NA",s1,"NA","NA",m1,sd1}'

temp_stats_out > temp_stats_out_runway
# Combine all
cp temp_stats_out temp_stats_out_b
cat temp_stats_out_runway temp_stats_out_approach temp_stats_out_b > temp_stats_out

else
if [ $recno -eq 1 ]
then
if [ $GA -eq 0 ]
then
# remove go arounds from the data
gawk '{if($25!="GA") print $0}' $input > temp_input1
else
# keep only go around data
gawk '{if($25=="GA") print $0}' $input > temp_input1
fi
fi
rm temp_stats_out
fi
# Compute and print out the stats for each flow
gawk -v direction=$direction -v level=$level -v runway=$runway -v procedure=$procedure -v fieldno=$fieldno -v function.min_max_mean_sd 3 -f function.mean -f function.std temp_input1 >> temp_stats_out
fi

File name: script_get_new_rnp_approach.gawk
# This script uses the existing RNP approach track data to generate RNP data for other runways
# input parameters
airport=$1
new_rnp_rwy=$3
base_rnp_rwy=$5
rotate=$7
reflect=$8
alat=$9
alon=${10}
rwylati=${11}
rwyloni=${12}
rwylat2=${13}
rwylon2=${14}
# input track file
infile="tracks_"$4"_"$5"_"$6

# outfile
out="tracks_"$2"_"$3"_RNP"
# get track points within 60NM of the airport
gawk -v fix_lat=$alat -v fix_lon=$alon -v check_radius=60 -v function.gcd_haversine_2 -v function.distairport $infile > temp_rnp_track_1
# reflect and rotate tracks
gawk -v alat=$alat -v alon=$alon -v rwylati=$rwylati -v rwyloni=$rwyloni -v rwylat2=$rwylat2 -v rwylon2=$rwylon2 -v rotate=$rotate -v reflect=$reflect -v baserwy=$base_rnp_rwy -v newrwy=$new_rnp_rwy -v scale=0 -v function.reflectrotate -v function.getcartesian_2 -v function.getlatlon -v function.radian temp_rnp_track_1 > temp_rnp_track_2
File name: script_get_new_rnp_approach0.gawk
# This script runs script_get_new_rnp_approach.gawk for all the records in
# rnp_gen_info.dat
# # runway_info="runway_info.dat"
# # airport_info="airport_info.dat"
# rnp_gen="rnp_gen_info.dat"
# airport="MDW" # Make sure to match this with the airport of the which the data need to be processed
# Get information about the rnp procedure to be generated for the airport
gawk -v airport="MDW" '{if($1==airport){print $0}}' $rnp_gen > temp_rnp_gen_1
# get airport coordinates
gawk '{NR==FNR}{arr[$1]=$2 " $3; next} ($1 in arr){print $0,arr[$1]}' $airport_info
# temp_rnp_gen_1 > temp_rnp_gen_2
# get the runway coordinates
gawk -v airport="MDW" '{if(NR==FNR){if($1==airport){rwy1[FNR]=$6; coord1[FNR]=$8 " $9 "$10 "$11; rwy2[FNR]=$7;coord2[FNR]=$10 "$11 "$8 "$9}} else{for(i=1;i<=length(rwy1);i++){if($5==rwy1[i]){print $0,coord1[i]; break} else{if($5==rwy2[i]){print $0,coord2[i]; break}}}}}' $runway_info
# temp_rnp_gen_2 > temp_rnp_gen_3
# run script_get_new_rnp_approach.gawk
gawk '{if($1!="#"){execute="/script_get_new_rnp_approach.gawk "$0; print execute; system(execute)}}' temp_rnp_gen_3
# get flow metrics, track distance/time and fuel burn for new RNP flow
gawk '{if($1!="#"){execute="/script_compute_flow_new_rnp0.gawk "$1 "$2 "$3 "$6; print execute; system(execute)}}' temp_rnp_gen_3
# get stats for the metrics
gawk 'BEGIN{execute="/script_compute_stats_new_rnp.gawk"; print execute; system(execute)}'

File name: script_get_non_BADA_coefficients.gawk
# This script get co-efficient for non BADA aircraft type
# input files
# Input1 BADA coefficients
# Input2 actypes in NOP data
# Input3 actype and MTOW
# Output file
# out=\"BADA_coefficient_2.dat\"
## remove bada actypes which do not have coefficient values namely cf1,cf2,cf3 and cf4
gawk '{if($2!=0 && $3!=0 && $4!=0 && $5!=0) print $0}' $badadata > temp_badagood
# Get aircraft type not in BADA
gawk '{if($29!="NA") print $29}' $nopactype | sort -u > temp_actypes_nop

# Get ac type that are not in bada
gawk '{NR==FNR}{arr[$1];next} !(1 in arr){print $0}' temp_badagood temp_actypes_nop > temp_actype_nonbada

## old code not to be used
###gawk '{if($30=="NA"){arr[$29]++; sum1++} END{for(no in arr){print no, arr[no],arr[no]/sum1,"NA"}}' NOP_data_all_good | sort -k1,1 > temp_actype_nonBADA

### Get MTOW for each aircraft type from actype_performance_faa.dat
###gawk '{if($4=="LBS"){arr[$1]=$5*0.453592} else{arr[$1]=$5}; next} ($1 in arr){$4=arr[$1]}1' aircraft_performance.dat temp_actype_nonBADA > temp_actype_nonBADA_MTOW

# get the MTOW for each non bada aircraft
gawk '{NR==FNR}{mtow[$1]=$2;engine[$1]=$3; next} ($1 in mtow){print $1,mtow[$1],engine[$1]}' $actypemtow temp_actype_nonbada > temp_actype_nonbada_mtow

gawk -f function.nonbadacoefficient -f function.absvalue temp_badagood temp_actype_nonbada_mtow > temp_subactype

gawk '{actual=$21; replace=$1; $1=actual; $21=replace}1' temp_subactype > temp_subactype2

cat temp_badagood temp_subactype2 > $out

---

File name: script_holding_check.gawk

# This script check if holding patterns happen at the same time as departures from a neighboring airport

# In case of MDW (its 13C ILS holding and 22L departures)

# Inputs
recno=$1
fileid=$2
holding_list=$3
deprwy=$4
depairport=$5

if { $recno -eq 1 }
then
gawk '{(print $0,",NA","NA","NA")' $holding_list > temp
    cp temp $holding_list
fi

# Get departure flight and bin them
infile1=$fileid"""$depairport""""_Dtracksrwy"
gawk -v deprwy=$deprwy '($21==deprwy)(print $1,strftime("%H",$2)))' $infile1 > temp_dep1
gawk '($22++) END(for(no in arr){print no, arr[no]})' temp_dep1 > temp_dep2

# Get holding list
gawk -v fileid=$fileid '($1==fileid) print $0)' $holding_list > temp_arr1

# Check if any departures were there in the current bin
gawk '{NR==FNR}{arr[$1]=$2; next} !(9 in arr){$10=arr[9]}1' temp_dep2 temp_arr1 > temp_arr2

# Check if any departures were there in the previous time bin bin
gawk '{NR==FNR}{arr[$1]=$2; next} !(9-1 in arr){$11=arr[9-1]}1' temp_dep2 temp_arr2 > temp_arr3

# Check if any departures were there in the next time bin bin
gawk '{NR==FNR}{arr[$1]=$2; next} !(9+1 in arr){$12=arr[9+1]}1' temp_dep2 temp_arr3 > temp_arr4

# update holdinglist

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The script does the following:

- **Determine excess fuel burn per year as a result of holding as a result of metroplex flow conflict:**

- **Determine excess departure delays as a result of metroplex flow conflict:**

- **The analysis is conducted for the years:**

  - **Year range:**
    - Year start = 2007
    - Year end = 2012

- **Time range:**
  - Time start = 7
  - Time end = 2

**Input files:**

- **MDW:**
  - Input1 Arpt = MDW_2007_2012_arr_rwy

- **ORD:**
  - Input2 Arpt = ORD_ASPM_airport.txt
  - Input3 Flts = ORD_flight_data_2007_2012.TAB
  - Input4 = ORD_2007_2012_dep_cancelled.tab

**Metroplex configuration conflict details:**

- Runways affected and the meteorological conditions:
  - Runway 1 = 13C
  - Runway 2 = 22L
  - Meteorological Condition = I

- **First run flag:**
  - Firstrun = 0

**Step 1 ORD delay saving benefits:**

- **Step 1a Get delay stats for Metroplex Configuration Conflict (MCC) days:**

  - Get list of days when the metroplex configuration conflict occurs

  ```bash
  gawk '{if($7==MC && $17==rwy1 && $23==rwy2){arr[$2"$3++];} else{flts[$2"$3]+=$20; delay[$2"$3]+=$21}} END{for(no in arr) print no, arr[no]/4, flts[no], delay[no]}' temp_arpt_delay_config3 | sort -k1n -k2n -k3n -k4n -k5n > temp_MCC_days_duration
  ```

- **Get number of flight delayed from flight data:**

  - Get records with MCC

  ```bash
  gawk '{if(length($2)==1){a1=$2} else{a1=$2}; if(length($3)==1){a2=$3} else{a2=$3}; arr[$1"a1"a2"$4]; next} ($1"$2"$3"$4
  ```
Combine delay and MCC duration information

```
gawk '{flts[$1]++}; if($5>0) {flts[$1]++}; delay[$1]++ END{for(no in flts) print no,flts[no],flts_d[no],delay[no]}'
```

```
gawk
BEGIN{FS=OFS="\|"}
{if(length($2)==1){a1=$2;} else{a1=$2};
return out}
function mean(mean, arr){zz1=0; yy1=0; for(no in arr){zz1+=arr[no]; yy1++}; out=zz1/yy1;
return out}
function std(mean, arr){zz2=0; xx2=0; yy2=0; for(no in arr){xx2=(arr[no]-mean)^2; zz2+=xx2; yy2++}; if(yy2==1){out=0} else{out=sqrt(zz2/(yy2-1))}; return out}
function sort(arr){zz1=0; yy1=0; for(no in arr){zz1+=arr[no]; yy1++} END{for(no in arr) print no, arr[no]/4,
```

# Get records with MCC

```
temp_MCC_duration_delays = 0
for(no in arr){temp_MCC_duration_delays[no, totaldays[no], totalduration[no]/totaldays] = 0
END{for(no in arr) print no, totaldays[no], totalflts[no], totalfltsdel[no], totalfltsdel[no]/totalflts[no]}
```

```
temp_MCC_flts_delays_2 = 0
for(no in arr){delay[no] = 0
END{for(no in arr) print no, arr[no]/4, delay[no]}
```

# Get list of days when the metroplex configuration conflict occurs

```
temp_arpt_delay_config3 = 0
for(no in arr){y[substr($1,1,4)]++} END{for(no in y) print no, y[no]}
```

```
temp_MCC_avg_ADR = 0
for(no in arr){y[substr($1,1,4)]++} END{for(no in y) print no, y[no]}
```

# Get mean and standard deviation of fuel burn per flight

```
temp_arpt_delay_config3 = 0
for(no in arr){y[substr($1,1,4)]++} END{for(no in y) print no, y[no]}
```

```
temp_MCC_cancel_counts = 0
for(no in arr){y[substr($1,1,4)]++} END{for(no in y) print no, y[no]}
```

# Get the ADR stats

```
temp_MCC_ADR = 0
for(no in arr){y[substr($1,1,4)]++} END{for(no in y) print no, y[no]}
```

# Get cancellation stats

```
temp_MCC_cancel_counts = 0
for(no in arr){y[substr($1,1,4)]++} END{for(no in y) print no, y[no]}
```

# Get Metroplex Configuration Conflict (MCC) days

```
temp_nonMCC_days_duration = 0
for(no in arr){temp_nonMCC_days_duration[no, totaldays[no], totalflts[no], totalfltsdel[no], totalfltsdel[no]/totalflts[no]} = 0
```

# Get number of flight delayed from flight data

```
temp_nonMCC_flts_delays = 0
for(no in arr){temp_nonMCC_flts_delays[no, totaldays[no], totalduration[no]/totaldays] = 0
```

# Combine delay and MCC duration information

```
temp_MCC_duration_delays = 0
for(no in arr){temp_MCC_duration_delays[no, totaldays[no], totalduration[no]/totaldays] = 0
```

```
temp_MCC_flts_delays_2 = 0
for(no in arr){delay[no] = 0
END{for(no in arr) print no, arr[no]/4, delay[no]}
```

```
temp_summary_stats = 0
for(no in arr){y[substr($1,1,4)]++} END{for(no in y) print no, y[no]}
```

# Combine delay and MCC duration information

```
temp_MCC_duration_delays = 0
for(no in arr){temp_MCC_duration_delays[no, totaldays[no], totalduration[no]/totaldays] = 0
```

```
temp_MCC_flts_delays_2 = 0
for(no in arr){delay[no] = 0
END{for(no in arr) print no, arr[no]/4, delay[no]}
```

```
temp_MCC_avg_ADR = 0
for(no in arr){y[substr($1,1,4)]++} END{for(no in y) print no, y[no]}
```

# Get cancellation stats

```
temp_MCC_cancel_counts = 0
for(no in arr){y[substr($1,1,4)]++} END{for(no in y) print no, y[no]}
```

# Get Metroplex Configuration Conflict (MCC) days

```
temp_nonMCC_days_duration = 0
for(no in arr){temp_nonMCC_days_duration[no, totaldays[no], totalflts[no], totalfltsdel[no], totalfltsdel[no]/totalflts[no]} = 0
```

# Get number of flight delayed from flight data

```
temp_nonMCC_flts_delays = 0
for(no in arr){temp_nonMCC_flts_delays[no, totaldays[no], totalduration[no]/totaldays] = 0
```

# Combine delay and MCC duration information

```
temp_MCC_duration_delays = 0
for(no in arr){temp_MCC_duration_delays[no, totaldays[no], totalduration[no]/totaldays] = 0
```

```
temp_MCC_flts_delays_2 = 0
for(no in arr){delay[no] = 0
END{for(no in arr) print no, arr[no]/4, delay[no]}
```

```
temp_MCC_avg_ADR = 0
for(no in arr){y[substr($1,1,4)]++} END{for(no in y) print no, y[no]}
```

# Get cancellation stats

```
temp_MCC_cancel_counts = 0
for(no in arr){y[substr($1,1,4)]++} END{for(no in y) print no, y[no]}
```

# Get Metroplex Configuration Conflict (MCC) days

```
temp_nonMCC_days_duration = 0
for(no in arr){temp_nonMCC_days_duration[no, totaldays[no], totalflts[no], totalfltsdel[no], totalfltsdel[no]/totalflts[no]} = 0
```

# Get number of flight delayed from flight data

```
temp_nonMCC_flts_delays = 0
for(no in arr){temp_nonMCC_flts_delays[no, totaldays[no], totalduration[no]/totaldays] = 0
```

# Combine delay and MCC duration information

```
temp_MCC_duration_delays = 0
for(no in arr){temp_MCC_duration_delays[no, totaldays[no], totalduration[no]/totaldays] = 0
```

```
temp_MCC_flts_delays_2 = 0
for(no in arr){delay[no] = 0
END{for(no in arr) print no, arr[no]/4, delay[no]}
```

```
temp_MCC_avg_ADR = 0
for(no in arr){y[substr($1,1,4)]++} END{for(no in y) print no, y[no]}
```
gawk 'NR==FNR{arr[$1 "$2"]=$3 "$4 "$5; next} (NR==FNR){print $1 $2 in arr}{print $1 $2 $3 $4 $5} else{print "error"}' temp_nonMCC_flts_delays_2 temp_nonMCC_days_duration > temp_nonMCC_duration_delays

# Take out MCC days

gawk 'NR==FNR{arr[$1$2$3$4]; next} (!($1$2$3$4 in arr){print $0})' temp_nonMCC_duration_delays temp_MCC_duration_delays > temp_nonMCC_duration_delays_2

# Get total number of MCC days, average duration, total delays, percentage flight delayed and average delays per flight for each year

gawk 'year=substr($1,1,4); totaldays[year]+=1; totalduration[year]+=$3; totalflts[year]+=$4; totalfltsdel[year]+=$5; totaldelay[year]+=$6' END{for(no in totaldays) print no,totaldays[no],totalduration[no]/totaldays[no],totalflts[no],totalfltsdel[no],totalfltsdel[no]*100/totalflts[no], totaldelay[no], totaldelay[no]/totalflts[no]}' temp_nonMCC_duration_delays_2 | sort -k1,1n > temp_ORD_nonMCC_stats

# Get mean and standard deviation of fuel burn per flight

gawk 'function mean(arr){zz1=0; yy1=0; for(no in arr){zz1+=arr[no]; yy1++}; out=zz1/yy1; return out} function std(mean, arr){zz2=0; xx2=0; yy2=0; for(no in arr){xx2=(arr[no]-mean)^2; zz2+=xx2; yy2++}; if(yy2==1){out=0} else{out=sqrt(zz2/(yy2-1))}; return out} {if(substr($1,1,4)!=x){if(FNR!=1){mean1=mean(arr); std1=std(mean1,arr); print x,mean1,std1}; x=substr($1,1,4); delete arr; arr[FNR]=$5} else{arr[FNR]=$5}}' temp_nonMCC_avg_flt_delay | sort -k1,1n > temp_nonMCC_avg_flt_delay

# Get the ADR stats

gawk 'v rwy1 = $rwy1 - v rwy2 = $rwy2 - v MC = $MC '{if($7==MC && $17!=rwy1 && $23==rwy2){print $2,$3,$4,$5,$24}}' temp_arpt_delay_config3 > temp_nonMCC_ADR

gawk 'function mean(arr){zz1=0; yy1=0; for(no in arr){zz1+=arr[no]; yy1++}; out=zz1/yy1; return out} function std(mean, arr){zz2=0; xx2=0; yy2=0; for(no in arr){xx2=(arr[no]-mean)^2; zz2+=xx2; yy2++}; if(yy2==1){out=0} else{out=sqrt(zz2/(yy2-1))}; return out} {if(substr($1,1,4)!=x){if(FNR!=1){mean1=mean(arr); std1=std(mean1,arr); print x,mean1,std1}; x=substr($1,1,4); delete arr; arr[FNR]=$5} else{arr[FNR]=$5}}' temp_nonMCC_ADR | sort -k1,1n > temp_nonMCC_avg_flt_delay

# Get cancellation stats

# Get the date time in the ASPM format

gawk 'BEGIN{FS="\t"} (NR==FNR){arr[$1 $2 $3 $4 $5 $6 $7 $8 $9 $10]; next} ($1 $2 $3 $4 $5 $6 $7 $8 $9 $10 in arr){y[substr($1,1,4)]++} END{for(no in y) print no, y[no]}' temp_nonMCC_records

gawk 'BEGIN{FS="\t"} (NR==FNR){arr[$1 $2 $3 $4]; next} ($1 $2 $3 $4 in arr){y[substr($1,1,4)]++} END{for(no in y) print no, y[no]}' temp_canceled_datetime | sort -k1,1n > temp_nonMCC_cancel_counts

# Get a count of total number of MDW arrivals

gawk 'v rwy1 = $rwy1 - v rwy2 = $rwy2 - v MC = $MC '{if($7==MC && $17==rwy1 && $23==rwy2){year=substr($2,1,4); configcon[year]++; configconops[year]+=$14; configconopsswa[year]+=$15}} END{for(no in configcon) print no, configcon[no]/4,configconops[no],configconopsswa[no]}' temp_arpt_delay_config3 | sort -k1,1n > temp_MDW_MCC_arrival_counts

else
gawk 'BEGIN{y="do nothing"}'}

gawk 'function mean(arr){zz1=0; yy1=0; for(no in arr){zz1+=arr[no]; yy1++}; out=zz1/yy1; return out} function std(mean, arr){zz2=0; xx2=0; yy2=0; for(no in arr){xx2=(arr[no]-mean)^2; zz2+=xx2; yy2++}; if(yy2==1){out=0} else{out=sqrt(zz2/(yy2-1))}; return out} {if(substr($1,1,4)!=x){if(FNR!=1){mean1=mean(arr); std1=std(mean1,arr); print x,mean1,std1}; x=substr($1,1,4); delete arr; arr[FNR]=$5} else{arr[FNR]=$5}}' temp_MCC_flts_delays | sort -k1,1n > temp_MCC_avg_flt_delay

# Get the ADR stats

gawk 'v rwy1 = $rwy1 - v rwy2 = $rwy2 - v MC = $MC '{if($7==MC && $17==rwy1 && $23==rwy2){print $2,$3,$4,$5,$24}}' temp_arpt_delay_config3 > temp_MCC_ADR

gawk 'function mean(arr){zz1=0; yy1=0; for(no in arr){zz1+=arr[no]; yy1++}; out=zz1/yy1; return out} function std(mean, arr){zz2=0; xx2=0; yy2=0; for(no in arr){xx2=(arr[no]-mean)^2; zz2+=xx2; yy2++}; if(yy2==1){out=0} else{out=sqrt(zz2/(yy2-1))}; return out} {if(substr($1,1,4)!=x){if(FNR!=1){mean1=mean(arr); std1=std(mean1,arr); print x,mean1,std1}; x=substr($1,1,4); delete arr; arr[FNR]=$5} else{arr[FNR]=$5}}' temp_MCC_flts_delays | sort -k1,1n > temp_MCC_avg_flt_delay

# Get the ADR stats

gawk 'v rwy1 = $rwy1 - v rwy2 = $rwy2 - v MC = $MC '{if($7==MC && $17==rwy1 && $23==rwy2){year=substr($2,1,4); configcon[year]++; configconops[year]+=$14; configconopsswa[year]+=$15}} END{for(no in configcon) print no, configcon[no]/4,configconops[no],configconopsswa[no]}' temp_arpt_delay_config3 | sort -k1,1n > temp_MDW_MCC_arrival_counts

e else
gawk 'BEGIN{y="do nothing"}'}

gawk 'function mean(arr){zz1=0; yy1=0; for(no in arr){zz1+=arr[no]; yy1++}; out=zz1/yy1; return out} function std(mean, arr){zz2=0; xx2=0; yy2=0; for(no in arr){xx2=(arr[no]-mean)^2; zz2+=xx2; yy2++}; if(yy2==1){out=0} else{out=sqrt(zz2/(yy2-1))}; return out} {if(substr($1,1,4)!=x){if(FNR!=1){mean1=mean(arr); std1=std(mean1,arr); print x,mean1,std1}; x=substr($1,1,4); delete arr; arr[FNR]=$5} else{arr[FNR]=$5}}' temp_MCC_flts_delays | sort -k1,1n > temp_MCC_avg_flt_delay

# Get the ADR stats
File name: script_mplex_arr_dep_count.gawk

# This script counts the number of arrivals and departures for neighboring airports
# In case of Chicago metroplex, count number of ILS arrivals onto 13C at MDW
# and departures from 22L at ORD at the same time.

# Input
recno=$1 # record number
tstart=$2 # bin start time
ten=$3 # bin end time
fileid=$4 # file id
buffer=$5 # time buffer for each bin
arr_count=$6 # arrival counts
deprwy=$7 # dep runway
depairport=$8 # dep airport

if [ $recno = -eq 1 ]
then
gawk 'print "$0,"NA"' $arr_count > temp
fi

# Get departure flight and bin them
infile=$fileid"_"$deairport"_Dtracksrwy"
# Count the number of departures for record

gawk -v tstart=$tstart -v tend=$tend -v deprwy=$deprwy -v fileid=$fileid -v
buffer=$buffer -v recno=$recno 'BEGIN{count=0; if(buffer==0 ||
buffer>=1800){buffer2=1800} else{buffer2=buffer}} (if($21==deprwy){if($2>=tstart-
buffer2 && $2<tend){count++}}) END{print recno,fileid, count}' $infile1 >
temp_count1

# gawk

gawk -v v tstart=$tstart -v tend=$tend -v deprwy=$deprwy -v fileid=$fileid
BEGIN{count=0} (if($21==deprwy){count++}) END{print fileid, count}' $infile1 >
temp_count1

# update count

gawk '($NR==FN R){arr[$1" "$2]=$3; next} ($1" "$7 in arr){$8=arr[$1" "$7]}1'
temp_count1 $arr_count > temp2

cp temp2 $arr_count

File name: script_plot_tracks_by_flow.gawk

# This script plot track for each flow
# The flows and their colors are defined in flow_color_2.dat

# Input
direction=$1
runway=$2
procedure=$3
color=$4

input1="NOP_data_all_good_2"
input2="NOP_filelist.dat"

# filter out flows and print kml files
# change type to NA for normal tracks and GA for tracks with excess turn angle

gawk -v direction=$direction -v runway=$runway -v procedure=$procedure -v type="NA" -v
actype="B73" '($22==runway && $23==direction && $24==procedure && $25==type &&
$29~/"$actype"/){' $input1 > temp_test1

# remove temp_test2
rm temp_test2

# get track info for ids in temp_test1
# The output of this script in temp_test2 containing the track info

gawk -v flightids="temp_test1" './script_print_error_tracks.gawk "$1"
"flightids; print execute; system(execute)}' $input2

# Copy temp_test2 to another file
# change remove "_GA" while processing normal tracks
# out1="tracks "$direction" "$runway" "$procedure"_GA"

out1="tracks "$direction" "$runway" "$procedure"
cp temp_test2 $out1

# print temp_test2 in kml format

gawk -v out1=$out1 -v color=$color 'BEGIN{execute="./script_print_kml.gawk "out1" color; print execute; system(execute)}' $out1

File name: script_plot_tracks_by_flow0.gawk

# This script executes script_plot_tracks_by_flow.gawk
# The script is executed for all valid entries in flow_color_2.dat

flowcolor="flow_colors_2.dat"

# get valid entries from flow_color_2.dat

gawk '(!(if($1=="#") print $0))' $flowcolor > temp_flowcolor

# execute script_plot_tracks_by_flow.gawk

gawk 'execute="./script_plot_tracks_by_flow.gawk "$0; print execute; system(execute)}' temp_flowcolor
# File name: script_print_error_testing.gawk
# This script prints out error files

gawk '{execute="./script_print_error_tracks.gawk "$1; print execute; system(execute)"");
NOSP_filelist.dat}

File name: script_print_error_tracks.gawk
# This script print all track for error testing
infile=$1
input1=$infile"_MDW_Atracks"
input2=$2
gawk '(NR==FNR){arr[$1]=next} ($1 in arr){print $0}' $input2 $input1 >> temp_test2

# File name: script_print_flow_label_kml.gawk
# Given the label information, this script print out a kml file for locating the label on google earth
# Input is the flow legend file
# Should have the flow name, color, location coordinates to place the legend on the map
# The file should be tab separated

BEGIN{FS=OFS="\t"}
{flow[FNR]=$1;color[FNR]=$2;lat[FNR]=$3;lon[FNR]=$4}
END{
# print header
print "<?xml version="1.0" encoding="UTF-8"?>";
print "<kml xmlns="http://www.opengis.net/kml/2.2"
xmllns:gx="http://www.google.com/kml/ext/2.2"
xmllns:kml="http://www.opengis.net/kml/2.2"
xmllns:atom="http://www.w3.org/2005/Atom"">

# print document name and style information
print "<Document id="doc1">
print "<name>flowlabel</name>
print "<visibility>0</visibility>
print "<open>1</open>

# print style
for (i=1;i<=length(flow);i++){
colorcode=getcolor(color[i]);
# Specific line style and color
print "<Style id="style1">
print "<IconStyle>
print "<color>colorcode</color>
print "<scale>0.8</scale>
print "</Icon>
print "<href>airplane.png</href>
print "</IconStyle>
# Lable style
print "<LabelStyle>
print "<color>ffffff</color>
print "<scale>0.8</scale>
print "</LabelStyle>
# Line style
print "<LineStyle>
print "<color>colorcode</color>";
print "</LineStyle>";
print "</Style>";
}
# print folder information
print "<Folder id="Flight Tracks">";
print "<name>filename</name>";
print "<visibility>0</visibility>";
# print label information
for (i = 1; i <= length(flow); i++) {
print "<Placemark id="flow[i] >>
print "<name>flow[i]</name>";
print "<visibility>0</visibility>";
print "<styleUrl>#style"i"</styleUrl>";
print "<Point>";
print "<altitudeMode>clampToGround</altitudeMode>";
print "<coordinates>";
print ""lon[i],"lat[i];
print "</coordinates>";
print "</Point>";
print "</Placemark>";
}
# Close open tags
print "</Folder>";
print "</Document>";
print "</kml>";

File name: script_print_kml.gawk
# This script converts track data to kml format to be viewed on google earth
# Syntax to run the script
# ./script_print_kml.gawk inputfile trackcolor
# The inputfile should be space delimited
# It should have the following fields
# field 1 - flight id (unique)
# field 2 - timestamp (seconds)
# field 3 - Origin
# field 4 - Destination
# field 5 - Date (YYYY-MM-DD)
# field 6 - Time (HH:MM:SS)
# field 7 - flight latitude (-ve for eastern hemisphere)
# field 8 - flight longitude (-ve for southern hemisphere)
# field 9 - flight altitude (in feet)
# Should be sorted by field1 followed by field2
# Color has to be small cases
# Color options violet, indigo, blue, green, yellow, orange, red
# Inputs
filename=-f
linecolor=-l
out=-o

# Generate kml file
gawk -v filename=-f -v linecolor=-l -f function.getcolor -f function.kmlfile_1 $filename > $out

File name: script_print_kml_byrwy.gawk
# This script output kml file for each runway
infile=-f

infile2=$2
rwy=$3
color=$4
out1=${infile2} ""rwy

# Filter out runway tracks
awk -v rwy=$rwy '{if($NF==rwy) print $1}' $infile1 > temp_rwy_trackid
gawk 'NR==FNR{arr[$1]=next} ($1 in arr){print $0}' temp_rwy_trackid > temp_rwy_tracks

# print out kmil file
awk -v filename=$out1 -v linecolor=$color -f function.getcolor -f function.kmlfile_1 temp_rwy_tracks > $out1".kml"

File name: script_process_tracks_2.gawk
# This script assign each track at runway a flow
# Flow is defined as direction runway and procedure
# e.g W 13C ILS, E 13C RNP, E 31C Visual
# Logic
# Step1: Assign track to Airport using point in square algorithm
# Step2: Separate Arrivals from Departures
# Step3: Assign track to runway
# run using ./script_process_tracks_2 NOP_data
infile1=$1 # NOP data
airportinfo="airport_info.dat"
runwayinfo="runway_info.dat"
flowdirection="flow_direction.dat"
flowinfo="flow_info_all.dat"
fixinfo="MDW_fix.dat"
goaround_holding="goaround_holding.dat"
flowmeasuringfix="flow_measuring_fix.dat"
bada_data="BADA_coefficient_2.dat"
windinfo1="MDW_wind_info.dat"

# Filter out file and get the first and last hit for each record
awk -v infile1=$infile1 'BEGIN{execute="time ./script_get_first_last_hit.gawk "infile1; print execute; system(execute)}'

# Assign airport and separate arrivals from departures
awk -v infile1=$infile1 '{execute="time ./script_assign_airport.gawk " infile1" "$1" "$2" "$3" "$4" "$5; print execute; system(execute);"}' $airportinfo

# Assign runways to arrivals and departures
# Arrivals
awk -v arr=1 -v infile1=$infile1 -v runwayinfo=$runwayinfo '{execute="time ./script_assign_runway.gawk "arr" " infile1" "runwayinfo" "$1" "$2" "$3" ; print execute; system(execute);"}' $airportinfo

# Departures
awk -v arr=0 -v infile1=$infile1 -v runwayinfo=$runwayinfo '{execute="time ./script_assign_runway.gawk "arr" " infile1" "runwayinfo" "$1" "$2" "$3" ; print execute; system(execute);"}' $airportinfo

# Assign arrival or departure direction to each flight
# For instance identify general direction of flow
# i.e. if the flight is coming in from the south, east, west etc
# The flight tracks are assigned to flows by using heuristics
# The heuristic uses predefined boxes to filter and assign flows
# If a flight track passes through a box it is filtered out and labeled
# See appendix for input file format

# Assign flow direction to all entries in flow_direction.dat
awk '{if($1!="#") print $1,$2}' $flowdirection | sort -u > temp_airport_type

# For each entry of airport and type (arrival/departure) assign direction
A4. User defined functions

The list of function required to execute the script are provided below. Each function needs to be saved (as the file name provided) in the same directory at the GAWK scripts.

File name: function.absvalue

- This function return the absolute value of a number

```plaintext
function abs(num){if(num<0){newnum=-1*num} else{newnum=num}; return newnum}
```

File name: function.acos

- This function computes cosine inverse

```plaintext
function acos(x) {return atan2(sqrt(1-x*x),x)}
```
File name: function.airdensity
# This function computes density of air as a function of altitude
function rho_alt(h) {
    p0=101.325  # sea level standard atmospheric pressure kPa
    T0=288.15   # sea level standard temperature in K
    g0=9.80665  # acceleration due to gravity m/s^2
    L=-0.0065   # temperature lapse rate K/m
    R=8.31447   # ideal gas constant J/(mol*K)
    M=0.0289644 # molar mass of dry air kg/mol

    T=T0-L*h   # temperature at altitude h
    p=p0*(1-(L*h/T0))**(g0*M)/(R*L)
    rho_x=(p*M)/(R*T)*1000;  # air density in kg/m^3
    return rho_x;
}

File name: function.asin
# This function computes sine inverse
function asin(x) {return atan2(x, sqrt(1-x*x))}

File name: function.assignairports
# This function assigns airport to each track
# The arrival or departure information is also determined
 BEGIN{
    # Check if arrival or departure
    # If first point is within the airport then its a departure
    # If the last point is within the airport then its a arrival
    if($7>=lat-span && $7<=lat+span && $8>=lon-span && $8<=lon+span && $9<=alt) {print $0,airport,"D"}
    else if($10>=lat-span && $10<=lat+span && $11>=lon-span && $11<=lon+span && $12<=alt) {print $0,airport,"A"}}

File name: function.atan
# This function computes tan inverse
function atan(x) {return atan2(x, 1)}

File name: function.avgfb_allcases
# This function computes average of the total fuel burn for MDW for all the 5 cases
BEGIN{
    # kg to gallon conversion
    factor=(1/.81)*0.264172
    if($1!=x) {
        x=$1;
        base_v=$4*factor;
        a1_v=$5*factor;
        a2_v=$6*factor;
        a3_v=$7*factor;
        a4_v=$8*factor;
    } else {
        base[FNR]=($4+base_v)*factor;
        a1[FNR]=($5+a1_v)*factor;
        a2[FNR]=($6+a2_v)*factor;
        a3[FNR]=($7+a3_v)*factor;
        a4[FNR]=($8+a4_v)*factor;
    }
}
if($2=="I"){
    base_I[FNR]=$(4*factor);
    a1_I[FNR]=$(5*factor);  
    a2_I[FNR]=$(6*factor);
    a3_I[FNR]=$(7*factor);
    a4_I[FNR]=$(8*factor);
    if($2="I"){
        base_I[FNR]=$(4*factor);
        a1_I[FNR]=$(5*factor);
        a2_I[FNR]=$(6*factor);
        a3_I[FNR]=$(7*factor);
        a4_I[FNR]=$(8*factor);
    }
}

} END{
    # total fuel burn during IMC on an average
    mean_base_I=mean(base_I);
    sd_base_I=std(mean_base_I,base_I);
    mean_a1_I=mean(a1_I);
    sd_a1_I=std(mean_a1_I,a1_I);
    mean_a2_I=mean(a2_I);
    sd_a2_I=std(mean_a2_I,a2_I);
    mean_a3_I=mean(a3_I);
    sd_a3_I=std(mean_a3_I,a3_I);
    mean_a4_I=mean(a4_I);
    sd_a4_I=std(mean_a4_I,a4_I);
}

# total fuel burn during VMC on an average
mean_base_V=mean(base_V);
sd_base_V=std(mean_base_V,base_V);
mean_a1_V=mean(a1_V);
sd_a1_V=std(mean_a1_V,a1_V);
mean_a2_V=mean(a2_V);
sd_a2_V=std(mean_a2_V,a2_V);
mean_a3_V=mean(a3_V);
sd_a3_V=std(mean_a3_V,a3_V);
mean_a4_V=mean(a4_V);
sd_a4_V=std(mean_a4_V,a4_V);

# total fuel burn during VMC and IMC on an average
mean_base=mean(base);
sd_base=std(mean_base,base);
mean_a1=mean(a1);
sd_a1=std(mean_a1,a1);
mean_a2=mean(a2);
sd_a2=std(mean_a2,a2);
mean_a3=mean(a3);
sd_a3=std(mean_a3,a3);
mean_a4=mean(a4);
sd_a4=std(mean_a4,a4);

# Print all the numbers
print mean_base_V, sd_base_V, mean_base_I, sd_base_I, mean_base, sd_base;
print mean_a1_V, sd_a1_V, mean_a1_I, sd_a1_I, mean_a1, sd_a1;
print mean_a2_V, sd_a2_V, mean_a2_I, sd_a2_I, mean_a2, sd_a2;
print mean_a3_V, sd_a3_V, mean_a3_I, sd_a3_I, mean_a3, sd_a3;
print mean_a4_V, sd_a4_V, mean_a4_I, sd_a4_I, mean_a4, sd_a4;
}

File name: function.badacoefficient
# This file contains the fuel burn model and mapping information onto BADA OPF files
{
    # Get engine type
    if(FNR==14){engine=$NF-2);
    # Fuelburn(kg/min) = eta(kg/(min*kN)) * thrust (kN)
    # eta = Cf1 * (1+ (Vtas/Cf2))
    # Cf1 = 1st Thrust specific fuel consumption (kg/(min*kN))
    # Cf2 = 2nd Thrust specific fuel consumption (knots)
    # Vtas = True Airspeed (knots) (from NOP data) # Convert to m/s
    # Cf1 and Cf2 from BADA OPF file line 52, field 2 and 3
    if(FNR==52){Cf1=$2*1; # conversion to kg/(sec*kN)
        Cf2=$3*0.514444444;} # Conversion factor to m/s
    # Co-efficients for minimum fuel flow
    if(FNR==54){
        Cf3=$2*1; # kg/min
        Cf4=$3*1; # in feet
    }
    # Get the cruise fuel flow factor
    if(FNR==56){Cfcr=$2*1);
    # thrust = drag (kN) + mass(kg)*d(Vtas)/dt + mass*g0*(h0/Vtas)
    # drag = (Cd * rho * (Vtas)^2 * S)/2
### Cd = coefficient of drag (two cases Approach and Landing) (no unit)

#### Cd for Cruise
### Cd, CR = Cd0, CR + Cd2, CR * (Cl)^2

#### Cd for Approach
### Cd, AP = Cd0, AP + Cd2, AP * (Cl)^2

#### Cd for Landing
### Cd, LD = Cd0, LD + Cd0, delLD + Cd2, LD * (Cl)^2

#### Cd0, AP and Cd2, AP are parasitic and induced drag coefficients during approach

If co-efficient of drag is missing for AP use clean configuration.

```cpp
if(FNR==9) {Cd0CR=$(NF-3)*1; Cd2CR=$(NF-2)*1; VstallCR=$(NF-4)*1};
```

#### Cd0, AP and Cd2, AP from BADA OPF file line 32, field 6 and 7

```cpp
if(FNR==32) {Cd0AP=Cd0AP}$1; Cd2AP=Cd2AP}*1; VstallAP=$(NF-4)*1};
```

#### Cd0, LD and Cd2, LD are parasitic and induced drag coefficients during Landing

#### Cd, LD = Cd0, LD + Cd0, delLD + Cd2, LD * (Cl)^2

### Cd for Landing

```cpp
Cd,LD from BADA OPF file line 39 field 4
```

#### Cd0, delLD from BADA OPF file line 39 filed 4

```cpp
Cd0delLD=$(NF-3)*0; Cd2LD=$(NF-2)*1;
```

### Cd, CR = Cd0, CR + Cd2, CR * (Cl)^2

#### Cd0, CR and Cd2, CR are parasitic and induced drag coefficients during Cruise

```cpp
Cd0CR=$(NF-3); Cd2CR=$(NF-2)*1;
```

### S = wing reference area (m^2)

#### mass = reference mass of the aircraft type (tonnes) 3 Convert to kg

```cpp
mass=((S3*5)2/2)/1000; MTOW=$(S4*1000); # Conversion factor to kg
```

#### g0 = acceleration due to gravity (m/s^2)

```cpp
g0=9.80665;
```

#### rho = density of air (function of altitude) (kg/m^3) from NOP data and density

```cpp
function
```

#### flighttype, Cf1, Cf2, Cf3, Cf4, Cfcr, Cd0CR, Cd2CR, VstallCR, Cd0AP, Cd2AP, VstallAP, Cd0LD, Cd2LD, Cd0 delLD, VstallLD, mass, S, MTOW, engine;
```

### File name: function.bearing

This function gives the bearing given two lat lon

```cpp
function bearing(lat1, lon1, lat2, lon2){
  rlat1=radian(lat1);
  rlon1=radian(lon1);
  rlat2=radian(lat2);
  rlon2=radian(lon2);
  dellon=r12r-rlon1;
  var1=sin(dellon)*cos(rlat2);
  var2=cos(rlat1)*sin(rlat2)-sin(rlat1)*cos(rlat2)*cos(dellon);
  out=degrees(atan2(var1, var2));
  return out
}
```

### File name: function.combine_flow_stats

This function combines flow stats

```cpp
if(x1!=$2){
  if(FNR!=1){
    t=0;
    s=0;
    # get combined mean
    for(i=1;i<=length(count)[i];i++){
      t=t+mean[i]*count[i];
      s=s+count[i];
      if=1/t;
      m=1+mean[i]*t/length(count)
    }
```
# get combined standard deviation

\[
v_1 = 0;
\]

for (i=1; i<length(count); i++){
  \[v_1 = v_1 + \text{count}[i] \times (sd[i]^2 + (mean[i] - m_1)^2))\];
  \[sd_1 = \sqrt{v_1 / s}\];
  \[v_1 = v_1 + (1 / \text{length(count)}) \times (sd[i]^2 + (mean[i] - m_1)^2))\];
  \[sd_1 = \sqrt{v_1} \];
}  

# Print results

print x1, s, m1, sd1;  

# initialize array

delete count;
delete mean;
delete sd;

\[\text{count}[FNR] = 4\];
\[\text{mean}[FNR] = 7\];
\[\text{sd}[FNR] = 8\];
\[x_1 = 2\];
}

else{
  \[\text{count}[FNR] = 4\];
  \[\text{mean}[FNR] = 7\];
  \[\text{sd}[FNR] = 8\];
}

END{
  \[t_1 = 0\];
  \[s = 0\];

  # get combined mean

  for (i=1; i<length(count); i++){
    \[t_1 = t_1 + \text{mean}[i] \times \text{count}[i]\];
    \[s = s + \text{count}[i]\];
    \[m_1 = m_1 + \text{mean}[i] \times (1 / \text{length(count)})\];
  }

  # get combined standard deviation

  \[v_1 = 0\];
  for (i=1; i<length(count); i++){
    \[v_1 = v_1 + \text{count}[i] \times (sd[i]^2 + (mean[i] - m_1)^2))\];
    \[sd_1 = \sqrt{v_1 / s}\];
    \[v_1 = v_1 + (1 / \text{length(count)}) \times (sd[i]^2 + (mean[i] - m_1)^2))\];
    \[sd_1 = \sqrt{v_1} \];
  }

  # Print results

  print x1, s, m1, sd1;
}

File name: function.combine_flow_stats_2

# This function combines flow stats

{  
  if(x1!=2){  
    if(FNR!=1){
      t1=0;
      s=0;

      # get combined mean

      for (i=1; i<length(count); i++){
        \[t_1 = t_1 + \text{mean}[i] \times \text{count}[i]\];
        \[s = s + \text{count}[i]\];
        \[m_1 = m_1 + \text{mean}[i] \times (1 / \text{length(count)})\];
      }

      # get combined standard deviation

      \[v_1 = 0\];
      for (i=1; i<length(count); i++){
        \[v_1 = v_1 + \text{count}[i] \times (sd[i]^2 + (mean[i] - m_1)^2))\];
        \[sd_1 = \sqrt{v_1 / s}\];
        \[v_1 = v_1 + (1 / \text{length(count)}) \times (sd[i]^2 + (mean[i] - m_1)^2))\];
        \[sd_1 = \sqrt{v_1} \];
      }
    }
  }  
}

# Print results


print x1,s,m1,sd1;
}

# initialize array
delete count;
delete mean;
delete sd;
count[FNR]="4; mean[FNR]="7; sd[FNR]="8;

x1="2;
} else{
count[FNR]="4; mean[FNR]="7; sd[FNR]="8;
}}

## get combined mean
for(i=1;i<=length(count);i++){
##t1=t1+mean[i]*count[i];
s=s+count[i];
##m1=t1/s;

## get combined standard deviation
v1=0;
for(i=1;i<=length(count);i++){
##v1=v1+count[i]*(sd[i]^2+(mean[i]-m1)^2));
##sd1=sqrt(v1/s);
}
sd1=sqrt(v1);
# Print results
print x1,s,m1,sd1;
}

File name: function.computeTAS
# This function computes True Air Speed (TAS)
function airspeed(lat1,lon1,lat2,lon2,deltime,alt,w_dir,w_mag){
# Compute aircraft bearing
f_bearing=bearing(lat1,lon1,lat2,lon2);
if(f_bearing<0){f_bearing=360+f_bearing};
f_bearing_rad=radian(f_bearing);
# Compute wind bearing
if(w_dir<180){w_bearing=w_dir+180} else{w_bearing=w_dir-180};
w_bearing_rad=radian(w_bearing);
# Compute ground speed
dist1=gcd(lat1,lon1,lat2,lon2)*1852; # Convert to meter
g_speed=dist1/deltime; # meter per second
# Covert wind speed to meter per second
w_speed=w_mag*0.514444444;
# Adjust wind speed for altitude
w_speed2=w_speed1*(alt/33)^0.3 # using hellman wind gradient formula
# Compute airspeed
g_ver=g_speed*sin(f_bearing_rad);
g_hor=g_speed*cos(f_bearing_rad);
w_ver=w_speed2*sin(w_bearing_rad);
w_hor=w_speed2*cos(w_bearing_rad);
del_ver=g_ver-w_ver;
del_hor=g_hor-w_hor;
vtas=sqrt(del_ver^2 + del_hor^2);
return vtas;
}

File name: function.computefuelburn1
This function computes fuel burn using BADA model.
The fuel burn is computed for each time step in the NOP data.
It is assumed that the flight is in its approach phase throughout.

BEGIN{
    g = 9.80665;  # acceleration due to gravity m/s^2
    if (NR == FNR) {
        cfi[$1] = $2;  # thrust specific fuel consumption coefficient one unit kg/(min*N)
        cf2[$1] = $3;  # thrust specific fuel consumption coefficient two unit m/s
        cf3[$1] = $4;  # idle descent fuel flow coefficient one kg/min
        cf4[$1] = $5;  # idle descent fuel flow coefficient two in feet
        cfr[$1] = $6;  # Cruise fuel flow factor no unit
        cd0c[$1] = $7;  # parasitic drag coefficients during cruise no unit
        cd2c[$1] = $8;  # induced drag coefficients during cruise no unit
        vstallc[$1] = $9;  # cruise stall speed in knots
        cd0ap[$1] = $10;  # parasitic drag coefficients during approach no unit
        cd2ap[$1] = $11;  # induced drag coefficients during approach no unit
        vstallap[$1] = $12;  # approach stall speed in knots
        cd0ld[$1] = $13;  # parasitic drag coefficients during landing no unit
        cd2ld[$1] = $14;  # induced drag coefficients during landing no unit
        vstallld[$1] = $15;  # landing stall speed in knots
        mass[$1] = $17;  # mass in kg
        s[$1] = $18;  # wing reference area m^2
        engine[$1] = $20;  # engine type piston, turboprop, or jet
    } else {
        if ($1 != x) {
            x = $1;
            cumfb = 0;
            check1 = 0;  # check for clean to dirty
            actype = $18;
            mass1 = mass[actype];  # initialize mass of aircraft
            print $0, "NA", "NA", "NA"
        } else {
            fb = "NA";
            cumfb = "NA";
            phase = "NA";
            print $0, phase, fb, cumfb;
        } else {
            deltime = $13;  # time step
            alt_feet = $7;
            alt_agl = $7 - elev;  # altitude above ground level in feet
            alt_meter = $7 * 0.3048;  # altitude for calculating density in meter
            delalt = $14 * 0.3048;  # change in altitude in meter
            dist = $15;  # change in distance in meter
            vtas = $16;  # velocity in m/s
            vtas2 = $16 * 1.94384;  # velocity in knots
            accel = $17;  # acceleration in m/s^2
            rho1 = rho_alt(alt_meter);  # density of air at given alt in kg/m^3
            # Check phase of the flight
            # i.e., cruise, approach or landing
            Hmaxap = 8000;  # maximum altitude threshold for approach in feet
            Hmaxld = 1700;  # maximum altitude threshold for landing in feet
            Vcr = 1.3 * vstallc[actype];  # minimum velocity threshold for cruise in knots
            Vap = 1.3 * vstallap[actype];  # minimum velocity threshold for approach in knots
            # Check if flight in cruise phase, approach or landing, climb
            if (delalt <= 0) {
                if (alt_agl > Hmaxap) {phase = "CR"}
                else {
                    if (alt_agl >= Hmaxap && alt_agl > Hmaxld) {
                        if (vtas2 >= Vcr) {phase = "CR"}
                        else if (vtas2 >= Vap) {phase = "AP"}
                        else if (vtas2 > Vap) {phase = "AP"}
                        else if (vtas2 > Vap) {phase = "LD"}}
                    } else {
                        if (vtas2 > Vap) {phase = "AP"}
                        else if (vtas2 > Vap) {phase = "LD"}}
                }
            } else {
                phase = "IC";
# This function print out config info by every quater from 6:00 to 23:00

```c
## If descent in cruise phase then use minimum fuel flow model
if(alt_feet>=2000) {if(vtas2>=Vcr) {phase="CR"}} else {phase="AP"};
# if thrust is negative then apply minimum fuel flow model
if(thrust<0) {
    if(abs(cf2[actype])>0) {
        if(engine[actype]="Jet") {
            etaf=cf1[actype]*(1+(vtas2/cf2[actype]));
        } else {
            etaf=cf1[actype]*(1+(vtas2/cf2[actype]))*(vtas2/1000));
        } else {
            etaf=cf1[actype];
        }
    } else {
        fbt=etaf/thrust; # kg/min
    }
}
if(accel<0) {
    yyy="do nothing";
} else {
    fb=fb_t*(delalt/deltime);  # thrust
}
```

File name: function.configbyqtr
# This function print out config info by every quarter from 6:00 to 23:00

```c
x1[FNR] = -5;
x2[FNR] = -6;
```
```c
rec[FNR]=0;
}
END{
for(i=6.25;i<=23;i+=.25){
for(j=1;j<=length(x1);j++){
if(i=contime(x1[j]) && i<=contime(x2[j])){
    print i,rec[j];
    break
}}}
}
```

**File name: function.converttime**

# This function convert time from 6|1 format to 6.25
```c
function contime(intime){
split(intime,arr,"");
outtime=arr[1]+(arr[2]*.25);
return outtime
}
```

**File name: function.degrees**

# This function converts radian to degree
```c
function degrees(value){return value*57.2957795}
```

**File name: function.dist2thresh**

# This function computes the cumulative distance of track from start of data point to the end (runway threshold)
```c
if($1!=id){
    print $0, 0;
id=$1; lat1=$7; lon1=$8; cum_dis=0} else{
cum_dis=cum_dis+gcd(lat1,lon1,$7,$8);
print $0, cum_dis;
lat1=$7;
lon1=$8;
}
```

**File name: function.dist_point_line**

# This function calculates the distance from a point to a line
```c
function getdist(lat0,lon0,lat1,lon1,lat2,lon2,alat,alon){
    # lat0,lon0 are the co-ordinates of the point
    # lat1,lon1,lat2,lon2 are end of the airport
    # alat,alon is the center of the airport
    # step convert lat lon to cartesian coordinates using flat earth approximation
    getcar(alat,alon,lat0,lon0) # For the point
    x0=xl;
y0=yl;
    getcar(alat,alon,lat1,lon1) # For one end of the runway
    xa=xl;
y=yl;
    getcar(alat,alon,lat2,lon2) # For other end of the runway
    xb=xl;
yb=yl;
    # Apply formula
    numerator=abs((xb-xa)*(ya-y0)-(xa-x0)*(yb-ya));
    denominator=sqrt((xb-xa)^2 + (yb-ya)^2);
    ptoline=numerator/denominator;
    return ptoline;
}
```
File name: function.dist_point_line_2
# This function calculates the distance from a point to a line
function getdist(lat0,lon0,lat1,lon1,lat2,lon2,alat,alon){
    # lat0,lon0 are the co-ordinates of the point
    # lat1,lon1,lat2,lon2 are end of the line
    # alat,alon is the center of the line
    # step convert lat lon to cartesian coordinates using flat earth approximation
    getcar(alat,alon,lat0,lon0,scale) # For the point
    x0=x1;
y0=y1;
    getcar(alat,alon,lat1,lon1,scale) # For one end of the runway
    xa=x1;
y_a=y1;
    getcar(alat,alon,lat2,lon2,scale) # For other end of the runway
    xb=x1;
yb=y1;
    # Apply formula
    numerator=abs((xb-xa)*(ya-y0)-(xa-x0)*(yb-ya));
    denominator=sqrt((xb-xa)^2 + (yb-ya)^2);
    ptoline=numerator/denominator;
    return ptoline;
}

File name: function.distairport
# This function computes distance between flight location and a fix
# If within the specified threshold, it print the flight id
{dist=gcd(fix_lat,fix_lon,$7,$8); if(dist<=check_radius) {print $0};
 # debugging test print
 #print $0,fix_lat,fix_lon,$7,$8,dist; }

File name: function.distance
# This function computes flight track distance
{ if($1!=id){
    if(FNR!=1){print "dummy",id,cum_dis ; id=$1; lat1=$7; lon1=$8; cum_dis=0} else{
    cum_dis=cum_dis+gcd(lat1,lon1,$7,$8);
    lat1=$7;
    lon1=$8;
}}

File name: function.distfromfix1
# This function computes distance between flight location and a fix
# If within the specified threshold, it print the flight id
{dist=gcd(fix_lat,fix_lon,$7,$8);
 # For RNP check proximity and alignment with the fix
if(procedure=="RNP" && runway=="13C"){
    # second fix as reference to capture RNP flows
    fix2_lat=41.8263;
    fix2_lon=-87.8987;
    if(dist<=check_radius){
        bearing1=bearing(fix_lat,fix_lon,$7,$8); # Check bearing to see if its parallel to the
        bearing2=bearing(fix_lat,fix_lon,fix2_lat,fix2_lon); #}
diff1=abs(bearing1-bearing2);
if(diff1<3){
  # if perpendicular distance is less than some threshold 0.1 NM
  dist2=getdist($7,$8,fix_lat,fix_lon,fix2_lat,fix2_lon,fix_lat,fix_lon);
  if(abs(dist2)<1){if($9<2500 && $9>2000) print $1);
    } else{
      if(procedure=="RNP") vthres=100 else(vthres=200);
      if(vertical>0){v_diff=abs(vertical-$9); if(dist<=check_radius && v_diff<vthres) print $1} else(if(dist<=check_radius) {print $1});
    }
}
## Debugging test print
##print $0,fix_lat,fix_lon,$7,$8,dist;

File name: function.distfromfix2
# This function computes distance between flight location and a fix
# If within the specified threshold, it print the flight id
{dist=getdist($7,$8,fix_lat,fix_lon,fix2_lat,fix2_lon,fix_lat,fix_lon);
  #print $7,$8,fix_lat,fix_lon,fix2_lat,fix2_lon;
  print $0,dist;
  ## Debugging test print
  ##print $0,fix_lat,fix_lon,$7,$8,dist;
}

File name: function.distimefix2thresh
# This function compute the distance and time from a fix to the runway threshold
{if($1!=x){
  if(FNR!=1){
    asort(fdisarr);
    # Computing distance exactly from the fix line
    # Adding additional distance from the fix line to the closest point to the fix line
    disfix2thresh=dis2thresh-tdisarr[fdisarr[1]];
    timefix2thresh=(time2thresh-ttimearr[fdisarr[1]])/60;
    ##disfix2thresh=dis2thresh-tdisnearfix;
    ##timefix2thresh=(time2thresh-timenearfix)/60;
    ## debug print
    ##print x,dis2thresh,disnearfix,disfix2thresh,time2thresh,timenearfix,timex2thresh;
    delete tdisarr;
    delete ttimearr;
    delete fdisarr;
    ##check=0;
    dis2thresh=$11;
    ##disfix=$12;
    time2thresh=$2; x=$1} else{
      ###if(check==0){if($12>disfix){disnearfix=dis2thresh; timenearfix=time2thresh; check=1}};
    dis2thresh=$11;
    ###disfix=$12;
    time2thresh=$2
tdisarr[$12]=$11;
ttimearr[$12]=$2
fdisarr[$12]=$12;
}
}
END{
###disfix2thresh=dis2thresh-disnearfix;
###timefix2thresh=(time2thresh-timenearfix)/60;
## Debugging test print
##print x,dis2thresh,disnearfix,disfix2thresh,time2thresh,timenearfix,timefix2thresh;
##print x,disfix2thresh,timefix2thresh;
asort(fdisarr);
disfix2thresh=dis2thresh-tdisarr[fdisarr[1]];
timefix2thresh=(time2thresh-ttimearr[fdisarr[1]])/60;
print x,disfix2thresh,timefix2thresh;
}

File name: function.distimefix2thresh_2
# This function compute the distance and time from a fix to the runway threshold
{if ($1!=x){
if (FNR!=1){
asort(fdisarr_index,fdisarr2);
##for(i=1;i<=length(fdisarr2);i++){print i,fdisarr2[i]};
# Compute distance error from perpendicular of fix
add_dist=fdisarr[fdisarr2[1]];
##if(direction=="W"){add_dist=dist_error*-1} else{add_dist=dist_error};
# Compute time error from perpendicular of fix
# Compute velocity
#fix_dist=abs(fdisarr[fdisarr2[1]]-fdisarr[fdisarr2[2]]); # Distance flown around the fix
#fix_time=abs(ttimearr[fdisarr2[1]]-ttimearr[fdisarr2[2]])/60; # Time flown around the fix
#fix_velocity=fix_dist/fix_time;
#add_time=add_dist/fix_velocity;
add_time=add_dist/4; # 4 nautical miles per minute average terminal velocity close to the corner post
# Computing distance exactly from the fix line
# Adding additional distance from the fix line to the closest point to the fix line
dis2thresh=dis2thresh-tdisarr[abs($1)];
timefix2thresh=(time2thresh-ttimearr[abs($1)])+add_time;
##disfix2thresh=dis2thresh-disnearfix;
##timefix2thresh=(time2thresh-timenearfix)/60;
## debug print
# print
dist_error,add_dist,fix_dist,fix_time,fix_velocity,add_time,dis2thresh,disnearfix,disfix2thresh,time2thresh,timenearfix,timefix2thresh;
print x,disfix2thresh,timefix2thresh;
delete tdisarr;
delete ttimearr;
delete fdisarr;
delete fdisarr_index;
delete fdisarr2;
##check=0;
dis2thresh=11;
##disfix=12;
time2thresh=$2;
tdisarr[abs($12)]=11;
ttimearr[abs($12)]=2
fdisarr[abs($12)]=-12;
fdisarr_index[abs($12)]=abs($12);
};x=-11} else{
###if(check==0){if($12>disfix){disnearfix=dis2thresh; timenearfix=time2thresh; check=1}};
dis2thresh=11;
###disfix=12;
time2thresh=$2;
tdisarr[abs($12)]=-11;
ttimearr[abs($12)]=-2
fdisarr[abs($12)]=12;
fdisarr_index[abs($12)]=abs($12);
};x=-11} else{
###if(check==0){if($12>disfix){disnearfix=dis2thresh; timenearfix=time2thresh; check=1}};
dis2thresh=11;
###disfix=12;
time2thresh=$2;
tdisarr[abs($12)]=-11;
ttimearr[abs($12)]=-2
fdisarr[abs($12)]=12;
fdisarr_index[abs($12)]=abs($12);
}}
END
###disfix2thresh=dis2thresh-disnearfix;
###timefix2thresh=(time2thresh-timenearfix)/60;
### debug print
### print x,dis2thresh,disnearfix,disfix2thresh,time2thresh,timenearfix,timefix2thresh;
###print x,disfix2thresh,timefix2thresh;
asort(fdisarr_index,fdisarr2);

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for(i=1;i<=length(fdisarr2);i++){print i,fdisarr2[i]};
# Compute distance error from perpendicular of fix
add_dist=fdisarr[fdisarr2[1]];
# if(direction=="W"){add_dist=dist_error*-1} else{add_dist=dist_error};
# Compute time error from perpendicular of fix

fix_dist=abs(fdisarr[fdisarr2[1]]-fdisarr[fdisarr2[2]]); # Distance flown around the fix
fix_time=abs(ttimearr[fdisarr2[1]]-ttimearr[fdisarr2[2]])/60; # Time flown around the fix

fix_velocity=fix_dist/fix_time;

add_time=add_dist/fix_velocity;

add_time=add_dist/4;
# 4 nautical miles per minute average terminal velocity close to the corner post

.disfix2thresh=dis2thresh-tdisarr[fdisarr2[1]]+add_dist;
timefix2thresh=((time2thresh-ttimearr[fdisarr2[1]])/60)+add_time;

# Computing distance exactly from the fix line
# Adding additional distance from the fix line to the closest point to the fix line
disfix2thresh=dis2thresh-dnearfix;
timefix2thresh=(time2thresh-timenearfix)/60;
## debug print
print x,dist_error,add_dist,fix_dist,fix_time,fix_velocity,add_time,dis2thresh,dnearfix,disfix2thresh,time2thresh,timenearfix,timefix2thresh;

}
This script gets the fuel burn per flight and the total time spent in level phase for all approaches.

```plaintext
if ($1 != x) {
    if ($1 != 1) {
        if (total_fb == "NA") {
            print x, "NA", "NA", "NA", "NA", "NA", "NA", "NA";
        } else {
            # get the cumulative fuel burn closest to the beam of the corner post
            assort(fdisarr_indx, fdisarr2);
            if (beam_dist < 0) {
                actual_fb = total_fb - cum_fb[fdisarr2[1]];
            } else {
                actual_fb = total_fb;
            }
            # print results
            print x, actual_fb, time_level/60, fuel_level, time_nonlevel/60, fuel_nonlevel, time_final/60, fuel_final;
        }
    }
    x = $1;
    # delete all arrays
    delete cum_fb;
    delete fdisarr_indx;
    delete fdisarr2;
    delete fdisarr;
    # Initialize array and variable
    beam_dist = $10;
    cum_fb[abs($10)] = $21;
    fdisarr[abs($10)] = $10;
    fdisarr_indx[abs($10)] = abs($10);
    time_level = 0;
    fuel_level = 0;
    time_nonlevel = 0;
    fuel_nonlevel = 0;
    time_final = 0;
    fuel_final = 0;
    z = 0;
    # record after it crosses the last way point on STAR
    # Compute time in level phase not decelerating
    if ($7 >= final) {
        # This specified as variable to the function and is the start of the final approach
        if ($10 > 0) {
            if ($14 >= 0) {
                if ($17 <= -0.1) {
                    time_nonlevel = time_nonlevel + $13;
                    fuel_nonlevel = fuel_nonlevel + $20;
                } else {
                    time_level = time_level + $13;
                    fuel_level = fuel_level + $20;
                }
            } else {
                time_nonlevel = time_nonlevel + $13;
                fuel_nonlevel = fuel_nonlevel + $20;
            }
        } else {
            time_final = time_final + $13;
            fuel_final = fuel_final + $20;
        }
    } else {
        # record the cumulative fuel burn and distance from corner post
        total_fb = $21;
        cum_fb[abs($10)] = $21;
        fdisarr[abs($10)] = $10;
        fdisarr_indx[abs($10)] = abs($10);
        # do not record level phase if in cruise phase and decelerating more than .1 m/s^2
        if ($7 >= final) {
            if ($10 > 0) {
                if ($14 >= 0) {
                    if ($17 <= -0.1) {
                        time_nonlevel = time_nonlevel + $13;
                        fuel_nonlevel = fuel_nonlevel + $20;
                    } else {
                        time_level = time_level + $13;
                        fuel_level = fuel_level + $20;
                    }
                } else {
                    time_nonlevel = time_nonlevel + $13;
                    fuel_nonlevel = fuel_nonlevel + $20;
                }
            } else {
                time_level = time_level + $13;
                fuel_level = fuel_level + $20;
            }
        }
    }
```

File name: function.fuelburn_levelsegment
}} else{
  time_nonlevel-time_nonlevel<$13;
  fuel_nonlevel-fuel_nonlevel<$20;
}}}) else{
  time_final-time_final+$13;
  fuel_final-fuel_final+$20;
}}

END{
if(total_fb=="NA") {print x,"NA","NA","NA","NA","NA","NA","NA"} else{
# get the cumulative fuel burn closest to the beam of the corner post
asort(fdisarr indx,fdisarr2);
if(beam_dist<0){
  actual_fb=total_fb-cum fb[fdisarr2[1]];
} else{
  actual_fb=total_fb;
};

# print results
print
x,actual_fb,time_level/60,fuel_level,time_nonlevel/60,fuel_nonlevel,time_final/60,fuel_final;
}

File name: function.gcd_haversine
# This function compute gcd between two points on earth
# The two points should be specified in lat lon format
# The radius of earth is assumed to be 3443.89849 nautical miles
function gcd(lat1,lon1,lat2,lon2){rad=3.1416/180; x1=lat1*rad; y1=lon1*rad; x2=lat2*rad; y2=lon2*rad; r=3443.89849; dellat=x1-x2; dellon=y1-y2;
  centralangle=2*asin(sqrt(sin(dellat/2)^2 + cos(x1)*cos(x2)*sin(dellon/2)^2));
  distance=r*centralangle; return distance}

File name: function.gcd_haversine_2
# This function compute gcd between two points on earth
# The two points should be specified in lat lon format
# The radius of earth is assumed to be 3443.89849 nautical miles
function gcd(lat1,lon1,lat2,lon2){
  rad=3.1416/180; x1=lat1*rad; y1=lon1*rad; x2=lat2*rad; y2=lon2*rad; r=3443.89849;
  dellat=x1-x2; dellon=y1-y2;
  a=sin(dellat/2)*sin(dellat/2)+cos(x1)*cos(x2)*sin(dellon/2)*sin(dellon/2);
  centralangle=2*atan2(sqrt(a),sqrt(1-a));
  distance=r*centralangle;
  return distance}

File name: function.get_rank_optimal_runway
# From the ASPM data, this function get the runway most optimal for the given wind.
# i.e. runway that has the best head wind for a given cross wind threshold
#
if(NR==FNR){rwy[FNR]=$1} else{
# for each runway compute the cross wind and tail wind
# get wind direction and speed
  wind_direction=radian($11);
wind_speed=$12;
for(i=1;i<=length(rwy);i++){
  rwy_bearing=radian(rwy[i]*10);
  a1=abs(rwy_bearing-wind_direction); # is the difference in wind and rwy bearing
  cross_wind=abs(sin(a1)*wind_speed);
  if(cross_wind<20){
    tail_wind=cos(a1)*wind_speed;
    if(tail_wind>0){
      rwy3=rwy[i];
      break;
    }
  }
  rwy2[tail_wind[i]]=rwy[i];
}
###n=asort(tail_wind);
#####rwy3=rwy2[tail_wind[n]];
print $0,rwy3
}

File name: function.get_track_profile_info
# This script computes for each track, at each time step
# change in time
# distance
# altitude
# velocity
# acceleration
{ if(x!=1){
  x=1;
  i=1;
  time=$2;
  lat=$7;
  lon=$8;
  alt=$9;
  wind_dir=$13;
  wind_mag=$14;
  print $1,$2,$3,$4,$7,$8,$9,$10,$11,$12,$13,$14,0,0,0,0,0
  deltime1=0;
  speed1=0;
} else{
  deltime2=$2-time;
  if(deltime2>=300){
    ###dist1=gcd(lat,lon,$7,$8)*1852; # Convert to meter
    delalt=$9-alt;
    # Altitude above ground
    alt_g=abs($9-elev);
    ###speed2=(dist1/deltime2); # in m/s
    speed2=airspeed(lat,lon,$7,$8,deltime2,alt_g,$13,$14);
    # Implementing simple differential relaxation equation based smoothings
    tau=20 # smoothing parameter
    dt=deltime2/tau
    # alpha=deltime1/(deltime1+deltime2);
    # alpha=0 # no smoothing
    #if(i>1){alpha=0} else{alpha=0};
    # alpha=speed1/(speed1+speed2);
    # speed3=alpha*speed1+(1-alpha)*speed2;
    # speed3=(speed2+speed1+speed1b+speed1c)/4;
    # if(i>1){
    # speed3=(speed1+dt*speed2)/(1+dt);
    #}
    # speed3=speed2;
    delspeed=(speed3-speed1)/deltime2 else{speed3=speed2; delspeed=0}; # in m/s^2
    print $1,$2,$3,$4,$7,$8,$9,$10,$11,$12,$13,$14,deltime2,delalt,dist1,speed3,delspeed;
    #print $1,$2,$3,$4,$7,$8,$9,$10,$11,$12,$13,$14,deltime2,delalt,dist1,speed3,delspeed,f_bearing_rad,w_bearing_rad,w_speed1,w_speed2;
BEGIN{ 
    # This function print out the actual arr dep distributiona at chicago metroplex
    # From the ASPM data, this function get the runway most optimal for the given wind.
    # i.e. runway that has the best head wind for a given cross wind threshold
    #
    # for each runway compute the cross wind and tail wind
    # get wind direction and speed
    wind_direction=radian($11);
    wind_speed=$12;
    # initialize tail wind array
    delete tail_wind;
    for(i=1;i<=length(rwy);i++){
        rwy_bearing=radian(rwy[i]*10);
        a1=abs(rwy_bearing-wind_direction); # is the difference in wind and rwy bearing
        cross_wind=abs(sin(a1)*wind_speed);
        if(cross_wind<20){
            tail_wind[i]=cos(a1)*wind_speed
        }
    }
    n=assort(tail_wind);
    rwy3=rwy2[tail_wind[n]];
    print $0,rwy3
}

BEGIN{
    bin=15*60;
    arr[1]="22L_13C";
    arr[2]="22L_Others";
    arr[3]="28_13C";
    arr[4]="28_Others";
    arr[5]="13C_ILS";
    arr[6]="13C_RNP";
    for(i=1;i<=length(arr);i++){
        count[i]=0;
        if(i==1){
            printf "%s	Date\n",arr[i] else{
                printf "\n",arr[i]}
            } else{printf "%s",arr[i])}
        if(i==length(arr)){printf "%s\n",arr[i])}
    }
    if(FNR==1){binstart=$2; binend=binstart+bin;}
    if($2>binstart && $2<binend) {
        for(i=1;i<=length(arr);i++){
            if($FNF==arr[i]) (count[i]++)
        }
    if(i==1)printf "%s	%*s\n",strftime("%F",binend,UTC-1),strftime("%T",binend,UTC-1),count[i]) else{
        for(i=1;i<=length(arr);i++){
            if(i==1)printf "%s	%*s\n",strftime("%F",binend,UTC-1),strftime("%T",binend,UTC-1),count[i]) else{
            printf "\n", count[i])
        }
    }
}
```c
printf "\t%s", count[1])}; count[1]=0;
binstart=binend;
binend+=bin;
for(i=1;i<length(arr);i++){
    if($NF==arr[1]){count[1]++}
}
END{
for(i=1;i<length(arr);i++){
    if(i==1){printf "%s\t%s\t%s", strftime("%F",binend,UTC-1),strftime("%T",binend,UTC-1),count[1]}
    else{
        printf "\t%s",count[1]}
}
}

File name: function.getcartesian
# This function converts lat lon to cartesian co-ordinates using flat earth approximation
# lat1 and lon1 are co-ordinates of the airport
# lat2 and lon2 are the lat lon to be converted
function getcar(lat1,lon1,lat2,lon2){
    lat0=lat1-.2;
    lon0=lon1-.2;
    x1=((lon2-lon0)*cos(lat1*0.0174532925))*60; # Unit nautical miles
    y1=(lat2-lat0)*60; # Unit nautical miles
}

File name: function.getcartesian_2
# This function converts lat lon to cartesian co-ordinates using flat earth approximation
# lat1 and lon1 are co-ordinates of the airport, used to interpolate
# lat2 and lon2 are the lat lon to be converted
# scale decides the distance of the origin from the airport center
# Larger the scale lesser the accuracy
# e.g scale can be .2 for co-ordinates inside the airport, and upto 4 for considering whole area of NOP data
function getcar(lat1x,lon1x,lat2x,lon2x,scale){
    lat0x=lat1x-scale;
    lon0x=lon1x-scale;
    x1=((lon2x-lon0x)*cos(lat1x*0.0174532925))*60; # Unit nautical miles
    y1=(lat2x-lat0x)*60; # Unit nautical miles
}

File name: function.getcolor
# This function gets the color code for the specified color
function getcolor(color){
    arr["indianred"]="ff5c5ccd";
    arr["salmon"]="ff7280fa";
    arr["red"]="ff0000ff";
    arr["crimson"]="ff3c14dc";
    arr["firebrick"]="ff2222b2";
    arr["darkred"]="ff00008b";
    arr["pink"]="ffbc00ff";
    arr["hotpink"]="ffb469ff";
    arr["deepink"]="ff9314ff";
    arr["mediumvioletred"]="ff8515c7";
    arr["palevioletred"]="ff9370db";
    arr["coral"]="ff571a":
    arr["tomato"]="ff4763ff";
    arr["orangered"]="ff0045ff";
    arr["orange"]="ff00a5ff";
    arr["gold"]="fff0d7ff";
    arr["yellow"]="ff00ffff";
    arr["peachpuff"]="ffb9daff";
    arr["khaki"]="ff8ce6f0";
```
arr ["darkkhaki"] = "#f6bb7bd";
arr ["thistle"] = "#fdd8bdf8";
arr ["plum"] = "#fda0dd";
arr ["violet"] = "#f8e91c";
arr ["orchid"] = "#ff69b4";
arr ["magenta"] = "#ff00ff";
arr ["mediumpurple"] = "#ff99cc";
arr ["blueviolet"] = "#8a2be2";
arr ["darkviolet"] = "#9400d3";
arr ["darkorchid"] = "#ff32d9";
arr ["darkmagenta"] = "#8b008b";
arr ["purple"] = "#800080";
arr ["indigo"] = "#7a00d7";
arr ["darkslateblue"] = "#ff008070";
arr ["slateblue"] = "#f0ead4";
arr ["greenyellow"] = "#9abdb5";
arr ["lime"] = "#ff00ff00";
arr ["limegreen"] = "#ff333333";
arr ["lightgreen"] = "#ff0080ff";
arr ["seagreen"] = "#008080";
arr ["green"] = "#00ff00ff";
arr ["darkgreen"] = "#00800080";
arr ["yellowgreen"] = "#ff00ff00";
arr ["olivedrab"] = "#cc00ff";
arr ["olive"] = "#ff00ff00";
arr ["darkolivegreen"] = "#ff00ff00";
arr ["darkseagreen"] = "#ff00ff00";
arr ["mediumspringgreen"] = "#ff0080ff";
arr ["lightseagreen"] = "#ff00ff00";
arr ["seagreen"] = "#008080";
arr ["darkseagreen"] = "#ff00ff00";
arr ["lightseagreen"] = "#ff00ff00";
arr ["darkcyan"] = "#ff00ff00";
arr ["teal"] = "#ff00ff00";
arr ["cyan"] = "#ff00ff00";
arr ["paleturquoise"] = "#ff00ff00";
arr ["aquamarine"] = "#ff00ff00";
arr ["turquoise"] = "#ff00ff00";
arr ["darkturquoise"] = "#ff00ff00";
arr ["cadetblue"] = "#ff00ff00";
arr ["steelblue"] = "#ff00ff00";
arr ["lightsteelblue"] = "#ff00ff00";
arr ["skyblue"] = "#ff00ff00";
arr ["deepskyblue"] = "#ff00ff00";
arr ["dodgerblue"] = "#ff00ff00";
arr ["cornflowerblue"] = "#ff00ff00";
arr ["royalblue"] = "#ff00ff00";
arr ["blue"] = "#ff00ff00";
arr ["darkblue"] = "#ff00ff00";
arr ["wheat"] = "#ff00ff00";
arr ["burlywood"] = "#ff00ff00";
arr ["tan"] = "#ff00ff00";
arr ["rosybrown"] = "#ff00ff00";
arr ["sandybrown"] = "#ff00ff00";
arr ["goldenrod"] = "#ff00ff00";
arr ["darkgoldenrod"] = "#ff00ff00";
arr ["peru"] = "#ff00ff00";
arr ["chocolate"] = "#ff00ff00";
arr ["saddlebrown"] = "#ff00ff00";
arr ["sienna"] = "#ff00ff00";
arr ["brown"] = "#ff00ff00";
arr ["maroon"] = "#ff00ff00";
arr ["white"] = "#ff00ff00";
arr ["lightgray"] = "#ff00ff00";
arr ["silver"] = "#ff00ff00";
arr ["darkgray"] = "#ff00ff00";
arr ["gray"] = "#ff00ff00";
arr ["slategray"] = "#ff00ff00";
arr ["darkslategray"] = "#ff00ff00";
arr["black"] = "ff000000";
if(arr[color] != "") {hexcode = arr[color]} else {hexcode = arr["red"]};
return hexcode;

File name: function.getconfigstats
# This function computes for each day
# 1. Duration of runway configuration
# 2. Stats on meteorological conditions (ceiling, visibility, wind angle, wind speed)
# 2. Airport Arrival Rate and Airport Departure Rate
BEGIN{FS="\t"}
{
# print FNR;
if(FNR==1){
config = $12 "$13;
hour = $4
airport = $1
year = substr($2,1,4);
month = substr($2,5,2);
day = $3;
time_start = $4 "$5;

if(config!="$12" "$13 || abs(hour-4)>1){
# Compute stats and print output
rec = length(mc);
# print rec;
if(rec>1){
# Get MC count
IMC=0; VMC=0
for(i=1; i<=length(mc);i++) {if(mc[i]=="I") {IMC++;} else {VMC++;}}
# print IMC, VMC;
# get min max mean and std of ceiling
if(length(ceiling)>1){
minmaxmeansd(ceiling);
# print min, max, average, sd;
# for(no in ceiling){print no, ceiling[no];
ceilingmin = min;
ceilingmax = max;
ceilingmean = average;
ceilingsd = sd} else{
ceilingmin = ceiling[1];
ceilingmax = ceiling[1];
ceilingmean = ceiling[1];
ceilingsd = 0;
# get min max mean and std of visibility
minmaxmeansd(visibility);
# print min, max, average, sd;
visibilitymin = min;
visibilitymax = max;
visibilitymean = average;
visibilitysd = sd;
# get min max mean and std of wind_angle
minmaxmeansd(wind_angle);
# print min, max, average, sd;
wanglemin = min;
wanglemax = max;
wanglemean = average;
wanglesd = sd;
# get min max mean and std of wind_speed
minmaxmeansd(wind_speed);
wind_speedmin = min;
windspeedmax = max;
windspeedmean = average;
windspeedsd = sd;
# get min max mean and std of aar

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minmaxmeansd(aar);
aarmin=min;
aarmax=max;
aarmean=average;
aarsd=sd;
# get min max mean and std of adr
minmaxmeansd(aar);
#print min, max, average, sd;
adrmin=min;
adrmax=max;
adrmean=average;
adrstd=sd;
# print output
print
airport,yr,mon,day,time_start,time_end,config,VMC*100/rec|"IMC*100/rec,ceilingmin"|"IMC*100/rec,ceilingmax"|"ceilingmean"|"ceilingstd",visibilitymin|"visibilitymax"|"visibilitymean"|"visibilitystd",wind_anglemin|"wind_anglemax"|"wind_anglemean"|"wind_anglesd",wind_speedmin|"wind_speedmax"|"wind_speedmean"|"wind_speedsd,aarmin"|"aarmax"|"aarmean"|"aarstd,adrmin"|"adrmax"|"adrmean"|"adrsd";
} else{
xxx="donothing";

# Record new set of data
cfg="$12"|"$13;"
hour=$4; airport=$1; year=substr($2,1,4); month=substr($2,5,2); day=$3
time_start=$4|"$5;"
# delete all array
delete mc; delete ceiling; delete wind_angle; delete wind_speed; delete aar; delete adr;
# initialize array
# start recording into arrays again
i=1;
m[1]=6; # meteorological conditions
if($7!="na") {ceiling[i]=7}; # ceiling
if($8!="-"|"-" $8) {visibility[i]=8}; # visibility
if($9!="-"|"-" $9) {wind_angle[i]=9}; # wind angle
if($10!="-"|"-" $10) {wind_speed[i]=10}; # wind speed
aar[i]=16; # airport arrival rate
adr[i]=17; # airport departure rate
}
else{
hour=$4;
# Record data to compute stats
time_end=$4|"$5; # end time
i++; mc[i]=6; # meteorological conditions
if($7!="na") {ceiling[i]=7}; # ceiling
if($8!="-"|"-" $8) {visibility[i]=8}; # visibility
if($9!="-"|"-" $9) {wind_angle[i]=9}; # wind angle
if($10!="-"|"-" $10) {wind_speed[i]=10}; # wind speed
aar[i]=16; # airport arrival rate
adr[i]=17; # airport departure rate
}} END{
# Compute stats and print output
rec_length(mc);
# print rec; if(rec>1){
# Get MC count
IMC=0; VMC=0
for(i=1; i<=length(mc); i++) {if(mc[i]="I") {IMC++} else{VMC++});
# print IMC, VMC;
# get min max mean and std of ceiling
if(length(ceiling)>1){

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minmaxmeansd(ceiling);
# print min, max, average, sd;
# for(no in ceiling){print no, ceiling[no]};
cellingmin=min;
cellingmax=max;
cellingmean=average;
cellingsd=sd) else{
cellingmin=ceiling[1];
cellingmax=ceiling[1];
cellingmean=ceiling[1];
cellingsd=0};
# get min max mean and std of visibility
minmaxmeansd(visibility);
# print min, max, average, sd;
visibilitymin=min;
visibilitymax=max;
visibilitymean=average;
visibilitysd=sd;
# get min max mean and std of wind_angle
minmaxmeansd(wind_angle);
# print min, max, average, sd;
wind_anglemin=min;
wind_max=-max;
wind_anglemean=average;
wind_anglestd=sd;
# get min max mean and std of wind_speed
minmaxmeansd(wind_speed);
wind_speedmin=min;
wind_max=-max;
wind_speedmean=average;
wind_speedstd=sd;
# get min max mean and std of aar
minmaxmeansd(aar);
aarmin=min;
aarmax=max;
aarmean=average;
aarsd=sd;
# get min max mean and std of adr
minmaxmeansd(adr);
# print min, max, average, sd;
adrmin=min;
adrmax=max;
adrmean=average;
adrsd=sd;
# print output
print
airport, year, month, day, time_start, time_end, config, VMC*100/rec" | "IMC*100/rec, ceilingmin | "ceilingmax" | "ceilingmean" | "ceilingsd, visibilitymin | "visibilitymax | "visibilitymean | "visibilitysd, wind_anglemin | "wind_anglemax | "wind_anglemean | "wind_anglestd, wind_speedmin | "wind_speedmax | "wind_speedmean | "wind_speedstd, aarmin | "aarmax | "aarmean | "aarstd, adrmn | "adrmax | "adrmean | "adrsd
} else{
xxxx="donothing"}
# File name: function.geteq 
# given two lat lon, this script computes the equation of line for the two points 
{if($1==airport && $2==runway){
  elat=$4+$5/60;
  elon=1*($6+$7/60);
  getcar(lat,lon,elat,elon);
  e1x=x1;
  e1y=y1;
  e2lat=$8+$9/60;
  e2lon=1*($10+$11/60);
  getcar(lat,lon,e2lat,e2lon);
  e2x=x1;
  e2y=y1;
  m=(e2y-e1y)/(e2x-e1x);
  c=e1y-m*e1x;
  printf "%s %s %s %f %f
", airport,e1x,e1y, e2x,e2y; } }

# File name: function.geteq_2 
# given two lat lon, this script computes the equation of line for the two points 
{if($1==airport){
  getcar(lat,lon,$8,$9);
  e1x=x1;
  e1y=y1;
  getcar(lat,lon,$10,$11);
  e2x=x1;
  e2y=y1;
  m=(e2y-e1y)/(e2x-e1x);
  c=e1y-m*e1x;p
  printf "%s %s %s %f %f\n", airport,$6,$7,m,c; } }

# File name: function.getfbrwyconfig1 
# This function average fuel burn per flight for a given runway configuration 
BEGIN{
  if(flow_scope>1){
    delete Condition;
    delete runway;
    delete app;
    delete east;
  
  
}
if (NR==FNR)
    # record fuel burn per flow
    condition[FNR]=1;
    runway[FNR]=2;
    app[FNR]=3;
    east[FNR]=4;
    west[FNR]=5;
else
    # Filter out valid flows
    # Initialize arr
    if(FNR<20){
        delete rwy_index;
        delete app_index;
        delete fb_index;
        delete fb_actual;
        j=1;
        for(i=1;i<=length(runway);i++){
            # while the data provide the runway information, the information on the type of approach
            # has to be determined
            # The type of approach is decided based on fuel burn ranking
            # Based on the east west flow ratio compute average fuel burn for each approach type
            avg_fb=16*east[i]+(1-16)*west[i];
            # average fuel burn
            # record fuel for all possible approaches given the meteorological conditions
            if($7==condition[i]){  
                rwy_index(avg_fb)=runway[i];  # record runway info as function of fuel burn
                app_index(avg_fb)=app[i];  # record app information as a function of fuel burn
                fb_index(avg_fb)=avg_fb;  # record fuel burn as a function of runway
            }
        }
        # record fuel burn for actual configuration and meteorological conditions
        check=0
        if($7==runway[i] & $7==condition[i]){  
            fb_actual[j]=avg_fb
            app_actual[j]=app[i];
            check=1;
            j++;
        }else{  
            fb_actual[j]=999;  # If runway is not in the list
            app_actual[j]=999;
        }
    }
    # For each scope get the average runway fuel burn for actual runway configuration
    asort(fb_actual,fb_actual_2);
    actual_fb=fb_actual_2[1];
    actual_app=app_actual[actual_fb];

    # get optimal runway and the corresponding fuel burn
    if(flow_scope>1){
        asort(fb_index,fb_index_2);
        wind_direction=radian($11);
        wind_speed=$12;
        for(i=1;i<=length(fb_index_2);i++){
            rwy_bearing=radian(fb_index_2[i]*10);
            a=abs(rwy_bearing-wind_direction);  # is the difference in wind and rwy bearing
            cross_wind=abs(sin(a)*wind_speed);
            if(cross_wind<20){
                tail_wind=cos(a)*wind_speed;
                if(tail_wind>0){
                    opt_fb=fb_index_2[1];
                }
            }
        }
    }
opt_rwy=rwy_index[opt_fb];
opt_app=app_index[opt_fb];
break;
}}}

# Print results
if(flow_scope==1){
print $0,actual_fb; # for scope1
} else{
print $0,actual_app,actual_fb,opt_rwy,opt_app,opt_fb; # for scope 2 and 3
##if(flow_scope==3){
##for(no in rwy_index){print no, rwy_index[no],app_index[no]};
##for(no in fb_index_2){print no, fb_index_2[no]};
##}
##}
##} else {exit}
}

File name: function.getflowstats
# This function prints out flow stats
# BEGIN{
delete arr;
##print runway, direction,procedure;
}
{
if(level==1){
if($22==runway){
arr[FNR]=$fieldno} else{
if(level==2){
if($22==runway && $24==procedure){
arr[FNR]=$fieldno} else{
if(level==3){
if($22==runway && $23==direction && $24==procedure){
arr[FNR]=$fieldno}}}}
}
}
##for (no in arr){print no, arr[no]};
if(length(arr)>0){
minmaxmeansd(arr);
print direction,runway,procedure,n,min,max,average,sd;
}
}

File name: function.getheader
# This function get the header information of a file
{if(FNR==1){for(i=1;i<=NF;i++){print i,$i}} else{exit}}

File name: function.getlatlon
# This function converts cartesian coordinates to lat lon
# lat1 and lon1 are co-ordinates of the airport, used to interpolate
# lat2 and lon2 are the lat lon to be converted
# scale decides the distance of the origin from the airport center
# e.g scale can be .2 for co-ordinates inside the airport, and upto 4 for considering
# whole area of NOP data
function getlatlon(lat1x,lon1x,x1,y1,SCALE)
lat0X=lat1x;
lon0x=lon1x;
lon2x=x1/(cos(lat1x*0.0174532925)*60))+lon0x; # Unit degrees
lat2x=(y1/60)+lat0x; # Unit degrees
}
File name: function.getrunway

# This function assigns runway to each track co-ordinate
if (NR==FNR) { runway~2; m~3; c~$4$ } else{
  if ($10=="S") {flt_bearing=bearing($7,$8,$17,$18$)}
  else {flt_bearing=bearing($17,$18,$7,$8$)}; # get bearing information for flight track

if (flt_bearing<0) {flt_bearing=flt_bearing+360}; # convert to 360 degrees format

if (runway="L" || runway="R" || runway="C") {rwy_bearing=substr(runway,1,length(runway)-1)+10 } else{
  # Get runway bearing
  diff_bearing=flt_bearing-rwy_bearing;
  if (diff_bearing<0) {diff_bearing=diff_bearing+1};
  getcar(lat,lon,$7,$8$);

  upper=lat-c-up;
  lower=lat-c-down;

  if (upper<0 && lower>0 && diff_bearing<25) {
    print $1,runway,m,c,y1,x1,upper,lower,flt_bearing
  } else {
    print $1,"NA",m,c,y1,x1,upper,lower,flt_bearing
  }
}

File name: function.getrunway_2

# This function assigns runway to each track id
# BEGIN{delete runway1; delete runway2; delete lat1; delete lon1; delete lat2; delete lon2; delete dist;
if (NR==FNR) { runway1[FNR]~1; runway2[FNR]~2; lat1[FNR]~3; lon1[FNR]~4; lat2[FNR]~5; lon2[FNR]~6$ } # read the runway coordinates to an array
else{
  # Calculate the distance of the last two track hit from the runway centerline
  if (FNR!=1){delete dist};
  for (i=1;i<length(runway1);i++){
    if (runway1[i]=="13C" || runway1[i]=="31C" || runway2[i]=="13R" || runway2[i]=="31L") {
      # The runway 13C and 13R are too close to each other
      # Therefore distance of only the last point is computed and not the cumulative distance
      # This approach shows better results
      if (arr==1){
        dis_pnt2=getdist($17,$18,lat1[i],lon1[i],lat2[i],lon2[i],lat,lon);
        dist[dis_pnt2]=1;
      } else{
        dis_pnt1=getdist($7,$8,lat1[i],lon1[i],lat2[i],lon2[i],lat,lon);
        dist[dis_pnt1]=1;
      }
    } else{
      dis_pnt1=getdist($7,$8,lat1[i],lon1[i],lat2[i],lon2[i],lat,lon);
      dis_pnt2=getdist($17,$18,lat1[i],lon1[i],lat2[i],lon2[i],lat,lon);
      dist[dis_pnt1+dis_pnt2]=1;
    }
  }

  # for(no in dist){print no, dist[no]};
  # get the runway index with the minimum distance
  n=asorti(dist,desc);
  rwy_index=dist[n[1]];
  print rwy_index;

  # Calculate the bearing of flight track
  flt_bearing=bearing($7,$8,$17,$18$); # get bearing information for flight track
  if (flt_bearing<0) {flt_bearing=flt_bearing+360}; # convert to 0 - 360 degrees format

  # Get runway bearing
  if (runway1[rwy_index]=="L" || runway1[rwy_index]=="R" || runway1[rwy_index]=="C") {
    rwy1_bearing=substr(runway1[rwy_index],1,length(runway1[rwy_index])-1)*10;
    rwy2_bearing=substr(runway2[rwy_index],1,length(runway2[rwy_index])-1)*10$}
  else{
    rwy1_bearing=runway1[rwy_index]*10;
    rwy2_bearing=runway2[rwy_index]*10$;
  }

  print runway1[rwy_index],runway2[rwy_index],rwy1_bearing,rwy2_bearing;

  # Compare bearing to track with bearing of runway

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if(abs(rwy1_bearing-flt_bearing)<30){print $0,runway1[rwy_index]}
else if(abs(rwy2_bearing-flt_bearing)<30){print $0,runway2[rwy_index]} else{print $0,"NA");}
}
#
#
File name: function.goaround_holding
# Step1: Calculate bearing between two consecutive points
# Step2: Calculate change in bearing
# Step3: Add up change in bearing
# Step4: If above threshold then classify as go around or holding pattern
(if($1!=x){if(FNR==1){
# Initialize variables
x=$1;
lat1=$7;
lon1=$8;
sumangle1=0;
sumangle2=0;
newbearing=0;
y=1;
print $0,"Start","Start","Start","Start","Start";
} else{
x=$1;
lat1=$7;
lon1=$8;
sumangle1=0;
sumangle2=0
newbearing=0;
y=1;
print $0,"Start","Start","Start","Start","Start";
}
else{
newbearing1=bearing(lat1,lon1,$7,$8);
if(newbearing1<0){newbearing1+=360};
lat1=$7;
lon1=$8;
print $0,newbearing1,"Start","Start","Start","Start","Start";
} else{
newbearing2=bearing(lat1,lon1,$7,$8);
if(newbearing2<0){newbearing2+=360};
turnangle=newbearing2-newbearing1;
if(abs(turnangle)>180){if(turnangle<0){turnangle=360-abs(turnangle)} else{turnangle+=360}};
if(turnangle<0){
sumangle1+=turnangle;
} else{
sumangle2+=turnangle;
};
newbearing1=newbearing2;
lat1=$7;
lon1=$8;
print $0,newbearing2,turnangle,sumangle1,sumangle2,abs(sumangle1+sumangle2);
}
}
END{
newbearing2=bearing(lat1,lon1,$7,$8);
if(newbearing2<0){newbearing2+=360};
turnangle=newbearing2-newbearing1;
if(abs(turnangle)>180){if(turnangle<0){turnangle=360-abs(turnangle)} else{turnangle+=360}};
if(turnangle<0){
sumangle1+=turnangle;
} else{
sumangle2=sumangle2+turnangle;
}
newbearing1=newbearing2;
lat1=$7;
lon1=$8;
print $0,newbearing2,turnangle,sumangle1,sumangle2,abs(sumangle1+sumangle2);
}

File name: function.holdingstats
# This function computes mean and standard deviation for holding metrics like time, track length and fuel burn
# BEGIN{
delete htime;
delete hdis;
delete hfb;
}
if(actype="all"){
htime[FNR]=$5;
hdis[FNR]=$6;
hfb[FNR]=$7;
} else{
if($2~actype){
htime[FNR]=$5;
hdis[FNR]=$6;
hfb[FNR]=$7;
}
}
} END{
n=length(htime);
mean_htime=mean(htime);
mean_hdis=mean(hdis);
mean_hfb=mean(hfb);
sd_htime=std(mean_htime,htime);
sd_hdis=std(mean_hdis,hdis);
sd_hfb=std(mean_hfb,hfb);
print actype,n,mean_htime,mean_hdis,mean_hfb;
}

File name: function.kmlfile_1
# This function produces a kml file for track data, to be viewed on google earth
BEGIN{
colorcode=getcolor(linecolor); # get kml color code for line color specified
# print header
print "<kml version=""1.0"" encoding=""UTF-8"">"
print "<kml xmlns=""http://www.opengis.net/kml/2.2"">
print "<gx:KMLDocument>
print "<gx:Figure>
print "<gx:Style id=""style1""><gx:IconStyle>
print "<gx:Icon>
print "<gx:Color>##000000</gx:Color>
print "<gx:IconSize>"m <gx:image url=""file://img/zoom.png""/>
print "<gx:IconProjection>3D</gx:IconProjection>
print "<gx:IconOffset>0,0</gx:IconOffset>
print "</gx:Icon>
print "</gx:IconStyle>
print "</gx:Style>
print "</gx:Figure>
print "</gx:KMLDocument>
print "</kml>
print "</atom:feed>"
print "\t\t<IconStyle>";
print "\t\t	<color>00000000</color>";
print "\t\t	<fill>0</fill>";
print "\t\t	<color>0000ffff</color>";
print "\t\t	<fill>0</fill>";
print "\t\t</IconStyle>";

# Lable style
print "\t\t<LabelStyle>";
print "\t\t	<color>00000000</color>";
print "\t\t	<fill>0</fill>";
print "\t\t	<color>0000ffff</color>";
print "\t\t	<fill>0</fill>";
print "\t\t</LabelStyle>";

# Line style
print "\t\t<LineStyle>";
print "\t\t	<color>00000000</color>";
print "\t\t	<fill>0</fill>";
print "\t\t	<color>0000ffff</color>";
print "\t\t	<fill>0</fill>";
print "\t\t</LineStyle>";

# Create a folder for the track information
print "\t<Folder id=42Flight Tracks42>";
print "\t\t<name>filename</name>";
print "\t\t<visibility>0</visibility>";

# Body of the script, print the track information
if($1=~x) {x=~$1; if($NR==1) {
print "\t\t\t<Placemark id=42$142">";
print "\t\t\t\t<name>$1</name>";
print "\t\t\t\t<visibility>0</visibility>";
print "\t\t\t\t<description>$1</description>";
print "\t\t\t\t<styleUrl>#style1/styleUrl</styleUrl>";
print "\t\t\t\t<gx:Track kml:id=42null42>";
print "\t\t\t\t\t<when></when>";
print "\t\t\t\t\t<gx:coord>$8","$7","$9*.3048</gx:coord>";
}} else {
print "\t\t\t</Placemark>";
print "\t\t</Placemark>";
print "\t\t<Placemark id=42$142>";
print "\t\t\t<name>$1</name>";
print "\t\t\t<visibility>0</visibility>";
print "\t\t\t<description>$1</description>";
print "\t\t\t<styleUrl>#style1/styleUrl</styleUrl>";
print "\t\t\t<gx:Track kml:id=42null42>";
print "\t\t\t\t<when></when>";
print "\t\t\t\t<gx:coord>$8","$7","$9*.3048</gx:coord>";
}}

END
print "\t\t</gx:Track>";
print "\t\t</Placemark>";
print "\t\t</Folder>";
print "\t</Document>";
print "\t</kml>

File name: function.kmlfile_2

# This function produces a kml file for track data, to be viewed on google earth
BEGIN{
FS="\t";
colorcode1=getcolor(linecolor1); # get kml color code for line color specified
colorcode2=getcolor(linecolor2); # get kml color code for line color specified
# print header
print "<?xml version="1.0" encoding="UTF-8"?>";
print "<kml xmlns="http://www.opengis.net/kml/2.2"
xmlns:gx="http://www.google.com/kml/ext/2.2"
xmlns:kml="http://www.opengis.net/kml/2.2"
xmlns:atom="http://www.w3.org/2005/Atom">

# print document name and style information
print "<Document id="42doc1"">
print "<name>Flight Tracks</name>
print "<visibility>0</visibility>
print "<open>1</open>">

# Specific line style and color
print "<Style id="42style1">
#
# Line style
print "<LineStyle>
print "<color>colorcode1</color>
print "<width>5</width>
print "</LineStyle>

# Specific line style and color
print "<Style id="42style2">
#
# Line style
print "<LineStyle>
print "<color>colorcode2</color>
print "<width>4</width>
print "</LineStyle>

# Create a folder for the track information
print "<Folder id="42Flight Tracks">
print "<name>filename</name>
print "<visibility>0</visibility>
}

# Body of the script, print the track information
if (NF==2) {if (FNR==1) {
print "<Placemark id="$1"></Placemark>
print "<Placemark id="$2"></Placemark>
print "<Placemark id="$3"></Placemark>
}


print "<Placemark id="$1" alternateId="$2"
print "<name>$2</name>
print "<visibility>0</visibility>
if ($1="STAR") {
print "<description>
print "<content>
print "</content>
print "</description>
}

print "<description>
print "<content>
print "</content>
print "</description>
if ($1="STAR") {
print "<description>
print "<content>
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print "</description>
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}
File name: function.kmlfile_3

# This function produces a kml file for track data, to be viewed on google earth

BEGIN{
FS="\"t\";

colorcode1=getcolor(linecolor1); # get kml color code for line color specified

colorcode2=getcolor(linecolor2); # get kml color code for line color specified

# print header

print "<kml xmlns="http://www.opengis.net/kml/2.2">
print "<Document id="filename"1.0/>
print "<kml xmlns="http://www.google.com/kml/ext/2.2">
print "<kml xmlns="http://www.opengis.net/kml/2.2">
print "<kml xmlns="http://www.w3.org/2005/Atom">

# print document name and style information

print "<Document id="doc1"1.0">
print "<name>"filename"</name>
print "<visibility>0</visibility>
print "<open>1</open>">

# Specific line style and color

print "<Style id="style1"1.0">

# Icon style

print "<IconStyle>">
print "<color>"colorcode1"</color>
print "<scale>0.5</scale>">

# Label style

print "<LabelStyle>">
print "<color>"fff</color>
print "<scale>0.8</scale>">

# Line style

print "<LineStyle>">
print "<color>"colorcode1"</color>
print "<scale>0.8</scale>">

# Specific line style and color

print "<Style id="style2"1.0">

# Icon style

print "<IconStyle>">
print "<color>"colorcode2"</color>
print "<scale>0.8</scale>">

# Label style

print "<LabelStyle>">
print "<color>"fff</color>
print "<scale>0.8</scale>">

# Line style

print "<LineStyle>">
print "<color>"colorcode2"</color>
print "<scale>0.8</scale>">
}
# Create a folder for the track information
print "\t<Folder id="42Flight Tracks\42">";
print "\t\t<name>"filename"</name>";
print "\t\t<visibility>0</visibility>";
}

# Body of the script, print the track information
if($1="FIX1"){
print "\t\t<Placemark id="42\$1"_"$2"\42">";
print "\t\t\t<name>"$2"</name>";
print "\t\t\t<visibility>0</visibility>";
if($1="FIX1"){
print "\t\t\t\t<styleUrl>#style1</styleUrl>" } else{print "\t\t\t\t<styleUrl>#style2</styleUrl>" } END;
print "\t\t\t<Folder>";
print "\t\t\t</Document>";
print "\t\t</Folder>";
print "\t</Document>"}

File name: function.mean
# This function computes mean for a given set of values
function mean(arr){
zzl=0; yy1=0;
for(no in arr){zz1+=arr[no]; yy1++;}
out=zz1/yy1; return out}

File name: function.mean_sd_1
# This function computes the mean and std of one variable
# input is of the format
gawk -v recno1=5 -v fields=124 -f function.mean -f function.std -f function.mean_sd_1
inputfile
# recno1 is the field for which the mean and variance is to be computed
# fields are the field number of the unique identifier over which the mean and std is to be computed
# the input file should be sorted by the fields of the unique identifier
{for(i=1;i<=length(fields);i++)
{if(i==1){fld1=$substr(fields,i,1)} else{fld1=fld1
"$substr(fields,i,1)}};
if(fld1!="fld2"){
mean_recno1=mean(arr_recno1);
std_recno1=std(mean_recno1,arr_recno1);
print fld2,count,mean_recno1,std_recno1;
 fld2=fld1;
delete arr_recno1; arr_recno1[FNR]=$recno1;count=0;count++}
else{arr_recno1[FNR]=$recno1;count++} END{
mean_recno1=mean(arr_recno1);
std_recno1=std(mean_recno1,arr_recno1);
print fld2,count,mean_recno1,std_recno1}

File name: function.min_max_mean_sd_3
function minmaxmeansd(arr1){
n=asort(arr1, arr2);
min=arr2[1];
max=arr2[n];
average=mean(arr1);
.sd=std(average,arr1);
File name: function.nonbadacoefficient
# This function gets the BADA coefficient for a non BADA actype by matching it with the BADA actype MTOW
#
if (NR==FNR){
    if($1!="#") {actype[FNR]=$1; MTOW[FNR]=$19; enginetype[FNR]=$20; record[FNR]=$0} else if($1!="#"){
        FNR=-1; delete arr1; delete arr2;
    # Compute the weight difference between the unknown actype and BADA actypes
    for(i=1;i<=length(actype);i++){
        if($3==enginetype[i]){
            arr1[abs(MTOW[i]-$2)]=abs(MTOW[i]-$2);
            arr2[abs(MTOW[i]-$2)]=actype[i]}
        else
            yy="do nothing"};
    # assign the aircraft with the smallest difference in MTOW
    if(length(arr1)>0){
        asort(arr1);
        # substitute actype
        subtype=arr2[arr1[1]];
        print record[subtype],$1;
    }}}
}

File name: function.opserrwy
# This function compute ops per runway for a given day, for given timebins
if (NR==FNR){
time1[FNR]=$1;
time2[FNR]=$2;
bin1[FNR]=$3;
bin2[FNR]=$4;
i=1;
count=0;
} else{
    if($2>bin1[i] && $2<bin2[i]){
        count++;
    if($NF!="NA") {arr[$NF]++};
    } else if(count>0 && i<=length(time1){
        printf "%s %s ", time1[i],count;
        for(no in arr){printf "%s(%s)", no,arr[no]);
        printf "\n";
        i++; count=0; count++; delete arr;
    if($NF!="NA") {arr[$NF]++};
    } END{ if(count>0 && i<=length(time1){
        printf "%s", count;
        for(no in arr){printf "%s(%s)", no,arr[no]);
        printf "\n";
    }}}
}

File name: function.pointinrectangle
# This function check if a point is within a rectangle
BEGIN{
    # Get the center of the reactangle as reference
    alat=(lat1+lat2+lat3+lat4)/4;
    alon=(lon1+lon2+lon3+lon4)/4;
    # Convert all the four vertices coordinated to cartersian
}
# vertex 1
getcar(alat,alon,lat1,lon1,scale)
xx1=x1;
yy1=y1;

# vertex 2
getcar(alat,alon,lat2,lon2,scale)
xx2=x1;
yy2=y1;

# vertex 3
getcar(alat,alon,lat3,lon3,scale)
xx3=x1;
yy3=y1;

# vertex 4
getcar(alat,alon,lat4,lon4,scale)
xx4=x1;
yy4=y1;
}

# Convert the track hit to ccartesian point
getcar(alat,alon,$7,$8,scale);
px1=x1;
py1=y1;

# Check if the point if within the rectangle
xa=xx1; ya=yy1; xb=xx2; yb=yy2; x0=px1; y0=py1;
check1=((xb-xa)*(ya-y0)-(xa-x0)*(yb-ya));

xa=xx2; ya=yy2; xb=xx3; yb=yy3; x0=px1; y0=py1;
check2=((xb-xa)*(ya-y0)-(xa-x0)*(yb-ya));

xa=xx3; ya=yy3; xb=xx4; yb=yy4; x0=px1; y0=py1;
check3=((xb-xa)*(ya-y0)-(xa-x0)*(yb-ya));

xa=xx4; ya=yy4; xb=xx1; yb=yy1; x0=px1; y0=py1;
check4=((xb-xa)*(ya-y0)-(xa-x0)*(yb-ya));

if(check1>0 && check2>0 && check3>0 && check4>0){print $0,fix}

File name: function.radian
# This function converts degrees to radian
function radian(value){return value*.0174532925}

File name: function.reflectrotate
# This function reflect and rotate tracks
#
# convert to cartesian
# track points
getcar(alat,alon,$7,$8,scale);
track_x=x1;
track_y=y1;

# runway coordinates
getcar(alat,alon,rwylat1,rwylon1,scale);
rwy_x1=x1;
rwy_y1=y1;
getcar(alat,alon,rwylat2,rwylon2,scale);
rwy_x2=x1;
rwy_y2=y1;

# get angle to rotate
angle_rotate=(baserwy*10)-(newrwy*10);
theta=radian(angle_rotate);
# reflect the co-ordinate with respect to the runway
if (reflect==1)
{
# get the line vector (runway vector)
l_x=rwy_x1-rwy_x2;
l_y=rwy_y1-rwy_y2;
# do the dot products
ldotl=l_x*l_x+l_y*l_y;
vdotl=track_x*l_x+track_y*l_y;
scalar=2*(vdotl/ldotl);
l_x2=scalar*l_x;
l_y2=scalar*l_y;
track_x2=track_x2-track_x;
track_y2=track_y2-track_y;
}
else
{
track_x2=track_x2;
track_y2=track_y2;
}
# rotate the co-ordinate with respect to the center of the airport
if (rotate==1)
{
track_x3=track_x2*cos(theta)-track_y2*sin(theta);
track_y3=track_x2*sin(theta)+track_y2*cos(theta);
}
else
{
track_x3=track_x2;
track_y3=track_y2;
}
# convert back to lat lon
getlatlon(alat,alon,track_x3,track_y3,scale);
# print results
$7=lat2x;
$8=lon2x;
}

File name: function.statsFld
# This function computes stats for a given field
if ($field1!="NA" && $field2!="" && $field1>0 && $25!="GA")
{
level1[$FNR]="$field1";
if ($field2!="NA" && $field2!="" && $field2>0 && $25!="GA")
{
level2[$FNR]="$field2";
if ($field3!="NA" && $field3!="" && $field3>0 && $25!="GA")
{
level3[$FNR]="$field3";
}
}
print field1,n,min,max,average,sd;
print field2,n,min,max,average,sd;
print field3,n,min,max,average,sd;
}

File name: function.std
# This function computes the standard deviation for a given set of values
function std(mean, arr)
{
zz2=0;
xx2=0;
yy2=0;
for (no in arr)
{
xx2+=arr[no]-mean)^2;
zz2+=xx2;
}
if (yy2==1) out=0
else out=sqrt(zz2/(yy2-1));
return out}
A5. List of Output Files

The code outputs .kml file for visualization purpose. These can directly be opened in google earth. In addition of the kml file the code generates the following files for further analysis.

File name: NOP_trackmile_stats
This file contains the track mile (NM) statistics for the various flow at MDW.

File name: NOP_tracktime_stats
Same as above. but contains the track time (min) statistics

File name: NOP_fuelburn_stats
Same as above. but contains the fuel burn (kg) statistics for all aircraft type at MDW

File name: NOP_fuelburn_B737s_stats
Same as above. but contains the fuel burn (kg) statistics for B73’s aircraft type at MDW

File name: MDW_all_flows_mean_fb
Contains fuel burn stats for current and hypothesized flows at MDW.
File name: temp_flight_count_fb_by_year2
This file contains total fuel burn statistics at MDW for all aircraft; shown in table 27

File name: temp_flight_count_fb_by_year2_swa
This file contains total fuel burn statistics at MDW for all Southwest Airlines; shown in table 27

File name: temp_ORD_MCC_stats
This file contains delay statistics shown in table 12.

File name: temp_ORD_nonMCC_stats
This file contains delay statistics shown in table 13.

File name: MDW_13C_holding_stats
This file contains holding stats for MDW arrivals to 13C.

<table>
<thead>
<tr>
<th>actype_count</th>
<th>mean_hitime</th>
<th>sd_hitime</th>
<th>mean_hdis</th>
<th>sd_hdis</th>
<th>mean_hfb</th>
<th>sd_hfb</th>
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</thead>
<tbody>
<tr>
<td>all</td>
<td>83</td>
<td>18.3725</td>
<td>9.08</td>
<td>79.7546</td>
<td>38.6666</td>
<td>346.27</td>
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<td>B73</td>
<td>42</td>
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REFERENCES


Aviation Today. (2012b). JetBlue to Fly RNP AR Approaches into JFK.


FAA. (2012i, August). The Business Case of Next Generation Air Transportation System.


U.S. Department of Commerce. (2012). GDP by Metropolitan Area. Retrieved from http://www.bea.gov/iTable/drrldown.cfm?reqid=70&stepnum=11&AreaTypeKeyGdp=5&GeoFipsGdp=XX&ClassKeyGdp=naics&ComponentKey=200&IndustryKey=1&YearGdp=2012&YearGdpBegin=-1&YearGdpEnd=-1&UnitOfMeasureKeyGdp=Levels&RankKeyGdp=1&Drill=1&nRange=5


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