NASA/CR—2011-217302

A Concept for Flexible Operations and Optimized Traffic into Metroplex Regions

Daniel DeLaurentis, Steve Landry, and Dengfeng Sun
Purdue University, West Lafayette, Indiana

Fred Wieland and Ankit Tyagi
Intelligent Automation, Inc., Rockville, Maryland

December 2011

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Report Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers, but having less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include creating custom thesauri, building customized databases, and organizing and publishing research results.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at *http://www.sti.nasa.gov*

- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA STI Help Desk at 443-757-5803

- Phone the NASA STI Help Desk at 443-757-5802

- Write to:
  NASA STI Help Desk
  NASA Center for AeroSpace Information
  7115 Standard Drive
  Hanover, MD 21076-1320

NASA/CR—2011-217302

A Concept for Flexible Operations and Optimized Traffic into Metroplex Regions

Daniel DeLaurentis, Steve Landry, and Dengfeng Sun
Purdue University, West Lafayette, Indiana

Fred Wieland and Ankit Tyagi
Intelligent Automation, Inc., Rockville, Maryland

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

Prepared for Langley Research Center
under Contract NNL10AA15C

December 2011

Acknowledgments

The authors acknowledge, first and foremost, the sponsorship of this research by the National Aeronautics and Space Administration under contract NNL10AA15C. In particular, the input and coordination of project Technical Monitor, Michael Sorokach, and Metroplex Lead Scientist, Rosa Oseguera-Lohr (both from the NASA Langley Research Center) were of tremendous value to our research team. Finally, the authors acknowledge the significant efforts of the dedicated team of graduate students at Purdue University without whom much of the progress reported in this document would not have been possible: Seung Yeob (Simon) Han, Yiwu Jian, Taehoon Kim, Vishnu Vinay, and Peng Wei. We sincerely thank them all and hope their education was enhanced by this project experience.

Available from:

NASA Center for AeroSpace Information
7115 Standard Drive
Hanover, MD 21076-1320
443-757-5802

Table of Contents

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

AAR	Airport Arrival Rate
ACES	Airspace Concepts Evaluation System
AOC	Airline Operational Control
ARB	Airport Runway Balancer
ARTCC	Air Route Traffic Control Center
ASDI	Aircraft Situation Display to Industry
ASPM	Aviation System Performance Metrics
AT	Air Taxi
ATC	Air Traffic Control
ATCSCC	Air Traffic Control System Command Center
ATM	Air Traffic Management
BGL	Boost C++ Graph Library
BTS	Bureau of Transportation Statistics
CCC	Capacity Coverage Chart
CNS	Communication, Navigation and Surveillance
DOT	Department of Transportation
ERAM	En Route Automation Modernization
ETA	Estimated Time of Arrival
FAA	Federal Aviation Administration
FACET	Future ATM Concepts Evaluation Tool
FAR	Federal Aviation Rules
FAST	Final Approach Spacing Tool
FFS	Flexible Flight Selection
GA	General Aviation
JPDO	Joint Planning and Development Office
KTG	Kinematic Trajectory Generator
LTV	Linear Time-Varying
McTMA	Multicenter Traffic Management Advisor
NAS	National Airspace System
OEP	Operational Evolution Partnership
PAX	Passengers
PDARS	Performance Data Analysis and Reporting System
RTA	Required Time of Arrival
SCT	Southern California Tracon
TFM	Traffic Flow Management
TTI	Travel Time Index

1. Introduction

1.1. Context: Delays at Metroplexes

In commercial air transportation, system inefficiencies occur when air traffic demand exceeds system capacity. The resulting flight delays increase direct operating costs for airlines, air traffic controllers' workload, and passengers' missed connections and dissatisfaction. Moreover, the demand for air travel is expected to increase significantly in the future. The Federal Aviation Administration (FAA) estimated in 2007 that the number of passengers is projected to increase by an average of 3.0 percent every year until 2025 (1). Much of the increase in passenger demand will be in metropolitan areas usually served by two or more large airports. The Joint Planning and Development Office (JPDO) defines this type of region, with a group of two or more nearby airports whose arrival and departure operations are highly interdependent, as a metroplex. The New York Metroplex (N90 TRACON), for example, consists of John F. Kennedy (JFK) airport, LaGuardia (LGA) airport, and Newark (EWR) airport, all within driving distance to each other, as well as several smaller airports. Other examples of metroplexes include Chicago (C90 TRACON, which includes O'Hare and Midway airports) and Southern California (SCT TRACON, which includes Los Angeles, Long Beach, Orange County, and Van Nuys airports). The traffic to and from most metroplexes has increased significantly over the years. Studies reveal that N90 is reaching its maximum capacity under current operational rules. Therefore, increasing the capacities of N90 airports may be required to satisfy the growing traffic rate.(3). Because operations at these airports are inter-dependent, the predicted increase in demand placed on already-constrained operations has the potential to push flight delays to unacceptable levels, which can lead to a greater number of cancellations. Further, the impact of these delays is felt beyond individual flights or airports due to the propagation downstream to subsequent flight schedules. Addressing delays that are particular to metroplex airspace regions can also propagate the benefits to other airports. One method of reducing delays in a metroplex is through better coordination of runway usage among the airports within a metroplex. Better coordination can balance traffic load among metroplex airports, potentially reducing the delays by allowing some flights to use runways with lower demand levels (again, with additional benefits system-wide).

There are two trends in aviation that, if not properly managed, can exacerbate delay management challenges. The first trend is well known: increasing traffic to and from popular metroplexes. The canonical example is the New York TRACON (N90). Many new concepts and approaches have been proposed to resolve this increase, most of them focusing on the increase of throughput (or decrease in delays) at or around metroplex airports. Other concepts for increasing the passenger and aircraft throughput are to add more metroplex capacity by using larger aircraft and/or build more runways. Yet another concept focuses on increasing throughput efficiency through reduction in dependencies between metroplex airports by “Rational” scheduling (e.g. smart scheduling) and airspace/procedure redesign. Increasing flexibility through efficient use of resources to exploit dependencies is another way to increase throughput. One example of this is metroplex runway management. Since a metroplex consists of two or more adjacent airports with interdependent arrival and departure operations, the coordination of metroplex airport runways can increase throughput at these airports.

The second trend is that of passengers preferring the lowest-fare flight, enabled by the ubiquitous use of internet price-searching. Passengers will often drive to a distant airport if the airfare is low enough to justify the travel. Simultaneously, airlines are motivated to utilize low-throughput airports to increase operational predictability, reduce costs, and therefore offer the lowest price possible. While this second trend might seem desirable—airlines are profitably employing underutilized resources—realizing it complicates metroplex traffic management. As flight densities increase, the potential for conflicts also increases.

One way to effectively manage these trends is to recognize that they exist and develop a concept for incorporating them into the airspace system. In other words, if passengers are willing to travel to/from alternate airports in a metroplex, then they might be motivated to travel on a flight where the destination airport can be any airport in a metroplex. This business idea may appear to be infeasible, but with appropriate pricing policies and service levels, it can be an attractive option for price-sensitive passengers.

1.2. Concept Summary and Objectives of the Study

Whether or not the underlying business model is sustainable, the idea does spawn a unique and hitherto unstudied operational concept. We call the this the "***flexible operations concept***". The underlying principle of this concept is the sharing of metroplex resources, in particular, the runways. Figure 1 illustrates this with graphs of flights bound to the three major N90 airports on November 7th in 2008. The white horizontal line represents the airport arrival rate (AAR) at the airport, and the Y axis represents the number of flights bound to N90. Traffic is congested at EWR between 1700 and 1800, but JFK and LGA have available slots for landing during the same period. If it is possible to share the available runways at the metroplex, delays might be mitigated considerably.

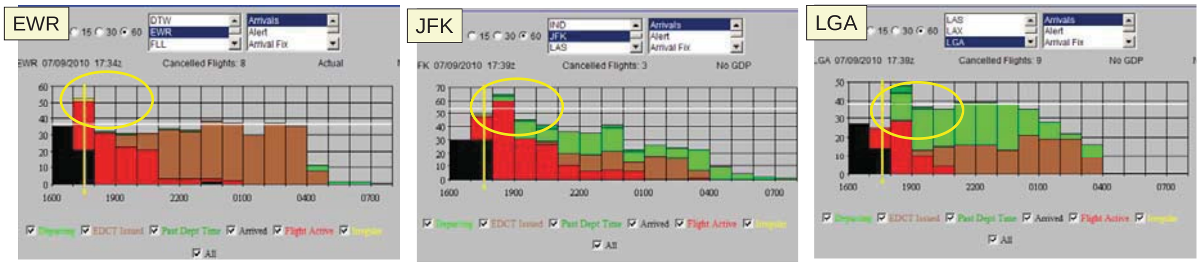


Figure 1: Example snapshot of flights and runway usage at three N90 airports

Under the flexible operations concept, airlines (and General Aviation, GA, operators) have the option of filing two different types of flight plans when their destination airport is at a crowded metroplex (such as N90, SCT, NorCal, or C90 TRACONs). Airlines may file a flight plan listing a particular destination airport in the metroplex, as they do today, or they would also have the option of filing a flexible flight plan, which lists the departure airport and the proposed departure time, as well as a route of flight to a decision boundary outside the destination metroplex. The destination airport is labeled as the metroplex identifier (e.g. N90), with no specific airport listed. The Air Traffic Management (ATM) system determines the destination airport and runway as the flight reaches a decision horizon outside its destination metroplex.

Figure 2 represents a comparison of the hourly maximum capacity between theoretical, observed, and new concepts at N90. Theoretical maximum capacity is the sum of the maximum decoupled capacities of all N90 airports. Observed maximum capacity is the recorded maximum hourly capacity at N90 in 2009. Note that the box shows the runway configurations employed when maximum capacity was observed. There is about a 15% difference between the theoretical maximum hourly capacity and observed maximum hourly capacity at N90. Clarke et al. (5) reported potential for 79% reduction in delay minutes through scheduling with redesigned metroplex airspace (annotated as "GT MP Report" in Figure 2). It is expected that this delay reduction may allow N90's hourly capacity to be higher than observed maximum capacity but lower than the theoretical one. The primary motivation for the flexible operations concept is to reduce the gap between the theoretical and realized maximum capacity. Thus, the operational value of the proposed concept would likely be realized in the far-term. From a purely abstract position, this concept can allow the ATM to maximize metroplex airport throughput, increase its resiliency to disruptions, allow maximum flexibility for users, and degrade gracefully under adverse conditions. Thus, the concept can be advantageous for the airlines, the FAA, and passengers.

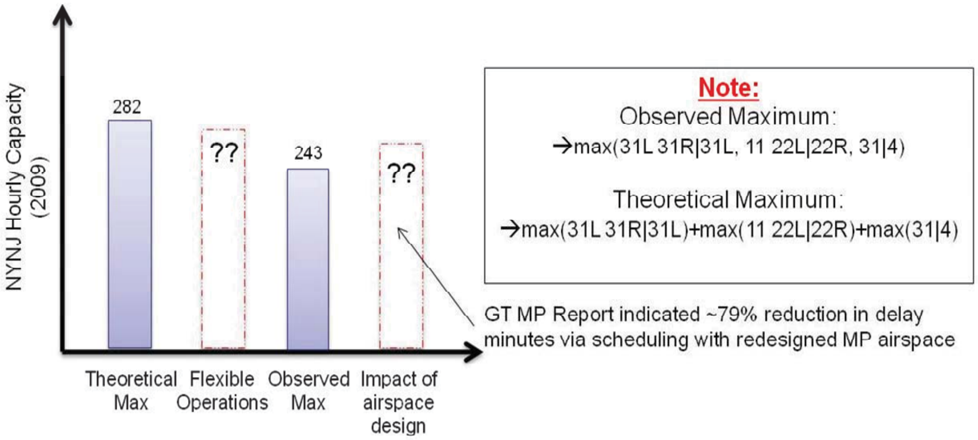


Figure 2: Comparison of New York-New Jersey Metroplex (N90) hourly maximum capacity between theoretical, observed, and new concepts. [Theoretical and observed maximums derived from Aviation System Performance Metrics (ASPM) data].

However, there are many unknown issues, including: Is the concept feasible? Can the airspace system handle a mixed set of traditional and flexible flight plans? What percentage of flights must file "metroplex only" flight plans for the system to exhibit increased efficiency, resiliency and robustness? What type of ground infrastructure must exist to handle connecting passengers, baggage transfers and airframe dislocation? At what point does this concept break down, if at all, and what elements contribute to this failure? Excluding issues relating to baggage transfer and airframe dislocation, all of these questions are addressed in detail in the following sections. The ultimate ***concept objective*** is to significantly enhance throughput at the key metroplexes in the NAS in a manner that does not require extensive (or expensive) infrastructure investment. As a first step in answering these myriad of questions, the overall ***study objective*** was to develop an upper bound on the possible delay reduction achieved through use of the concept, cognizant that later studies must incorporate more of the practical constraints and reassess the benefits.

2. Flexible Operations Concept

2.1. Operator CONOPs

This section presents a narrative of how the overall concept would work from the airline operator's perspective and also from the passenger's perspective. Currently, a flight departing from a departure location is scheduled to a fixed arrival airport. Once the flexible operations concept is introduced a flight can be scheduled to a metroplex instead of an airport, i.e. a flight can arrive at any of the airports that comprise a metroplex. The new concept allows for two types of flight plans, one in which the destination is fixed, as done today, and another in which the destination is labeled as a metroplex (exemplified in Figure 3). Therefore, the concept will have both *"airport-bound flights"* and *"metroplex-bound flights"*.

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
(FAA US
FLIGHT PLAN
1. TYPE ☐ VFR ☑ IFR ☐ DVFR
2. AIRCRAFT IDENTIFICATION: UAS 1234
3. AIRCRAFT TYPE SPECIAL EQUIPM: B737/G
8. ROUTE OF FLIGHT: LAX.RUSTT.PGS.TBC.RSK.PUB.HLC.P
9. DESTINATION (Name of airport and city): John F. Kennedy (New York) JFK
10. EST. TIME EN: HOURS 04 MI 52
12. FUEL ON BOARD: HOURS 05 MINUTES 30
13. ALTERNATE AIRPORT(S): EWR

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
(FAA USE ONLY)
FLIGHT PLAN
1. TYPE ☐ VFR ☑ IFR ☐ DVFR
2. AIRCRAFT IDENTIFICATION: UAS 1234
3. AIRCRAFT TYPE / SPECIAL EQUIPMENT: B737/G
4. TRUE AIRS: 450
8. ROUTE OF FLIGHT: LAX.RUSTT.PGS.TBC.RSK.PUB.HLC.PWE.LMN.B
9. DESTINATION (Name of airport and city): New York Metroplex (N90)
10. EST. TIME ENROUTE: HOURS 04 MINUTES 52
11.
12. FUEL ON BOARD: HOURS 05 MINUTES 30
13. ALTERNATE AIRPORT(S): EWR
14. F: J.

Figure 3: On left: Flight plan with fixed destination airport, as done today; On right: Flight plan with metroplex destination

In the flexible operations concept, the exact destination airport and runway assignment of the flight will be made at a decision horizon outside the airport. Until the aircraft reaches that decision horizon, neither the operator nor the ATC system knows the exact destination airport.

2.2. Potential Passenger CONOPs

From the passenger's perspective, for the new concept to work, a very reliable ground transportation link must exist between all the airports in a metroplex as well as from airport to key points of interest in the local area. In addition to easy access to ground transport, the passenger must also not have to lose time and money by choosing a metroplex-bound flight over a traditional flight. The following vignette presents a potential use-case scenario of the new concept based on how a passenger purchases tickets from an internet travel website such as *Expedia*.

Internet travel websites are the main source of information on flights (and other travel related services) for most airline travelers in the US. Planning includes options such as flight+car, flight+hotel, flight+car+hotel and so on. In order for the flexible operations concept to be practical, a passenger must be able to conveniently reach his or her final destination from any of the constituent airports in the metroplex. In addition, availability of information on the time and money saved by choosing a metroplex-bound flight will potentially lead to a larger number of metroplex travelers choosing metroplex-bound flights over traditional flights. Figure 4 presents the current *Expedia* (6) interface in which the destination airport is fixed (JFK in this case), which is the common practice today.


○ Flight
○ Hotel
○ Car
○ Cruise
○ Activities
○ Flight + Hotel
● Flight + Car
○ Flight + Hotel + Car
○ Hotel + Car

☐ My dates are flexible (popular US routes only)

Leaving from: Indianapolis, IN (IND-Indianapolis Intl.)
Going to: JFK
Departing: 9/8/2010
Time: Anytime
Returning: 9/15/2010
Time: Anytime
Car type: No Preference
Adults (19-64): 1
Seniors (65+): 0
Children (0-18): 0

Figure 4: Snapshot of current Expedia® interface (© Expedia, Inc.) with destination listed as an airport

Some travel websites allow travelers to search for tickets to a particular city instead of an airport, whereby they allow them to search for more convenient prices and times. The websites also provide travelers with information on car rental facilities at the airport allowing for advance reservations through the website as well. Under a flexible operations concept, the travel websites could adopt a similar approach but with a more extensive listing of not only flight departure/arrival time and ticket fare but also ground transportation links. These links, as mentioned above, should include airport to airport as well as airport to popular locations within the destination city. Figure 5 shows how *Expedia* might appear if the flexible operations concept is in place; note that travelers now have the option to choose metroplex-bound flights.


○ Flight
○ Hotel
○ Car
○ Cruise
○ Activities
○ Flight + Hotel
○ Metroplex
○ Flight + Hotel + Car
○ Hotel + Car
● Metroplex + Ground Transportation

☐ My dates are flexible (popular US routes only)

Leaving from: Indianapolis, IN (IND-Indianapolis Intl.)
Going to: ○ Airport ● Metroplex
N90 (New York Metroplex)
Departing: 9/8/2010
Time: Anytime
Returning: 9/15/2010
Time: Anytime
Car type: No Preference
Adults (19-64): 1
Seniors (65+): 0
Children (0-18): 0

Figure 5: Altered interface with metroplex-bound option included

If "Metroplex" option is chosen, the traveler would be presented with flights that the airlines plan to operate as "metroplex bound". In considering their choices, travelers would have information to compare available ground transport links in terms of mode, timings and price. Above all, travelers must also be able to compare prices of metroplex-bound flights to traditional, fixed airport flights so that they can be aware of the economic advantages or disadvantages associated with such flights. Such information must be supplied to a traveler in advance in order to persuade him or her to buy a metroplex-bound flight.

3. Potential Benefits and Barriers of Flexible Operations Concept

3.1. Potential Benefits

The concept of flexible flights into a metroplex has two main advantages. First, it allows the air traffic control system to maximize resource utilization (runways, in this case) in an otherwise tightly constrained system. Second, it allows users to experience less delay when accessing crowded metroplex airports. We expect that the early adopters of this type of flight plan will be on-demand and general aviation users, and that the hub-and-spoke commercial air carriers will follow only if a clear benefit is very likely. In this sub-section, we review the major advantages from the perspective of all stakeholders: the FAA, the air taxi community, the general aviation community, the traditional commercial airline operators, and passengers.

<u>FAA perspective:</u> From the point of view of an air navigation service provider (ANSP), such as the FAA, metroplex-bound flights allow maximum flexibility in the planning and use of runways at a metroplex, especially considering the dynamic conditions that affect airport configuration and capacity (e.g., changing winds, changing visibility, stochastic demand realization). The realized metroplex capacity can thereby be increased without adding any additional runways.

There is a second, albeit indirect, benefit of the flexible operations concept for the ANSP. If metroplex-bound flight plans were to be supported in some future version of the NAS, then the flight planning system (e.g., En Route Automation Modernization (ERAM) and its supporting subsystems) must be programmed to determine the best available allocation of a flight when it reaches the decision horizon. In doing so, the system will consider a number of variables and assign the flight to the best available resource. The indirect benefit follows from the introduction of this capability into the planning environment. In the case of an emergency—perhaps an airport is completely closed due to weather, an accident or some other disruption—the airborne flights affected by the closed airport (or other emergency) will already be in the planning system; the system will be prepared to determine what course of action to take with these flights, alleviating this part of the workload from controllers. The airborne flights at the time of the disruption would be marked by controllers as “metroplex-bound” flights. The affected airport would be eliminated from consideration, and the planning system would then begin to assign these flights to the most efficient available runway, even considering other traffic already bound to the open airports.

<u>Air-taxi (on-demand operators) perspective:</u> There are some advantages that are bestowed upon the air-taxi community with this concept. Currently, air-taxi operators fly between one and six people between local airports and sometimes one of the airports lie within a metroplex. A typical air taxi flight might consist of three lawyers who have to travel to the state capital for a brief. Travel using air taxi allows them to complete the entire trip within one day, a considerable savings of time if they live far away from the capital. In such a scenario (and many similar ones in the air taxi community), the exact airport that the passengers arrive at the state capital is of less concern to them than that they are on time. If the state capital happens to be in a metroplex, then metroplex-bound flight plans would be an ideal option for the air taxi operator.

In discussions with air taxi operators, we discovered that the concept of dynamically changing the destination airport can be done even with today’s system, although the mechanism is inefficient. While airborne, an operator can re-file a flight plan and list a destination different than the original flight plan. This technique is useful if excessive traffic or weather causes the originally filed destination airport to be less attractive than a nearby airport. One air taxi operation in Florida would occasionally use this technique on their flights to the Miami area.

General aviation perspective: The general aviation community frequently flies into smaller airports and avoids the major congested airports. Nevertheless, when flying into a popular destination such as the New York metroplex, a general aviation operator would often rather be routed to the most efficient destination, as opposed to a filed, fixed destination which might be congested at the proposed landing time. In this model, it is assumed that the general aviation operator is flying from his/her home base to another location. If instead he or she is returning to the aircraft's home base (where it is hangared and serviced), then an airport-bound flight plan would have to be filed.

Commercial air carrier perspective: Advantages to the traditional commercial air carriers are more difficult to discern; while they would benefit from overall reduced delays at metroplex airports, their particular constraints could complicate use of flexible operations. Commercial carriers have fixed gates, ground crews at predetermined locations, ticket agents and baggage handlers only at certain airports. Thus their operations are set up to exploit the current airport-bound flight plans. For commercial carriers to effectively use a metroplex-bound flight plan, the business model would have to be rethought. If a commercial carrier has operations (i.e. gates, gate agents, baggage handlers, ticket counters) at all three major airports in N90 (JFK, EWR, and LGA), it can, in theory, file a metroplex-bound flight plan, and allow the system to route the flights to the most efficient destination. However, the system's definition of "most efficient" may not take into account whether there is gate availability for the commercial carrier at the assigned destination. For example, if too many metroplex-bound commercial flights for this (hypothetical) carrier are routed to the same airport, the carrier may use up its available gates quickly and be faced with other problems.

The flexible operations concept does, however, generate ideas for new business models. Imagine a future in which the gates, gate agents, and ticket sales were all decoupled from the airlines. That is, airline XYZ no longer had its own ground crew; instead, it relied upon a common set of ground crew and resources available at the airport. This type of pooling of ground resources has, all by itself, advantages and disadvantages. The advantages are economies of scale: by pooling ground resources, duplication is avoided and the efficiencies that are gained with uniform procedures and equipment can be exploited. The disadvantages are from a marketing perspective: airlines would no longer be able to differentiate themselves by offering superior ground service.

These considerations aside, if ground services were a pooled resource that could be shared by multiple airlines, then problems of ground and even gate availability are eliminated from consideration. All that is left is repositioning of flights and getting passengers to/from their final destination. The latter problem—getting passengers to/from their ultimate destination—is not even a problem the airlines solve today. Rather, the passengers are dependent upon local ground transportation. The former problem—repositioning airframes and crews—can be alleviated by offering "metroplex-bound" departures, wherein an airline promises passengers a seat on an aircraft, but tells the passenger from what airport he/she will be departing a few hours before the flight—enough time in advance for the individual to plan the ground transportation to the airport. The communication of the specific departure airport can be accomplished with contemporary media—text messages on a cell phone, an email, posting on a web site, or a phone call. Thus a possible future business model for a commercial carrier to exploit this idea would consist of ground crews which are a pooled resource, combined with flights that are metroplex-bound both on the arriving and departing end. Although this business model is a possibility, further analysis of this possibility is beyond the scope of this project.

3.2. Potential Barriers

The main barrier of the flexible operations concept is the uncertainty that it adds to user operations. If a user does not know exactly where the aircraft will land, planning may be problematic. Sufficient fuel must be loaded on to the aircraft to reach the furthest airport in the metroplex plus the required reserves, which itself depends upon whether the destination airport is operating under visual or instrument conditions at the projected time of arrival. For example, some of the airports in a metroplex might be forecasted as having visual conditions at the expected arrival time, but others might be forecasted as having instrument conditions. This consideration alone would require rulemaking to clarify what the fuel requirements are for metroplex-bound flights. For example, the rule might be that the carrier must use the airport for which the forecast is the worst when planning fuel loading, and must plan a trip length that would reach the farthest airport in the metroplex from the originating airport.

The uncertainty in planning affects all user groups. The service provider (i.e. FAA) will no longer have an accurate forecast of demand at each airport; instead, it would be an accurate forecast for each metroplex. In addition, the service provider is faced with the challenge of developing and building an algorithm that can effectively exploit the apparent efficiencies of metroplex-bound flights (i.e. build a scheduling algorithm that efficiently assigns metroplex-bound flights to destinations). For commercial airlines, the challenge starts with the problem of repositioning flights for departures. The airline may have to reposition crew, passengers, baggage, and even the airframes themselves. There have been many studies to date on recovering airline operations after a disruption. One of the techniques is to have frequent flights to popular destinations, so there are more choices for passengers; this method of operation allows the airlines to rapidly recover from a disruption. As will be discussed later, this and other considerations led us to conclude that short-haul “shuttle” flights with few connecting passengers are likely to be the most attractive choices for airlines for metroplex-bound tickets—although even those flights produce operational challenges.

All these challenges stem from the basic problem of additional uncertainty that is added to the operations. For passengers, the problem is (and has always been) traveling to the final destination. In the case of non-connecting passengers, the airport itself is not the final destination. He/she must rely on personal car, taxi, or public transport. In addition, if the passenger is connecting to another outbound flight that happens to be at a different airport, then additional time must be built into the passenger’s schedule to account for the inter-airport transportation that is required.

4. Technical Approach

4.1. Model Overview

An integrated simulation model was developed to validate the capabilities of a new concept in the U.S. National Airspace System (NAS). The model, in general, was developed to solve two classes of problems: a NAS-wide flight route optimization problem and a time-based metering/scheduling problem for en-route air traffic control associated with a group of adjacent sectors. As such, the model can analyze the flexible operations concept in metroplex regions. The model can estimate the impact of the new concept on system performance, not only at a single metroplex, but also at multiple metroplexes. The system-performance measure obtained from the integrated simulation model is total delay.

The integrated simulation model is comprised of five principal components (Figure 6). The model uses a variety of data to generate statistical distributions for the selection of flexible flights as a concept design variable and to describe the airport and airspace route network. The five principal components in the model are described next.

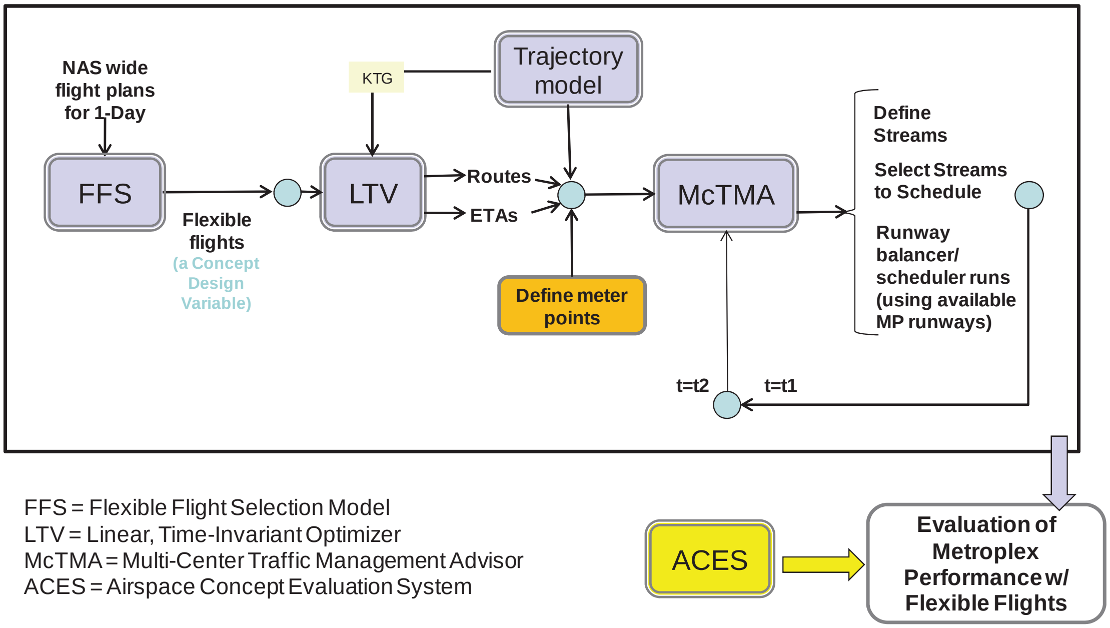


Figure 6: Overview of the integrated simulation model

1) Flexible Flight Selection (FFS) model: The FFS generates a flight data set (daily schedule) that is modified to include those flights designated as flexible flights. In detail, the model is employed to select flexible flights among NAS-wide flights based on the number of connecting passengers. Historical data of the number of connecting passengers are used to compute the probability of desirable flexible flights.
2) Linear Time-Varying (LTV) Optimizer model: LTV Optimizer model, originally developed by NASA Ames researchers, takes the flight data set as input and produces optimal routes for all flights to destinations, including estimated time of arrivals (ETAs) to key points. LTV solves a large integer programming optimization problem for this purpose
3) Kinematic Trajectory Generator (KTG): KTG is a product developed by IAI. Its main purpose is to provide high-resolution trajectory computations from the departure airport runway to the arrival airport runway.
4) Multicenter Traffic Management Advisor (McTMA) model: The McTMA extends TMA, a time-based metering tool for en-route air traffic control and management, for both in- and out-bound time-based metering within multiple centers. In addition, the model is used to schedule flights to runways for the optimized routes computed by LTV Optimizer model.
5) Airspace Concepts Evaluation System (ACES): ACES is a physics-based, fast-time simulation of the nationwide air traffic system, including air traffic management (ATM), flight, and airline operational control (AOC) functions. ACES is employed to test McTMA and optimal scheduling algorithms and compute NAS-wide impacts of the flexible metroplex operations concept.

4.2. Flexible Flights Selection (FFS)

4.2.1. Overview of FFS Model

The first step in the modeling of flexible flights concept is to select flexible flights as a concept design variable. The FFS model computes the probability of desirable flexible flights based on criteria described below. Once the FFS model determines flexible flights from a NAS-wide flight plan available for a day, it provides an output file, including both flexible flights and normal flights, to the LTV Optimizer model.

4.2.2. Criteria for Flexible Operations

In order to determine flexible flights, interests of airline operators and passengers are considered. Airline operators are interested in maximizing profit and minimizing crew and fleet disruptions. However, passengers usually consider price, connection quality or need for connection and predictability of arrival time to select a flight and operator. In the case of flexible operations, interests of these stakeholders remain the same. For example, operators decide what flights and routes are used for flexible operations based on decision criteria such as maximizing profit and minimizing crew and fleet disruptions. Passengers can decide whether they use a flexible flight or a normal flight based on price and connection qualities. The list of flexible operations criteria for both operators and passengers is described in Table 1.

Table 1: Criteria (by stakeholder) relevant for Flexible Operations Concept

Stakeholder			Criteria for Flexible Operations
Commercial Operator	Scheduled Operator	Hub-to-Spoke	- Minimize fleet disruption (Depends on heterogeneity of fleet mix) - Minimize crew disruption - Maximize profit
		In-between Hub-to-Spoke and Spoke-to-Spoke	- Minimize crew disruption - Maximize profit
		New Business Model (Only point-to-point service)	- Minimize crew & fleet disruption - Maximize profit
	Non-Scheduled Operator	Business/Factional/Charter	- Minimize operating costs - Maximize profit
Passenger			- Minimize price - Connection quality or need for connection - Improve predictability of arrival time

A hypothesized governing equation merging criteria for flexible operations consists of several components, including connecting passenger models, crew/fleet disruption models, etc (Table 1). Aircraft types (for those service providers with heterogeneous fleets) can also impact crew and fleet disruption levels. If airlines were to adopt the flexible operations concept, they have to reschedule their flight plans to optimize profits and to reduce disruption level using their own tools for crew coordination and operations management. Due to the lack of sufficient sources to analyze disruption level, it is difficult to develop probabilistic models for crew and fleet disruption in the FFS. Therefore, in the study described in this report, the only design variable in the flexible flight concept model is *the criterion of connecting passengers – the minimum number of passengers above which a flight will be deemed unqualified for flexible operations*.

4.2.3. Data Sources

Two databases maintained by the U.S. Bureau of Transportation Statistics (BTS) are used:
1) The T-100 Domestic segment (All US Carriers) database contains data on a monthly basis, including aircraft type, service class, seats and aircraft hours: ramp-to-ramp and airborne. Key values which are used for the analysis are flight date, departure/arrival airports, number of passengers on board, number of

flights, and airline information.

2) Airline Origin and Destination Survey (DB1B) database is a 10% sample of airline tickets from reporting carriers. Data includes origin, destination and other itinerary details of passengers transported. Also, data is provided on a quarterly basis.

4.2.4. How Many Passengers Connect?

The ‘probability of connecting passengers’ is the only variable in the FFS model and it value was derived from historical data. DB1B data were used to estimate the proportion connecting passengers at an airport. Since DB1B data only report a 10% sample of airlines tickets, the exact number of connecting passengers at an airport could not be determined. The percentage of connecting passengers is defined as the ratio of the total number of connecting passengers to the total number of arriving passengers at an airport. As expected, airline hub airports will have many connecting passengers, as seen for example at ATL (Table 2) which is a major connecting hub of Delta and AirTran airlines. SFO and JFK have elevated values since SFO is a hub of United and American airlines and JFK is a hub of JetBlue, Delta, and American airlines (based on 2006-2008 data). Among the N90 metroplex airports, JFK has the highest percentage of connecting passengers followed by EWR. LGA has the least. From this information one may expect for LGA to provide most of the candidate flexible flights for N90.

Table 2: Percentage of connecting passengers at popular airports from 2006 to 2008

Year	EWR	JFK	LGA
	% connecting	% connecting	% connecting
2006	12.42	14.49	6.97
2007	11.96	18.23	7.52
2008	13.83	17.18	7.88

Year	ATL	SFO	SJC
	% connecting	% connecting	% connecting
2006	61.55	21.85	6.82
2007	62.27	20.93	6.58
2008	63.85	17.85	5.92

4.2.5. Development of FFS Model based on the Number of Connecting Passengers

The FFS model uses both the T-100 Domestic segment (All US Carriers) database and the DB1B database to generate a probability of connecting passengers. The FFS algorithm consists of two processes: the first process constructs connecting passenger dataset and the second process computes probability of connecting passengers. The first process in the FFS is summarized on left of Figure 7, and involves collection of data on the number of passengers and flights between each pair of airports for an airline from T-100 Domestic segment database and data to compute the ratio of connecting to non-connecting passengers for each route connected to metroplex airports using DB1B. The data are processed for analysis on a quarter-year time scale.

The number of connecting passengers per flight per airline per route is obtained using the number of connecting passengers and the ratio of connecting to non-connecting passengers between each pair of airports for an airline. In the last step, we assume all passengers on a route for an airline are equally distributed to all flights on that route. The flowchart on right of Figure 7 shows the second process that computes the probability of a flight having connecting passengers less than or equal to a criterion using the result from the first process. This evaluation step is iterated 17 times from 1993 to 2009 (entire BTS data availability time span). Subsequently, the probability of a flight having connecting passengers less than or equal to the criterion number, 5, is obtained for every flight in the given 1-day flight plans.

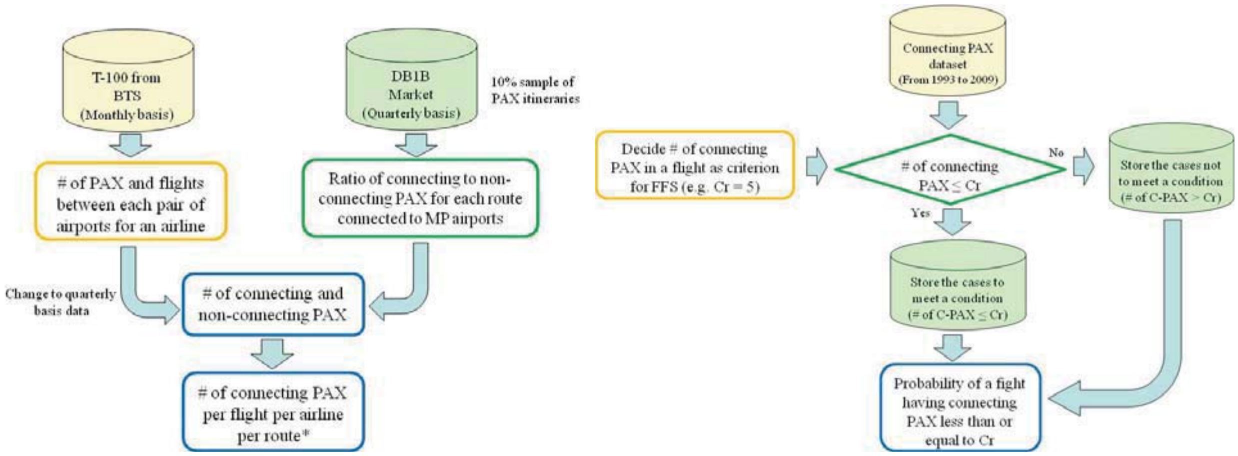


Figure 7: Two processes for FFS model. 'MP' = Metroplex

In summary, input variables used in the FFS include departure and arrival airports, airline type, and departure time of a flight in a 1-day flight plan. The output of the FFS is, for all commercial airline flights in the flight data set, the probability of each flight having connecting passengers less than or equal to the criterion number. An example working of FFS for Q3, 2008 with JFK as the destination airport is described next and illustrated in the histogram displayed in Figure 8. In Figure 8, the x-axis is origin airport index number (list of 348 airports in the flight data set) and the y-axis is the airline index (list of 238 airlines represented in the flight data set). The z-axis is the resulting probability of their being fewer than 5 connecting passengers on a flight for a particular route and airline in Q3, 2008 into JFK. Consider a United Airlines flight from DEN to JFK (coordinates on the plot are 77, 205). FFS gives an output of 0.7975 (highlighted in red on the plot) which means that when randomly choosing a UA flight from DEN to JFK in Q3 2008, the probability that such a flight has 5 or fewer connecting passengers is 79.75%. The figure also highlights two other cases, for different origin airports and airline.

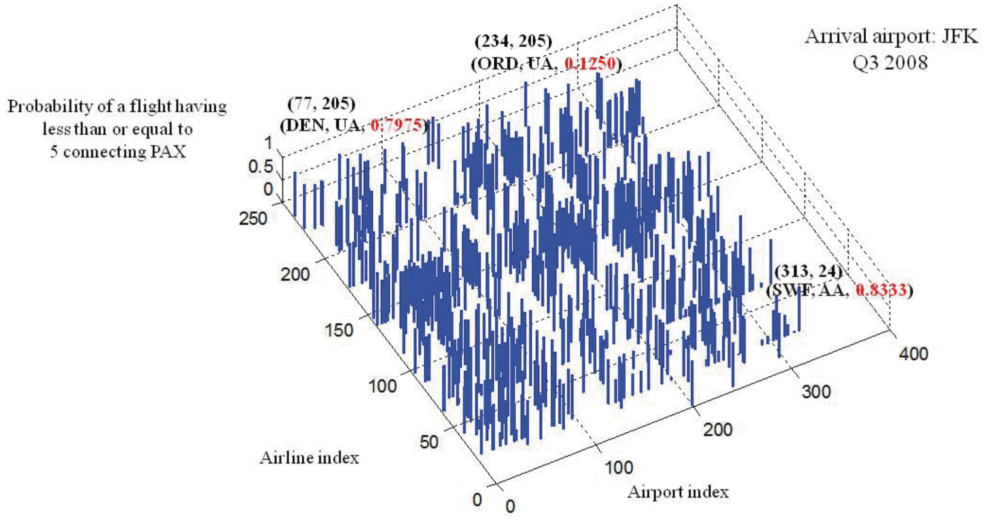


Figure 8: Distribution of FFS's outputs from histogram approach for Q3 2008 flights arriving at JFK

4.2.6. Simple Example of Selecting Flexible Flights using FFS model

Figure 9 illustrates an example use of the FFS output. Consider five flights on a given 1-day flight plan with each having its own departure and arrival airports, departure time, and operator. Given these conditions, FFS produces the probability of a flight having fewer than or equal to 5 connecting passengers for each flight. The probability is defined as Pr(C-PAX<=5|Departure, Arrival, Airline, Time) and each flight will have a probability attached to it. The percentage of flights selected as a flexible flights is a concept design variable whose value dictates the modified flight dataset provided by FFS to the integrated model. In this example, this concept design variable has a value of 0.6 (3 out of 5 flights). The next step includes selection of three flights with the highest probability of connecting passengers less than the criterion of 5. The larger the probability the more likely it is for a flight to have connecting passengers less than or equal to 5. FFS provides two groups: in this case, Flexible Flight Group with 3 flights and Normal Flight Group with 2 flights.

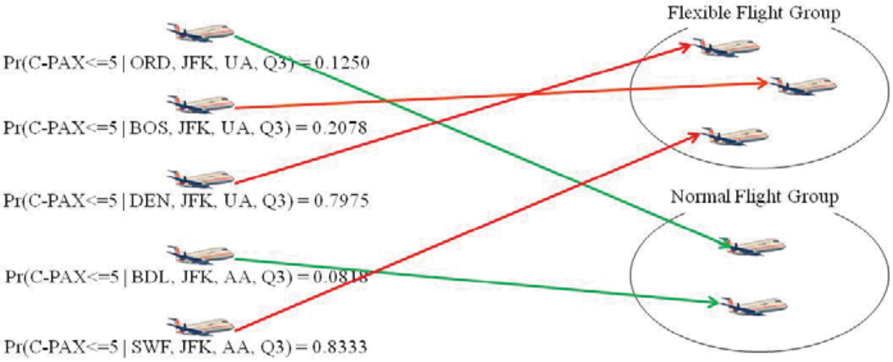


Figure 9: Notional selection of flexible flights using FFS model

4.2.7. Application of FFS Model to N90 and SCT Metroplex

The application of the FFS model begins with an assessment of the traffic on the day we use to analyze our concept. On that day (November 7, 2008), 1,706 flights including commercial, GA (General Aviation), and AT (Air Taxi) arrived at N90's three big airports (JFK, LGA, and EWR). Figure 10 shows the distribution of flights arriving at these three airports on that day, indicating an even distribution of flights across all three airports.

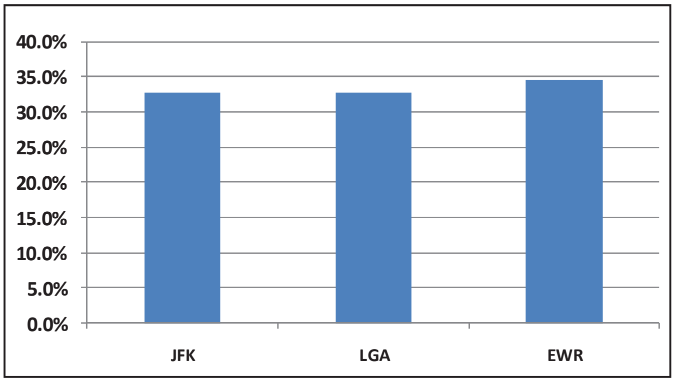


Figure 10: Distribution of flights arriving at N90 big-three airports on November 7th in 2008

We choose 30% (other levels of flexibility are addressed in the results section) as the design variable setting for the percentage of flexible flights we use to test the concept. In the case of N90, 511 commercial flights (30% of all flights) were selected from all flights arriving at one of the N90 big-three airports as flexible flights. The selection was based on the probability of a flight having connecting passengers less than or equal to 5. Figure 11 represents the distribution of FFS-selected candidate flights. As expected, results indicate that FFS takes the largest percentage of flexible flights from LGA followed by EWR and JFK, since a larger number of passengers use JFK as their connecting airport, with LGA having the lowest number of connecting passengers.

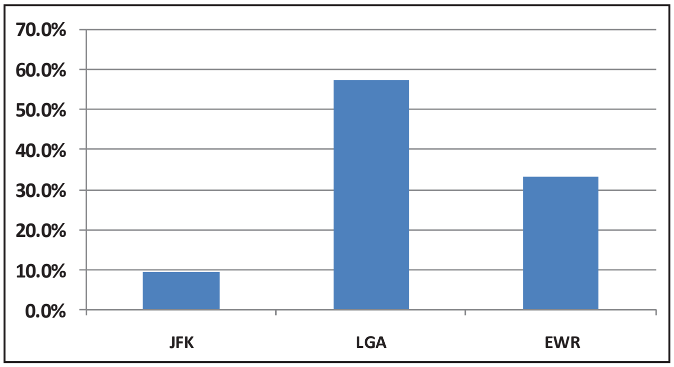


Figure 11: Distribution of FFS-selected candidate flights arriving at N90 big-three airports

In order to identify trends for choosing flexible flights by airlines at N90's "big three" airports, it was important to see the distribution of total flights and candidate flexible flights from the FFS model by airlines. Table 3 shows the number of total and candidate flexible flights arriving at N90's three big airports by airlines, compiled by using FFS on historical data (1993-2009). The largest number (13.5%) of total flights at N90 airports are operated by Continental airlines. ExpressJet airline tops the list when it comes to flexible flights; thus, ExpressJet airline does not have many connecting flights at N90 airports. The largest number of flexible flights at EWR is from ExpressJet Airlines. At LGA, American, America West, and Delta airlines have large portion of flexible flights.

Table 3: Number of total and candidate flexible flights at N90 big-three airports by airlines (Nov. 7, 2008)

	Total Flights				Candidate Flexible Flights			
Airlines	JFK	LGA	EWR	% flights	JFK	LGA	EWR	% flights
American Airlines	51	57	14	7.2%	2	55	10	13.1%
America West Airlines	6	42	12	3.5%	6	42	12	11.7%
Delta Air Lines	70	57	12	8.1%	6	50	9	12.7%
American Eagle Airlines	32	44	0	4.5%	9	30	0	7.6%
Northwest Airlines	6	21	9	2.1%	5	21	6	6.3%
United Airlines	13	20	15	2.8%	6	15	11	6.3%
AirTran Airways	0	17	5	1.3%	0	17	5	4.3%
JetBlue Airways	145	8	12	9.7%	1	8	12	4.1%
ExpressJet Airlines	0	0	141	8.3%	0	0	87	17.0%
Continental Airlines	0	17	213	13.5%	0	17	6	4.5%
				60.9%				87.7%

The distribution of flights that are not selected as flexible flights is presented in Figure 12 in order to show which airlines operate flights that are not good candidates. At EWR, Continental and ExpressJet airlines flights are likely to have more connecting passengers than other airlines, since EWR is their Hub airport. The same trend can be observed at JFK, but for different airlines: American, Delta Airlines and

JetBlue Airways.

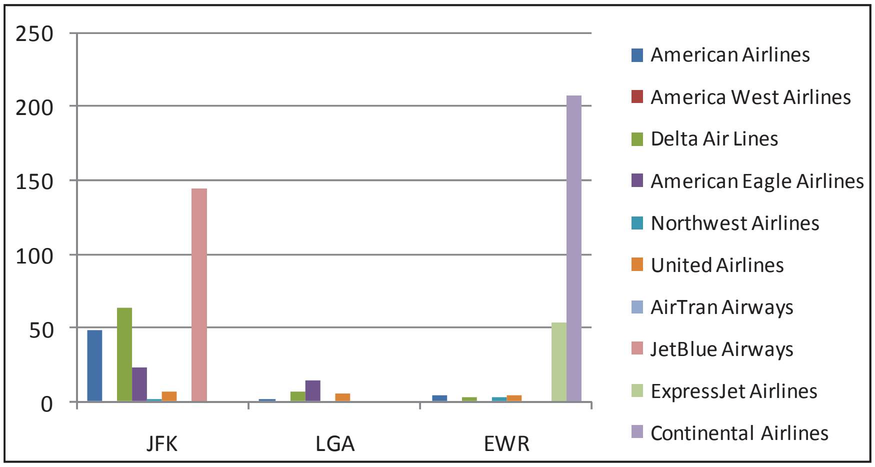


Figure 12: Distribution among flights NOT candidates for flexible operations

At the SCT metroplex, 294 commercial flights (30% of all flights) are selected from all flights (980 flights) arriving at one of the SCT airports as flexible flights based on the same connecting passenger criterion used in the N90 case. Results indicate that FFS chooses the largest number of flights from LAX, followed by SNA and BUR as shown on the left of Figure 13. Figure 13 also shows that flights at LAX that are provided by United, Delta, and American airlines have more connecting passengers than other airlines because LAX is the hub city of these airlines. The story is similar at LGB. Since LGB is the hub city of JetBlue Airways, the number of connecting passengers in JetBlue at LGB is high as shown in the figure.

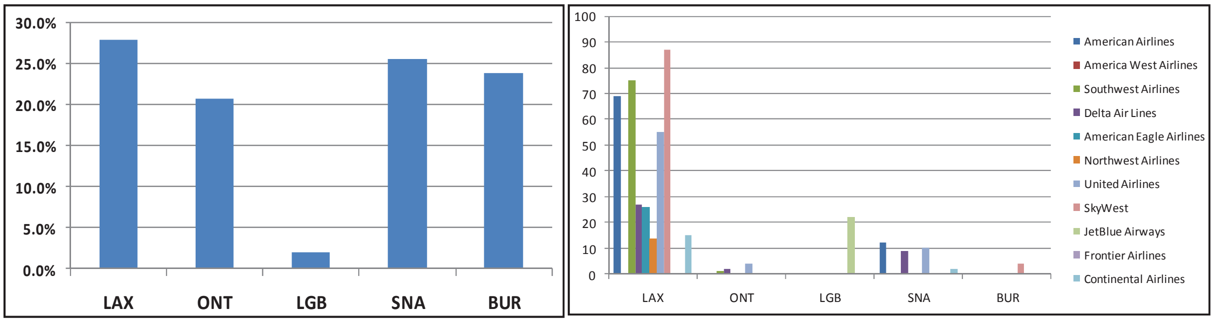


Figure 13: Distributions of FFS-selected candidate flights (Left) and flights NOT candidates for flexible operations (Right) for SCT metroplex airports

4.2.8. Factors addressed by the FFS model

The FFS model considers four important factors in generating probabilistic results: particular airline, time period, origin airport, and destination airport. Therefore, the model can capture these key characteristics of each flight in a schedule. For example, if a destination airport of a particular flight is not a hub of the operating airline, then the FFS model will output a low probability of connecting passengers. Also, if a flight is occurring on a point-to-point route, then the model will output a low probability of connecting passengers for that flight. However the FFS model currently cannot consider time of day when analyzing the historical flight data (for example, a flight that arrives at midnight, despite all other features, is unlikely to have many connecting passengers). Finally, the FFS does not address airline fleet management and crew management aspects.

4.3. Linear Time-Varying (LTV) Optimizer

The Linear Time Varying (LTV) Optimizer was developed by NASA Ames researchers (7). It is designed to compute NAS wide optimized flight routes and the ETAs.

4.3.1. LTV Overview

The number of aircraft at different times in each center is represented by a state variable. The number of landings in a center and transitions from the center to the neighboring centers in an interval of time ΔT are assumed to be proportional to the number of aircraft in the center at the beginning of the interval. Using the principle of conservation of flow in a center, the number of aircraft in center *i* at the next instant of time *k + 1* can be related to the number of aircraft in *i* at *k* via the difference in the number of aircraft that came into the center and the number of aircraft that left the center as follows:

$$x_i(k+1) = x_i(k) - \sum_{j=1}^{N} \beta_{ij}(k) x_i(k) + \sum_{j=1, j\neq i}^{N} \beta_{ji}(k) x_j(k) + d_i(k)$$

The number of arrivals in center *i* during the k^{th} time interval, denoted by $a_i(k) = \beta_{ii}(k)x_i(k)$, is a fraction of $x_i(k)$. In special cases, $\beta_{ii}(k) = 0$ implies that a transition must involve crossing an airspace boundary, and $\beta_{ii}(k) = 1$ implies physical transition from one time interval to another time interval. The departure within center *i i*s denoted by $d_i(k)$, which is independent of $x_i(k)$. For simplicity of illustration, “during the kth time interval ΔT” will also be understood as “at time *k*” here.

The inputs to the LTV include departures $d_i(k)$ within center *i* at time *k* and the fractions $\beta_{ij}(k)$. The direct output from the LTV is the aircraft count in the centers at each time step. It is also straightforward to generate other outputs, such as intercenter traffic flows, number of arrivals, etc., based on the information contained in variables $x_i(k)$, $d_i(k)$, $\beta_{ij}(k)$.

To implement the LTV, the fractions $\beta_{ij}(k)$ are obtained as the aggregated fractions of aircraft going from center *i* to *j* during the same k^{th} time interval in each day, using historic air traffic data. The departures $d_i(k)$ are computed from filed flight plans (deterministic). This is different from the original model in [7], which includes both deterministic and stochastic components. The LTV model is implemented in a deterministic manner because a deterministic optimization method can be used for traffic flow management (TFM). All centers of the U.S. airspace, oceanic centers, and part of the Canadian centers are included in the LTV.

LTV is designed to optimize flight routes and ETAs for traffic flow management. The selection of $\beta_{ij}(k)$ and $d_i(k)$ is equivalent to a traffic flow management strategy based on choosing optimal routes and aircraft ETAs to minimize a cost function.

Our optimization problem is formulated as follows:

$$\min_{\beta,d} \quad \mathcal{J}(x)$$

subject to

$$x(0) = x_0 \qquad \boxed{\text{Initial condition}}$$

$$x_i(k+1) = x_i(k) - \sum_{j=1}^{N} \beta_{ij}(k)x_i(k) + \sum_{j=1, j\neq i}^{N} \beta_{ji}(k)x_j(k) + d_i(k) \qquad \boxed{\text{Dynamics}}$$

$$0 \leq x_i(k) \leq C_i(k) \qquad \boxed{\text{Airspace capacity}}$$

$$0 \leq d_i(k) \leq D_i(k), \quad \sum_{k=0}^{t} d_i(k) \leq \sum_{k=0}^{t} S_i(k), \quad \sum_{k=0}^{T} d_i(k) = \sum_{k=0}^{T} S_i(k)$$

$$0 \leq a_i(k) \leq A_i(k), \quad \sum_{k=0}^{T} a_i(k) = R_i \qquad \boxed{\text{Airport capacity}}$$

$$\sum_{k=T_i}^{t+T_i} \left(\sum_{j=1}^{N} \beta_{ij}(k)x_i(k) + a_i(k) \right) \leq \sum_{k=0}^{t} \left(\sum_{j=1}^{N} \beta_{ji}(k)x_j(k) + d_i(k) \right) \qquad \boxed{\text{Min dwell time}}$$

The constraints and the cost function are described in the following subsections.

1) Initial Condition

The dynamics equation is presented at the very beginning of LTV Overview section.

2) Dynamics

The time-varying center capacity constraints restrict the number of aircraft in a center to be below the maximum number of aircraft allowed.

3) Airspace Capacity

Airport capacity includes departure constraint and arrival constraint. The departure constraint restricts the number of departures below the departure capacity at each time step. The arrival constraint restricts the number of arrivals below the arrival capacity.

4) Minimum Dwell Time

The amount of time an aircraft spends in a center depends on the design speed of the aircraft and the flight route in the center. The minimum dwell time is assumed to be identical for every flight flying through a center despite the fact that flights use different routes that need different travel times, that there are flights taking off and landing in the same center, and that flights taking off and landing have different dwell times than en route flights, etc.

The formulation of minimum dwell time constraints for the general case introduces one constraint for each route, whereas the special case has one constraint for each center; therefore, it is expected that the general case will take more computational time for the optimization.

5) Objective Function

The cost function is defined as follows: $J(x) = \sum_{i=1}^{N} \sum_{k=0}^{T} x_i(k)$

which is equivalent to minimizing the total flight time.

4.3.2. Virtualization for N90 and SCT Metroplexes

The NASA-developed FACET software is used to visualize flows. Figure 14 shows the N90-bound and SCT-bound traffic flow pattern and the zoom-in pictures. The Figure is generated by a playback of historical ASDI data, from a good weather day, 08/24/2005.

Figure 14: Traffic flow pattern of N90-bound

For N90, only JFK, EWR and LGA are considered in these visualizations. Figure 14 is plotted with flights whose destination is JFK, EWR or LGA. A zoom-in is displayed in Figure 15 and Figure 16, showing some of the common waypoints and arrival fixes which facilitate us to find out and define the metroplex boundaries.

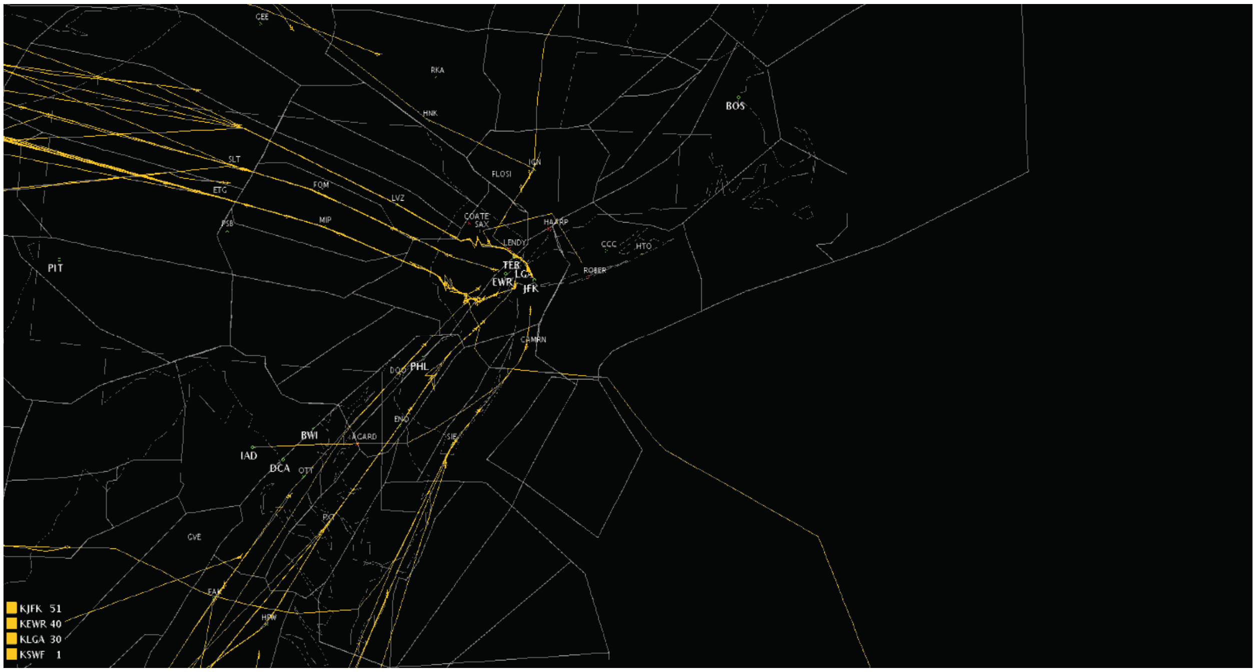


Figure 15: Traffic flow pattern of N90-bound zoom in 1

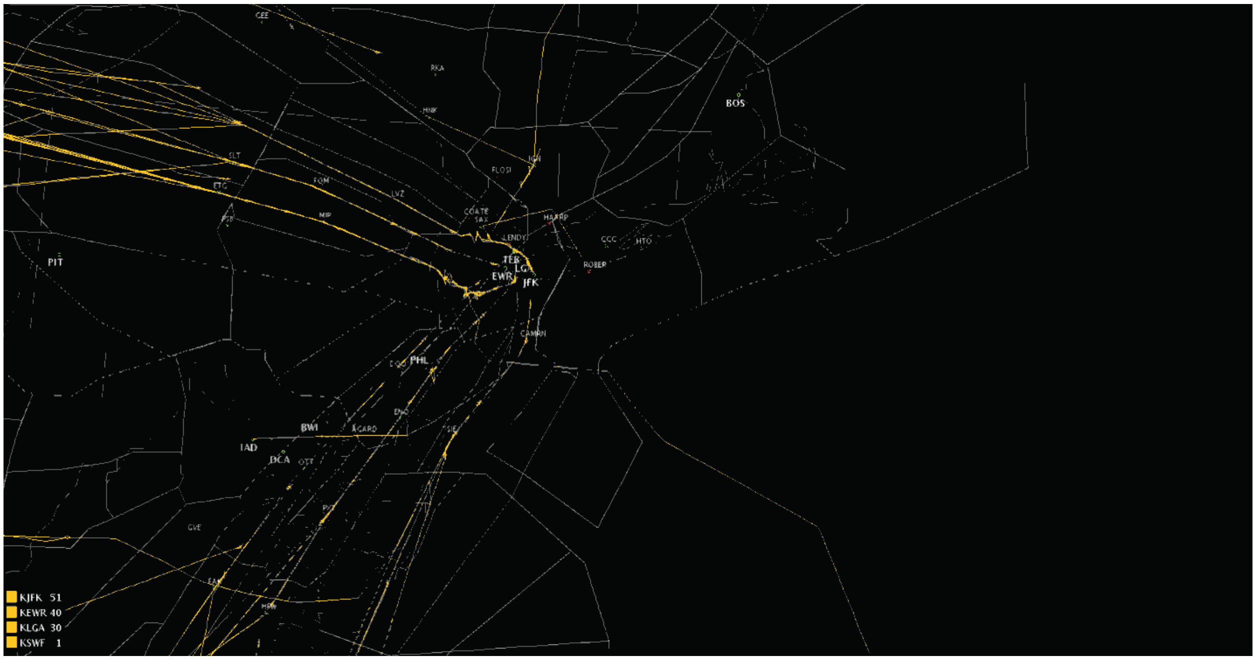


Figure 16: Traffic flow pattern of N90-bound zoom in 2

LAX, BUR, ONT, LGB and SNA are considered in the SCT metroplex shown in Figure 17. The zoomed in plots Figure 18 and Figure 19 provide views of arrival fixes and common waypoints around SCT.

Figure 17: Traffic flow pattern of SCT-bound

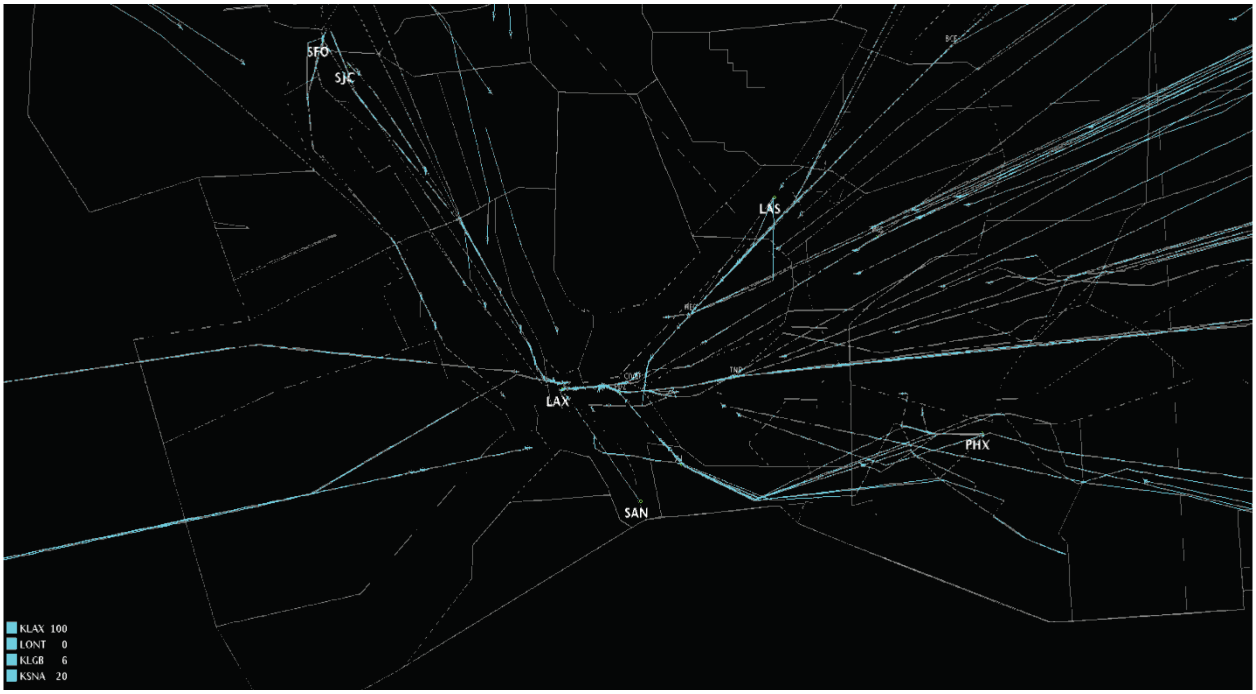


Figure 18: Traffic flow pattern of SCT-bound zoom in 1

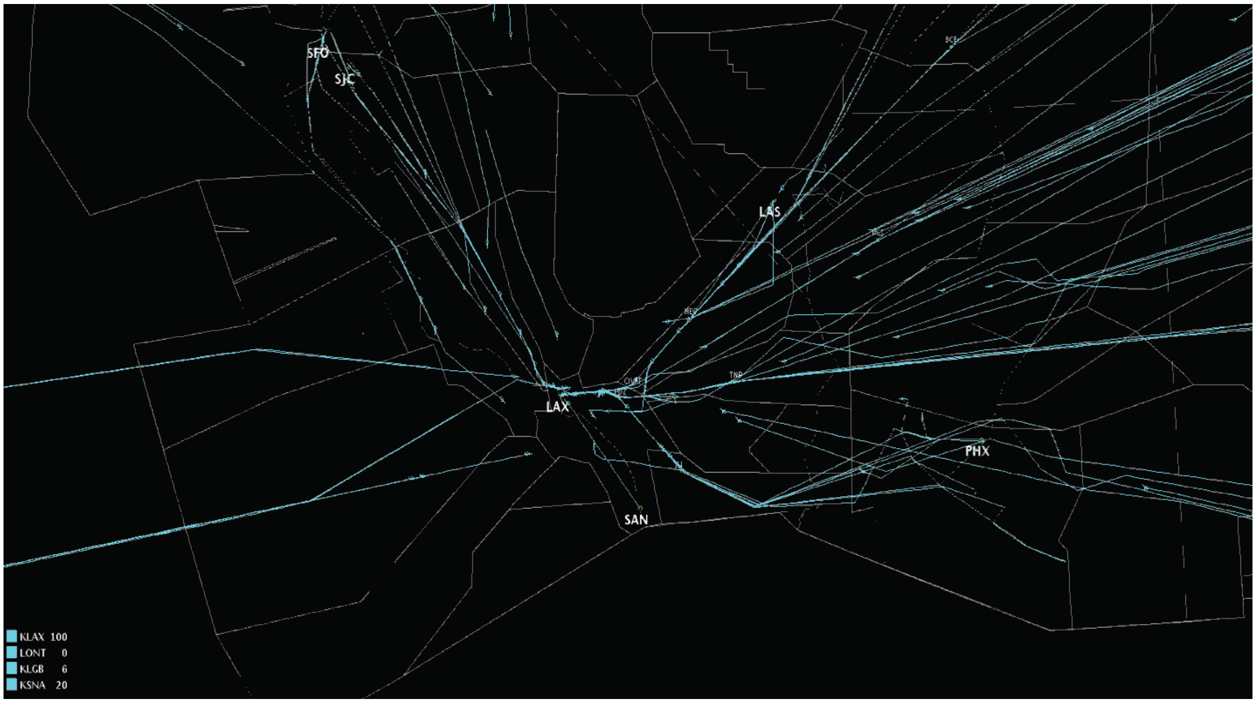


Figure 19: Traffic flow pattern of SCT-bound zoom in 2

Finally, both traffic flow patterns of N90 and SCT are shown in Figure 20.

Figure 20: Traffic flow pattern of N90 and SCT

4.3.3. Data inputs to LTV

A network data structure is required in order to apply the efficient and effective LTV metroplex routing algorithm. The waypoint-based network is exploited as the data structure to generate the optimal route for each flexible flight under sector congestion constraints. This initial network is built from waypoints provided by Future ATM Concepts Evaluation Tool (FACET) and is named as Jetway Network. Next, an extended ‘Jetway Plus Network’ is formulated by inserting additional waypoints; the ‘Jetway Plus Network’ is used as the final data structure for running LTV. The development of these networks from FACET is described next.

4.3.3.1. Obtain the waypoints and jet routes information from FACET

To accurately capture the real flight paths that air traffic follow, a jet route-based waypoint network is built. First, jet route and waypoint information are obtained from FACET. Using the NavigationInterface in FACET, the waypoint identifiers (index) and locations (longitude and latitude) are obtained for all waypoints. Also using the NavigationInterface, the sequence of waypoints that defines a jet route is obtained for all jet routes. To convert a jet route description in terms of waypoint locations to waypoint indices, the corresponding index is identified for each waypoint on a jet route using the waypoint information from FACET.

To form the network, we record the connection (edge) between two consecutive waypoints (vertices) for each jet route. Intersection points on the jet route system are automatically considered as waypoints when recording the connection along a jet route. Figure 21 illustrates how edges are obtained from a jet route, along with intersection points. Additional edges were created to connect airports to the jet route system. Collectively, the edges and vertices define the graph. The edges are not directed because a jet route can support traffic in both directions (in different altitudes).

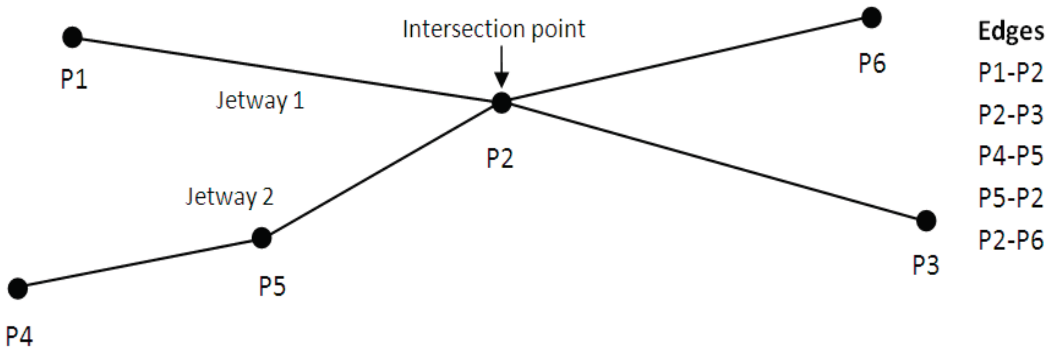


Figure 21: Obtaining graph edges from jet route, including intersection points

4.3.3.2. Establish the Jetway Network

In order to take advantage of the Boost C++ Graph Library (BGL) [3], we transform the obtained waypoints and the jet routes data into the BGL format. C++ BGL is an efficient tool for network analysis and optimization. The major advantage of the BGL is that it has a generic interface that allows access to a graph's structure, but hides the details of the implementation. This is an “open" interface in the sense that any graph library that implements this interface will be interoperable with the BGL generic algorithms and with other algorithms that also use this interface. The BGL provides some general purpose graph classes that conform to this interface.

According to the requirement of C++ BGL, we have each waypoint provided by FACET in a C++ struct and put all these waypoint structs in an indexed C++ map. Each struct contains the name, latitude, longitude information of the waypoint. The waypoints serve as the nodes in a Jetway Network graph. Each direct route between two nodes is considered as two directional edges in a Jetway Network graph and each of the two is recorded in a C++ struct which contains the starting point and the ending point. All the edges are also stored in an indexed C++ map. At the beginning of the network construction, the great circle distance of each edge is calculated and recorded as the non-negative weight in each edge struct. A Jetway Network graph is then built based on the waypoints and direct routes as nodes and edges respectively. Finally, a shortest-path algorithm (Dijkstra's Algorithm) provides the results of all the shortest paths from the origin airport to every other airport except those disconnected from the origin.

4.3.3.3. Hash Table

In order to insert new waypoints and dynamically maintain the network, the waypoints need to be indexed by a hash table. The similar hash table is built for direct route data. For simplicity, we only show how to build the hash table for waypoints in this section. The hash key in this paper is the rounded positive latitude-longitude pair of each waypoint; in other words, each waypoint's latitude and longitude are changed to their absolute values and then rounded into integers. Then the positive integers are stored in a hash key pair <lat, lon>. All of the existing waypoints in Jetway Network are processed to acquire their hash key pair. Initially the hash table H is set to be empty (φ). The hash key pair <lat, lon> is calculated according to the latitude and longitude of a waypoint WP_i and a search is started in the current hash table H based on <lat, lon>. If this hash key pair is not in H, a <lat, lon> is created in H and this waypoint WP_i is inserted under the newly created hash key pair; if it is already in the hash table, compare WP_i to all the waypoints under this existed hash key pair, insert WP_i if no same waypoint is found. This process is repeated until all the waypoints obtained from FACET have their hash indexes.

After we have all the waypoints in the hash table, it is very fast to insert new waypoints. To build the hash table, the NAS is divided into grids to build the hash pair index, which is critical in a hash table data structure. Each grid is a square with four corners whose latitude and longitude are integers as shown in Figure 22, where i and j are integers. When we have a new waypoint to be inserted, we first calculate its hash key pair and decide which grid it is in. As we use *floor* function to obtain <lat, lon> from the absolute latitude and longitude, if the waypoint exists, it should be in the grid with top-left corner coordinates (i, j) = <lat, lon>. Therefore only the existing waypoints WP_1, WP_2, WP_3 in this grid need to be checked instead of checking all the waypoints in the entire Jetway Network. This mechanism for the hash table substantially enhances the speed with which new waypoints are inserted.

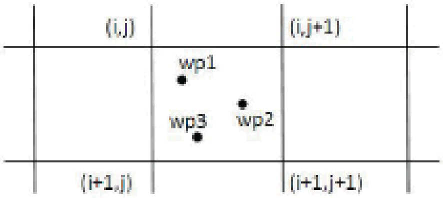


Figure 22: Hash table indexed grids with waypoints

The grids in the hash table are stored with sorted hash key pair as shown in Table 4. The grids are saved in ascending order of the first integer of the hash key pair, and with the same first integer, the grids are recorded in ascending order of the second integer of the hash key pair. The waypoints in each grid are recorded under the hash key pair <lat, lon> which is also actually the top-left coordinates (i, j) of the corresponding grid. If there is no waypoint in a grid, that grid will not be stored in the hash table.

Table 4: Hash table is stored with ordering

…	…
<lat_(i-1), lon_(j-1)>	wp4, wp8, wp12
<lat_(i-1), lon_(j)>	wp1, wp2, wp3, wp7, wp11
<lat_(i-1), lon_(j+1)>	wp5, wp6, wp9, wp10
…	…
<lat_(i), lon_(k-1)>	wp44, wp18, wp32, wp11, wp20
<lat_(i), lon_(k)>	wp31, wp12, wp53, wp47
<lat_(i), lon_(k+1)>	wp65, wp26, wp19
…	…

4.3.3.4. Establish the' Jetway Plus' Network

After generating the Jetway Network, the routes for input flight plans of flexible flights are optimized. Since the waypoints ordered by FACET may not be complete, the new waypoints mentioned in the input flight plans need to be imported to the Jetway Network. At the same time, all the airports are imported by treating them as waypoints as well. The additional edges are obtained from FACET by the historic flight track files. Together all the additional inserted elements with the Jetway Network formulate the 'Jetway Plus' Network, which is the final data structure to apply our routing algorithm. The entire process is exemplified in the following set of steps.

1) Input Flight Plans

Flight plans are documents filed by pilots or a flight dispatcher with the local Civil Aviation Authority (e.g. FAA in the USA) prior to departure. They generally include basic information such as departure and arrival points, the sequence of waypoints of the flight route, estimated time en route, alternate airports in case of bad weather, type of flight (whether instrument flight rules or visual flight rules), pilot's name and number of people on board.

2) Obtain and insert new waypoints from the input flight plans

From the input flight plans we obtain the sequence of waypoints of the flight route and insert the waypoints into the hashed Jetway Network. The related edges are also added. For each waypoint, we obtain its latitude-longitude pair and search for it in the existing Jetway Network hash table. If this waypoint exists, we move on to the next current flight plan; if this waypoint is new, it is inserted into the hash table. After all of the flight plans are processed and all the airports are inserted, the 'Jetway Plus' Network is formulated.

3) Flexible flight routing algorithms

A. Shortest path algorithm without sector congestion constraint

The waypoint-based 'Jetway Plus' Network obtained above is the routing data structure for the entire NAS. When the routing algorithm does not take the sector congestion into account, the weight of each edge is the great circle distance between two waypoints. The shortest path algorithm is used to find the optimal route (shortest weighted path) from origin to destination for each pair of origin/destination. Since the flexible flights are considered, the destination airport of each flight is selected from the airports inside its destination metroplex. In this research, the central airport of a metroplex is chosen as the destination of a flexible flight, determined by calculating the central point c of the airports in the Metroplex and then selecting the closest airport to that point. For example, the N90 metroplex has three major airports: JFK, LGA, and EWR. After the central point calculation is made, LGA is identified as closest to that point.

B. Shortest path algorithm with sector congestion constraint

To introduce sector congestion constraints, weights on edges that intersect congested sectors are increased. Therefore, the resulting shortest path route for a flight after Dijkstra's Algorithm is employed represents the shortest weather conflict free route from origin to destination. For advanced multiple-level sector congestion, the sector congestion impact is taken into account by assigning the edges with additional weights of different congestion statuses. The more congested is a sector, the heavier weight on each intersecting edge. The congestion weight will be summed up with the great circle distance weight for each edge and then the shortest path algorithm is applied in this new weighted 'Jetway Plus' Network.

In sum, our routing algorithm calculates the optimal path between origin and destination airports. At the same time, LTV can balance the traffic load to efficiently avoid the congested areas (Figure 23). The optimized flight plan is generated under the sector congestion constraints and is compared to its original flight plan. Assume that the congested sector is set to be the dark area in Figure 23 because of bad weather. The origin airport is LAX and the destination metroplex is NY90 whose central airport is LGA. The weighting scheme is on-off weighting and $\gamma = 10$. The result shows that the optimized route successfully avoids the congested area.

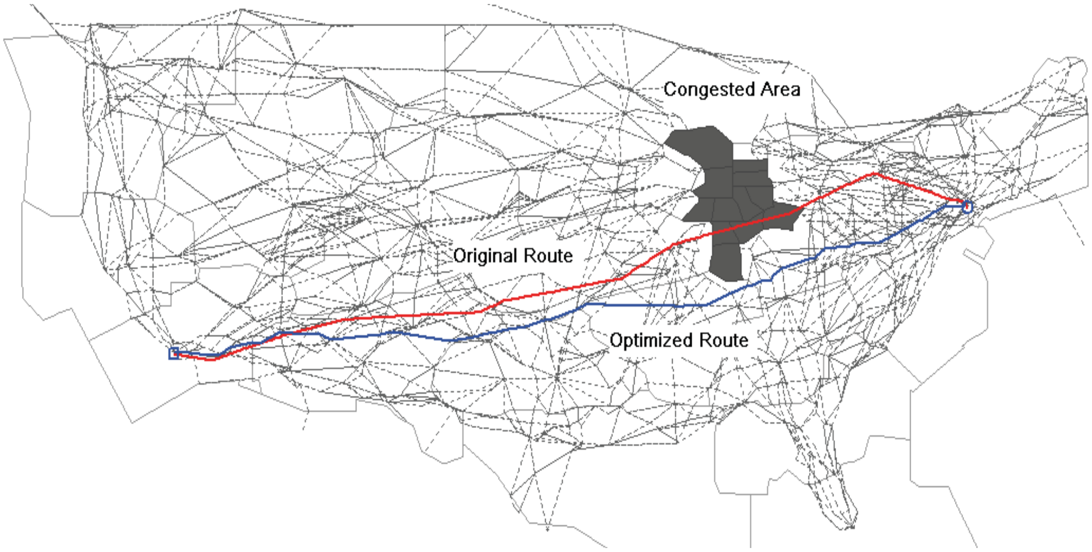


Figure 23: The original and optimized routes for a flexible flight

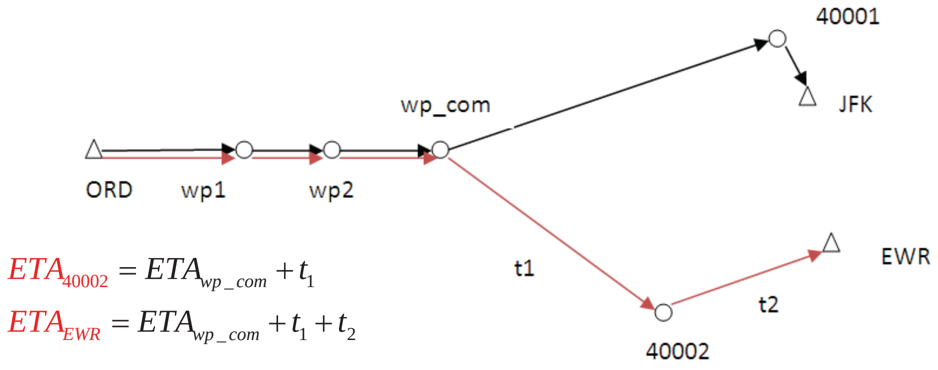
4.3.4. Estimation of all possible routes of a flexible flight

There are no flexible flights defined in the historical data. As a result, for each of the FFS-designated flexible flights, there is only one flight plan in the historical data. To compare among a set of alternate flight plans whose destinations cover all the candidate airports inside the metroplex, these alternate flight plans should be estimated. The process employed to do this is explained next via example.

Given a set of selected flexible flights, for the i-th flexible flight from ORD to JFK, whose model type is B747 and the weight category is “H”, we estimate the routes from ORD to EWR and LGA based on the historical data. For different situations, we use different estimation strategies, as follows.

- Case 1. Same Aircraft Type

We search for B747 from ORD to EWR inside the historical flight plans. In Figure 24, the route in black is the original route to JFK, the route in maroon is another B747’s route to EWR and wp_com is the last common waypoint of the two routes. This route is used for ORD-EWR flexible flights.



$$ETA_{40002} = ETA_{wp\_com} + t_1$$

$$ETA_{EWR} = ETA_{wp\_com} + t_1 + t_2$$

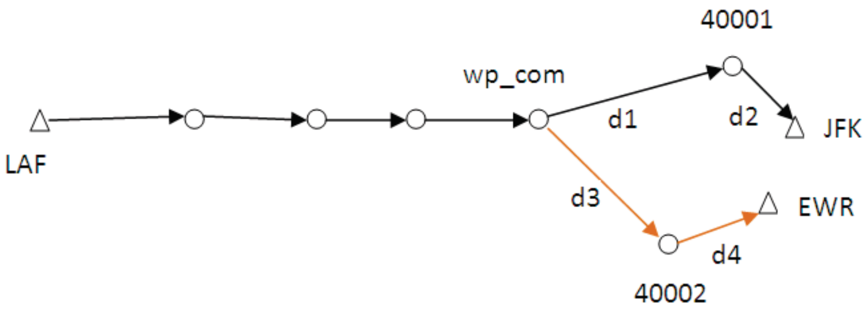
Figure 24: Original Routes of B747 to JFK and EWR

- Case 2. Same Weight Category

If no B747 (same aircraft type) found, we search for the flight with similar type (i.e. the same weight category “H”) and then employ same procedure as Case 1.

- Case 3. No same type or same weight category

Sometimes there is only one daily flight from a small airport to JFK. To estimate the ETAs of EWR and its arrival fix 40002, we use the ratio of the distance method as shown in Figure 25.



$$\frac{ETA_{40002} - ETA_{wp\_com}}{d_3} = \frac{ETA_{40001} - ETA_{wp\_com}}{d_1}$$

$$\frac{ETA_{EWR} - ETA_{wp\_com}}{d_3 + d_4} = \frac{ETA_{JFK} - ETA_{wp\_com}}{d_1 + d_2}$$

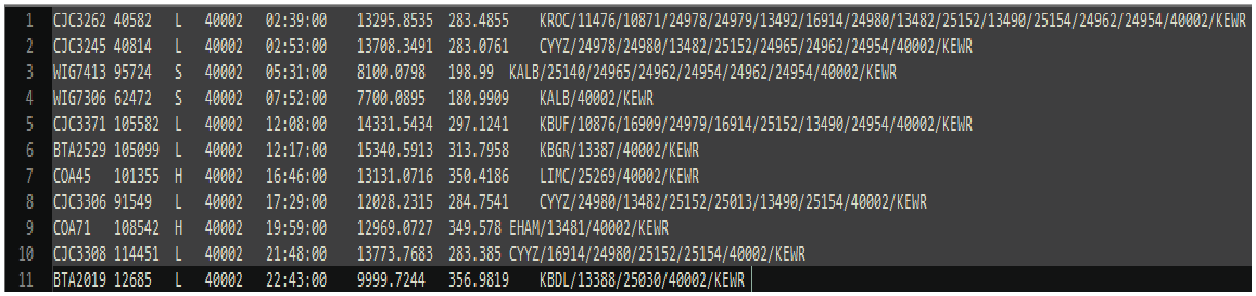
Figure 25: Virtual route of not existing city pairs

4.3.5. Final LTV output data sets

There are 4 sets of output data for N90 metroplex (same four for SCT).

- Data Set 1 – the historical data (Nov 7, 2008)
- Data Set 2 – the optimized data (LTV is applied on Data Set 1)
- Data Set 3 – the historical data + flexible flight operations (No optimization is applied)
- Data Set 4 – the historical data + flexible flight operations + LTV optimization

The output files contain the detailed flight plans including arriving destination airports and corresponding arrival fixes. Figure 26 depicts the example output format. The columns are AirlineID, CID, weight category, the arrival fix passing by, ETAs sorted by ascending time order, altitude at 40002, airspeed at 40002, the sequence of O/D airports and waypoints.



```
CJC3262 40582   L   40002   02:39:00    13295.8535  283.4855    KROC/11476/10871/24978/24979/13492/16914/24980/13482/25152/13490/25154/24962/24954/40002/KEWR
CJC3245 40814   L   40002   02:53:00    13708.3491  283.0761    CYYZ/24978/24980/13482/25152/24965/24962/24954/40002/KEWR
WIG7413 95724   S   40002   05:31:00    8100.0798   198.99  KALB/25140/24965/24962/24954/24962/24954/40002/KEWR
WIG7306 62472   S   40002   07:52:00    7700.0895   180.9909    KALB/40002/KEWR
CJC3371 105582  L   40002   12:08:00    14331.5434  297.1241    KBUF/10876/16909/24979/16914/25152/13490/24954/40002/KEWR
BTA2529 105099  L   40002   12:17:00    15340.5913  313.7958    KBGR/13387/40002/KEWR
COA45   101355  H   40002   16:46:00    13131.0716  350.4186    LIMC/25269/40002/KEWR
CJC3306 91549   L   40002   17:29:00    12028.2315  284.7541    CYYZ/24980/13482/25152/25013/13490/25154/40002/KEWR
COA71   108542  H   40002   19:59:00    12969.0727  349.578 EHAM/13481/40002/KEWR
CJC3308 114451  L   40002   21:48:00    13773.7683  283.385 CYYZ/16914/24980/25152/25154/40002/KEWR
BTA2019 12685   L   40002   22:43:00    9999.7244   356.9819    KBDL/13388/25030/40002/KEWR
```

Figure 26: The example of output format of LTV

Data Set 3 is the output of applying flexible flights to historical data. There are four steps to generate Data Set 3 (see steps below and Figure 27).

- Step 1 – FFS tells LTV which flights are designated as flexible flights.

- Step 2 – Based on Data Set 1, we estimate all possible routes and ETAs for each flexible flight. Now each flexible flight has three destination ETAs for EWR, JFK and LGA.
- Step 3 – At the same time, LTV passes all the regular flights to McTMA, which provides the runway balancer available time slots (holes) at each airport.
- Step 4 – Based on the estimated three ETAs and the available slots, the runway balancer decides which airport each flexible flight is going to land in. Then each flexible flight has one single destination ETA and only one flight plan.

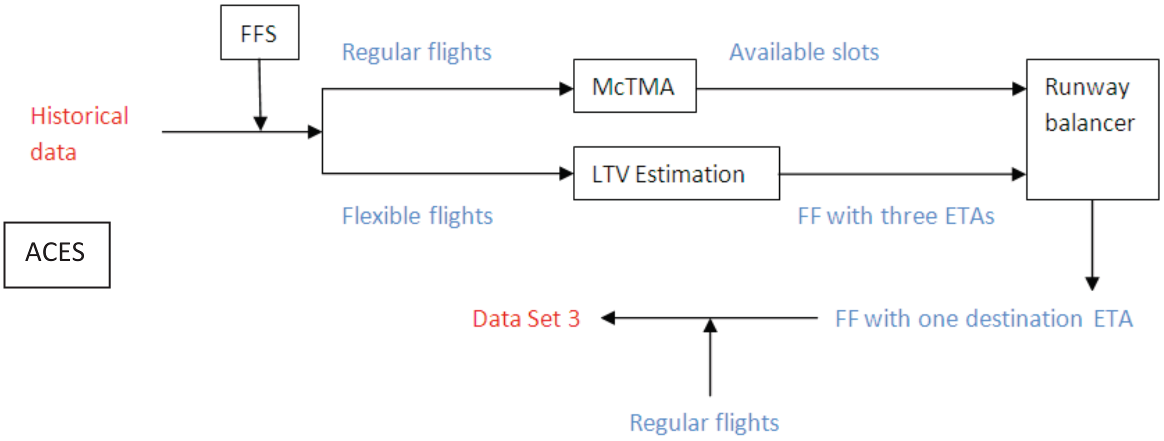


Figure 27: Data flow diagram of the entire system

The procedure of processing Data Set 4 is similar as Data Set 3 except that in Data Set 3 we deal with historical data while in Data Set 4 we deal with the optimized data.

4.4. Multi-center Traffic Management Advisor Model (McTMA)

For this project, a model of the Multi-center Traffic Management Advisor scheduling system (6) was adapted for the N90 and SCT airspaces. The model, originally in Matlab code, was transferred to Java code to enable future portability to the Aircraft Concept Evaluation System (ACES) or other systems.

Figure 28 depicts the scheduling system, which consists primarily of a number of scheduling entities that communicate between themselves using a publish/subscribe mechanism. An external module that assigns flexible flights to airport-runway combinations was also developed and is considered part of the scheduling system, although it is a separate module. The input to the system are estimated times of arrival (ETAs), determined by the LTV, which in turn uses ETAs generated by ACES.

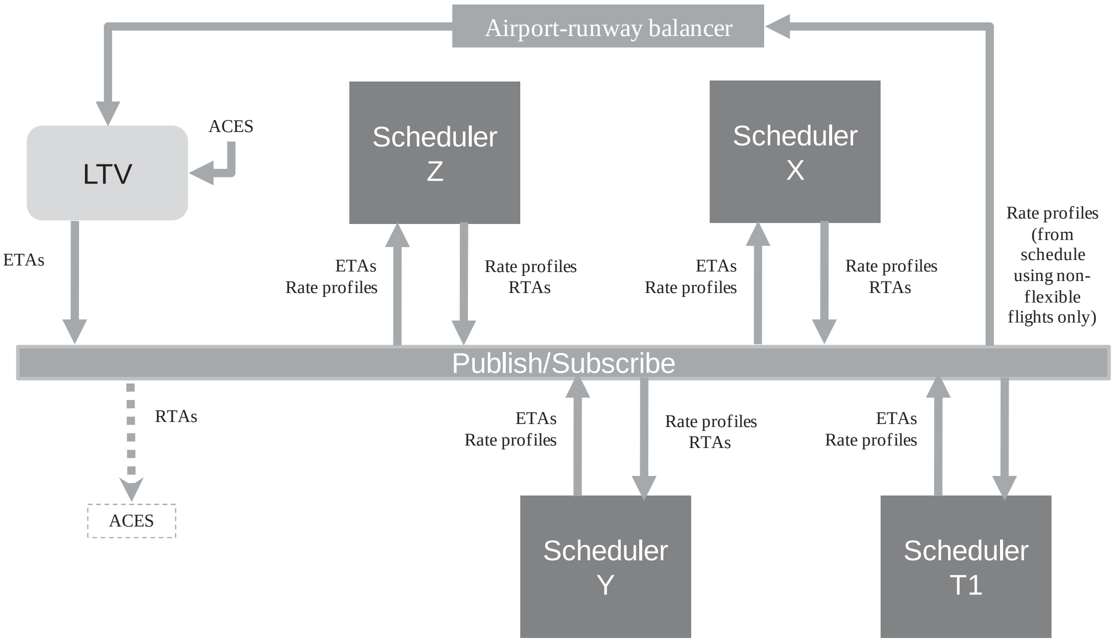


Figure 28: Multi-center Traffic Management Advisor model schematic

Each scheduler instance takes as input ETAs to the "meter point" at which it is scheduling, and applies local separation constraints. Specifically, the scheduler ensures that all aircraft crossing the meter point have appropriate lateral separation, which is 5 nautical miles (nmi), by assigning required times of arrival (RTAs) that equate to 5 nmi assuming the aircraft are flying the modeled groundspeed at the meter point. (As such, all aircraft are de-conflicted over the meter point.) The scheduler that schedules the airport runways and meter fixes ensures that wake vortex separation is met at the runway and that proper lateral separation is obtained at the meter fixes. No airport arrival rates were set.

In addition, when assigning the RTAs, the schedulers ensure that there is sufficient capacity downstream to allow each aircraft being delivered from the meter point to arrive at the downstream resource without excessive delay. Specifically, each resource (scheduler) computes a "rate profile," which is an estimate of the capacity assigned or available to an upstream resource (scheduler). A scheduler will delay an aircraft in excess of that required to meet lateral separation so as to be able to arrive at all downstream resources at times where assigned or otherwise available capacity exists. Once scheduling is complete, the scheduler computes a rate profile for each of the other resources which are delivering aircraft to the scheduler and publishes those rate profiles. The scheduler also publishes its RTAs.

The scheduler would ideally re-compute schedules whenever new information is obtained. In the actual McTMA system, this is done at least as frequently as radar updates are obtained, which is approximately every 12 seconds. In this system, the scheduler is only run for one full cycle. (As will be discussed, this involves two scheduler runs.) Additional details about the scheduler can be found in Landry (6). For this project, the scheduler was ported to JAVA code and adapted for scheduling arrivals in to N90 and SCT. In addition, an "airport-runway balancer" (ARB) was developed, and the scheduler was integrated with the ARB and LTV.

4.4.1. Airport-runway balancer (ARB)

Typically, the input to the McTMA scheduler includes the destination of the aircraft. Runways are assigned based on the current configuration of the destination airport. However, under the "flexible flights" concept, some aircraft would have destinations that are non-specific with respect to the airport. An algorithm for assigning aircraft to airports had to be added to the McTMA model.

Algorithms for this purpose were developed as part of ACES, for which we could find no documentation, and for the Final Approach Spacing Tool (FAST), which is part of NASA's Center-TRACON Automation System. Neither algorithm was adequate for the task; for example, the assignment algorithm in FAST utilized a complex rule-base that was highly adapted to the particular airport. A simpler and more general method that still produced near-optimal allocations was desired.

The general algorithm for the ARB proceeds as follows:

- run the scheduler on all airport-bound flights only, without the flexible flights;
- compute the rate profiles at the runways for all airports in the metroplex;
- pass the available capacity ("holes") at those airports to the ARB along with the ETAs of all flexible flights to each of the airport-runway combinations;
- ARB assigns aircraft in a first-come, first-served fashion to the available holes;
- aircraft are assigned the airport-runway combination associated with the hole to which they are assigned; and
- the assignments are passed to the scheduler, which re-computes the schedule to include flexible flights.

The process can be demonstrated using the example shown in Figure 29. In Figure 29, the holes computed by the scheduler are shown in the column labeled "holes." For example, there is available capacity for an aircraft at 1226, 1228, and 1235 at LaGuardia (LGA) runway 04, and capacity available at Kennedy (JFK) runway 13L at 1230 and 1234.

The aircraft ETAs to JFK and LGA are shown in the middle and right columns. (The other airports in the metroplex are not shown to improve readability.) The ARB accepts the holes and ETAs as inputs.

Starting from the first hole, 1226 at LGA-04, the ARB looks for the next flight arriving at LGA. That flight is DAL1217, which can arrive at LGA at 1226. Since it can arrive at or before 1226, it could utilize the 1226 LGA-04 hole, and it is therefore assigned to that airport and runway. DAL1217 is then removed from further consideration by the ARB, which is accomplished by removing its ETA from all lists.

The next hole, also at LGA-04, is at 1228. The next LGA ETA is UAL42, which arrives at 1228 and is assigned LGA-04. UAL42 is then removed from all ETA lists. This continues until all aircraft are assigned airport-runway combinations.

Holes	JFK ETAs	LGA ETAs
1235 – LGA-04	1236 – BAW35	1238 – BAW35
1234 – JFK-13L	1235 – AAL13	1234 – USA1200
1233 – EWR-04L	1233 – CHQ410	1234 – AAL13
1230 – JFK-13L	1231 – UAL42	1230 – AAL440
1228 – LGA-04	1231 – DAL1217	1228 – UAL42
1226 – LGA-04	1230 – AAL440	1226 – DAL1217

DAL1217	LGA-04
UAL42	LGA-04
AAL440	JFK-13L

Figure 29: ARB example

The assignment of a hole confers only an airport-runway assignment, it does not confer a particular scheduled time of arrival. The scheduler, run subsequently to the ARB, may assign the aircraft a different RTA than was used by the ARB to assign an airport-runway to the aircraft.

4.5. How the models were linked

The following description and Figure 30 summarize how the inputs/outputs from the models were linked. This linkage was done manually, but future work may warrant automating this procedure. The LTV accepts ETA and routing information from an ACES run in the form of a static input file. ACES provides the historical flight plan data with Airline ID, computer ID, aircraft type, weight category, origin airport, destination airport, the sequence of waypoints and the ETAs, altitude, airspeed along the trajectory. LTV then optimizes the route according to the method described previously. LTV outputs the ETAs to all meter points, meter fixes, and the airport runway thresholds.

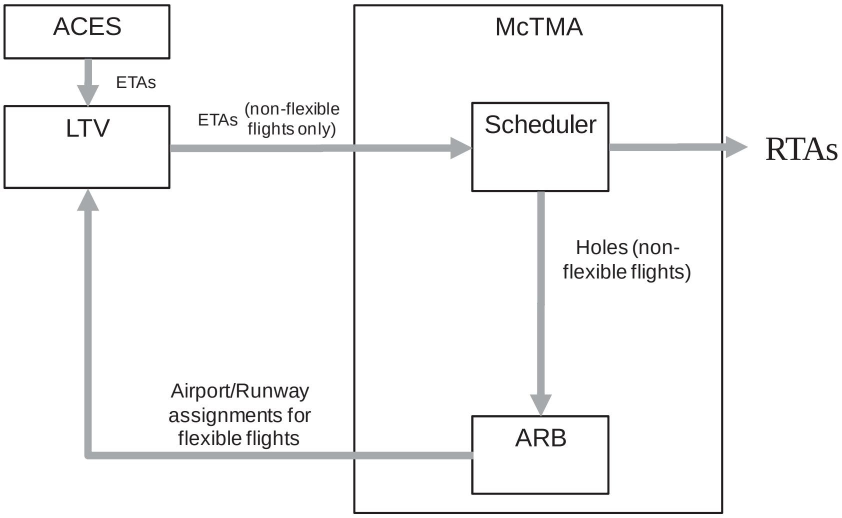


Figure 30: ACES/LTV/McTMA model interactions

Other necessary information for each flight such as aircraft type, altitude, ground speed, and route are also output to the McTMA scheduler so that it can be used to estimate the wake vortex separation between aircraft and perform other calculations. That output is accepted as input by the scheduler, which operates as described above. In essence, McTMA takes the optimized regular flights and runs the scheduler to find out the available time slots (holes) for the flexible flights. These holes are then sent to Runway Balancer that will decide which destination airport a flexible flight should land in. Now every flexible flight only has one destination airport and one flight plan.

4.6. Airspace Concepts Evaluation System (ACES)

Airspace Concepts Evaluation System (ACES) is a fast-time simulation of the nationwide air traffic system, including air traffic management (ATM), flight, and airline operational control (AOC) functions (7). The Airspace Concept Evaluation System (ACES) was developed under the Virtual Airspace Simulation Technologies element of the VAMS Project at NASA Ames Research Center, and development continued under a subcontract with Raytheon Corporation through May of 2011. During the development period, Intelligent Automation, Inc. was one of the subcontractors responsible for ACES software development. ACES (summarized in Figure 31) enables comprehensive assessment of the impact of new tools, concepts, and architectures, including those that represent a revolutionary change in current NAS operations. ACES is composed of interoperable models that represent the gate-to-gate actions and highly coupled interactions between key participants within the National Airspace System.

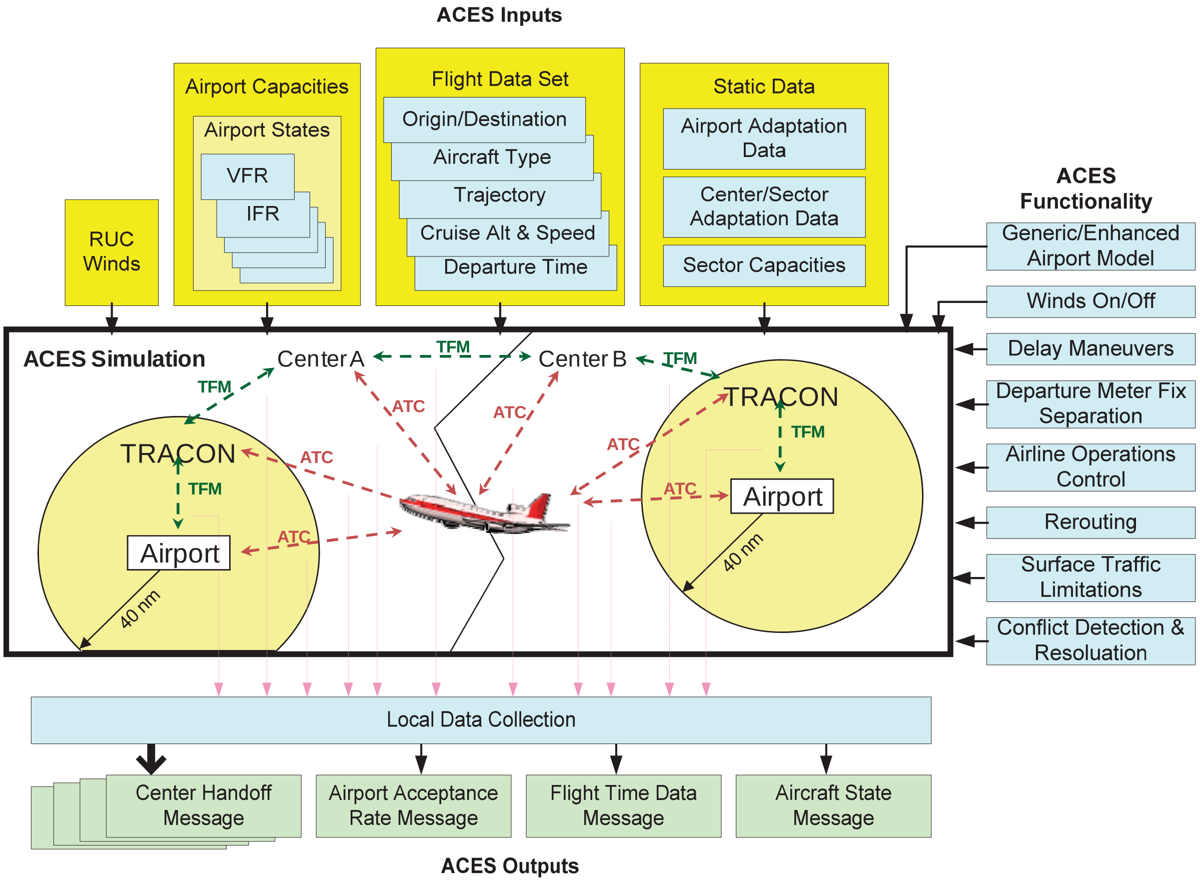


Figure 31: High Level System Diagram of ACES

The core components of ACES infrastructure consist of:

1. The simulation agents and containers that model the current National Airspace System (NAS)
2. CybelePro, the simulation infrastructure that provides a publish/subscribe communications mechanism with an agent-based modeling and simulation framework
3. The Multiple Run Manager, which provides a batch mode and interactive run-time interface
4. Visualization and scenario control tools
5. Message and internal data collection and logging functionality
6. Performance monitoring tools

ACES includes models of following air traffic management functions:

- Airport- Traffic Flow Management (TFM)
- Airport- Air Traffic Control (ATC)
- Terminal Radar Approach Control (TRACON) TFM
- TRACON ATC
- Air Route Traffic Control Center (ARTCC) TFM
- ARTCC ATC
- Air Traffic Control System Command Center (ATCSCC) TFM
- Airline Operations Center (AOC) and Weather
- Traffic Management Advisor (TMA)
- Communication, Navigation and Surveillance (CNS)

The current ACES design instantiates:

- As many flight agents as specified in the traffic data set
- 21 pairs of ARTCC TFM and ATC agents, one pair for each domestic ARTCC, and 1 pair for the international airspace
- Airport TFM and ATC and TRACON TFM and ATC agents, where a set of these four agents is constructed as required to fly the flights
- One ATCSCC TFM agent,
- 18 AOC agents (for traffic demand generation), and
- A trajectory generator model, parameterized for different aircraft types, used to construct trajectories individually for each flight

ACES performs a gate-to-gate simulation of each flight. Flight movement is modeled from the departure airport terminal gate, through the departure airport surface taxi system to and through the takeoff runway system, through the terminal airspace to a departure fix, through a series of en route ARTCCs and their sectors to an arrival fix on a terminal airspace boundary, through the terminal airspace to and through the landing runway system, and through the arrival airport surface taxi system to the arrival airport terminal gate. ACES TFM models develop traffic flow plans and issue traffic restrictions and advisories to each other and ATC agents. ACES ATC models manage flight movement and apply operating procedures subject to satisfaction of the TFM traffic restrictions. These operating procedures are based upon common standard operating procedures within the Centers in the NAS. These simulations are driven by input data describing the arrival and departure schedule by airport and flight plan for each flight. ACES provides various levels of modeling fidelity. En route operations generally are simulated with higher fidelity than terminal. An aircraft trajectory model is used to simulate detailed, time-stepped flight dynamics in en route airspace, whereas node-to-node transit times are used to simulate terminal flight movement. The boundaries of the 20 domestic ARTCCs and all en route sectors are encoded in ACES databases.

4.7. Demand / Business Model

4.7.1. Introduction

Before presenting the results of the analysis models and tools presented in the above portions of Section 4, in this part of the report, we discuss the economics of flexible flights with regard to all three markets—on-demand, general aviation, and commercial operators. First we discuss the various data sources and how we processed them. Next we apply this data to several questions: (1) if commercial airlines were to use the flexible flight option, what markets are they most likely to target? (2) What are the differences in implementing flexible flights for commercial vs. on demand users? (3) From a commercial passenger perspective, what ticket price reductions (if any) would they expect when purchasing a metroplex-bound flight option? (4) From a passenger perspective, what is the total cost (airline fare + ground transportation) of traveling to their ultimate destination (a downtown location, for example)? This final question includes the more general concept of intermodal transportation, where we model the transit time from airport to downtown as an additional delay in the traveler's itinerary.

4.7.2. Airline Origin and Destination Survey (DB1B)

The primary data source for the study is Airline Origin and Destination Survey (DB1B) provided by the Bureau of Transportation Statistics (8). DB1B is a 10% sample of all airline tickets reported by airlines to the Office of Airline Information of the Bureau of Transportation Statics. There are three table categories available in DB1B: Coupon, Market and Ticket. This study uses only Coupon and Market tables. Data from these tables help in investigating traffic patterns, airline market share, passenger flow and some information on ticket pricing. The survey contains quarterly data from 1994 to 2011.

DB1B Coupon

The table provides information about each domestic itinerary of the Origin and Destination survey, including operating carrier, origin, and destination, number of passengers, fare class, trip break and distance. Appendix A has more information on this table.

DB1B Market

This table contains the Origin-Destination specific characteristics of each domestic itinerary of the Origin and Destination survey, including reporting carrier, origin and destination, prorated market fare, number of coupons, and miles flown. Appendix A has more information on this table.

DB1B Ticket

This table consists of summary characteristics of each itinerary. Data on carrier, fare, number of passengers, origin airport, roundtrip indication and miles flown are reported.

4.7.3. Combining DB1B Database Tables

The Coupon and Market tables report different fields of the same airline reported data set. The tables contain a few common fields that associate databases with each other. Table 5 shows some of the fields reported by database. The field "Coupons" refers to individual legs of a journey that is either direct or part of a connecting itinerary. “Market Fare” is the total amount paid for OD journey. “Fare Class” identifies the tickets as economy or business class.

Table 5: DB1B Coupon and Market Fields Comparison

Field	COUPON	MARKET
Itinerary ID	✓	✓
Market ID	✓	✓
Year	✓	✓
Quarter	✓	✓
Sequence No.	✓	✗
Coupons	✓	✓
No. of Passengers	✓	✓
Fare Class	✓	✗
Market Fare	✗	✓
Distance	✓	✓
Origin	✓	✓
Destination	✓	✓
Carrier	✓	✓

This study uses the common field ‘Itinerary ID’ to merge the two databases. Itinerary ID is a set of unique identifiers for each coupon and OD pair. The field ‘Market Fare is reported’ is reported only in Market table while Fare Class is unique to Coupon only. The merged database helps in identifying the number of stops made, ticket price for each leg, market share of each airline etc.

4.7.4. DB1B Data Interpretation

The merged data from the tables above provides all the information about the OD travel. Consider the itinerary ID 2004219. Table 6 to Table 8 show the data snippets from Market and Coupon tables. Within the Coupon database there are three entries with the same itinerary ID 2004219, these are three segments of one round trip between ABQ and BOS. The three entries belong to the same Fare Class ‘X’ or economy. Figure 32 shows the three entries on the map. The table shows the exact movement of the passenger who was on this trip; without any other information it would be difficult to ascertain if the destination was BOS or ABQ. Also, Coupon table also does not report any ticket price information which is very important for any demand-fare modeling.

Table 6 : Coupon Table for Itinerary 2004219

ID	Itinerary ID	Market ID	Seq No.	Coupons	Year	Quarter	Origin	Destination	Carrier	PAX	Fare Class	Dist
186440	2004219	2004236	1	3	2004	2	ABQ	BOS	UA	1	X	1974
186441	2004219	2004219	2	3	2004	2	BOS	ORD	UA	1	X	867
186442	2004219	2004219	3	3	2004	2	ORD	ABQ	UA	1	X	1118

Market table helps in determining ticket price. There are two entries within the Market database with the itinerary ID 2004219 – the first is from ABQ to BOS and second from BOS to ABQ. This shows that this is a round trip from ABQ to BOS. Market table also shows that the ticket price paid for each way was $207.47 and $208.62 respectively. Market table does not break down the journey into segments like Coupon does and therefore ticket price data for each segment is not reported. Merged tables provide complete data including ticket price on each segment.

Table 7: Market Table for Itinerary 2004219

ID	Itinerary_ID	Market_ID	Year	Quarter	Origin	Destination	PAX	Dist	Market Fare
2480259	2004219	2004236	2004	2	ABQ	BOS	1	1974	207.47
2480260	2004219	2004237	2004	2	BOS	ABQ	1	1974	208.62

DB1B Market reports prorated ticket price based on miles flown; i.e. the ratio between ticket price and total distance flown can provide the ticket price for all the segments involved. The merged table shown in Table 8 represents the ticket fare for each segment of the return leg of the journey.

Table 8: Merged Coupon and Market Tables for Itinerary 2004219

ID	Itinerary ID	Market ID	Seq No.	Coupons	Year	Quarter	Origin	Destination	Carrier	PAX	Fare Class	Dist	Fare
186440	2004219	2004236	1	3	2004	2	ABQ	BOS	UA	1	X	1974	207.47
186441	2004219	2004219	2	3	2004	2	BOS	OR	UA	1	X	867	91.12
186442	2004219	2004219	3	3	2004	2	ORD	ABQ	UA	1	X	1118	117.5

Figure 32: Coupon Table results, three entries[1]

---

[1] Image from Great Circle Mapper, http://www.gcmap.com/

Figure 33: Market Table results, two entries[2]

This study requires OD data for each passenger. Market tables reports all required fields except fare class, which is obtained from coupon table.

4.7.5. On-Time performance data

4.7.5.1. T-100 Tables

This table contains on-time arrival and departure data for all non-stop domestic flights by major carriers. It provides departure and arrival delays, origin and destination, and scheduled and actual arrival times. On-time performance data helps in constructing statistical models that predict arrival delays at each airport.

Figure 34 and Figure 35 show arrival delays at JFK during 2009 Q1. Erlang and Poisson distribution provide a good fit for the data and can be used instead for future analyses.

---

[2] Image from Great Circle Mapper, http://www.gcmap.com/

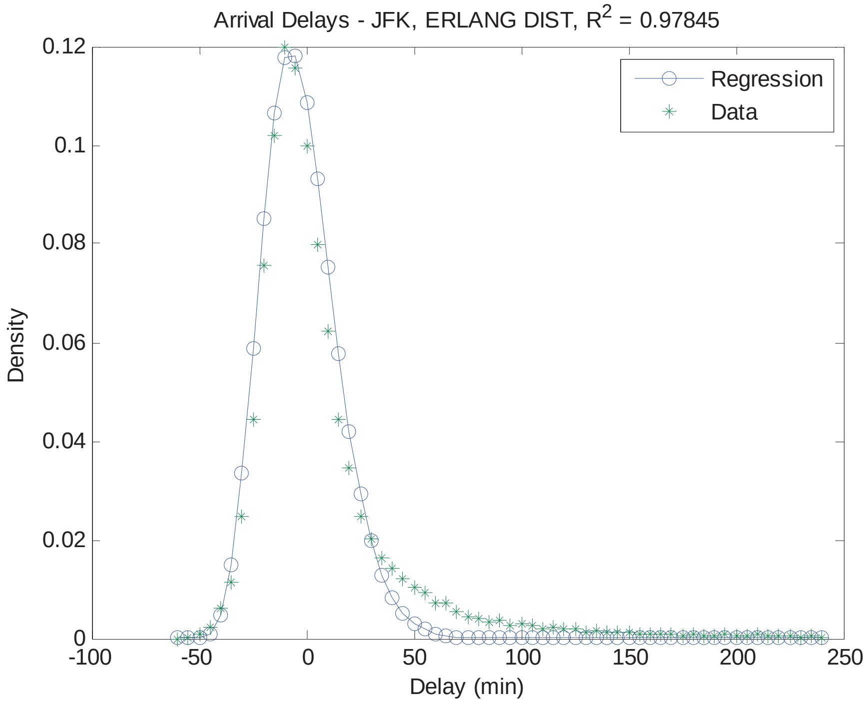


Figure 34: Erlang distribution, JFK arrival delays for 2009, Q1

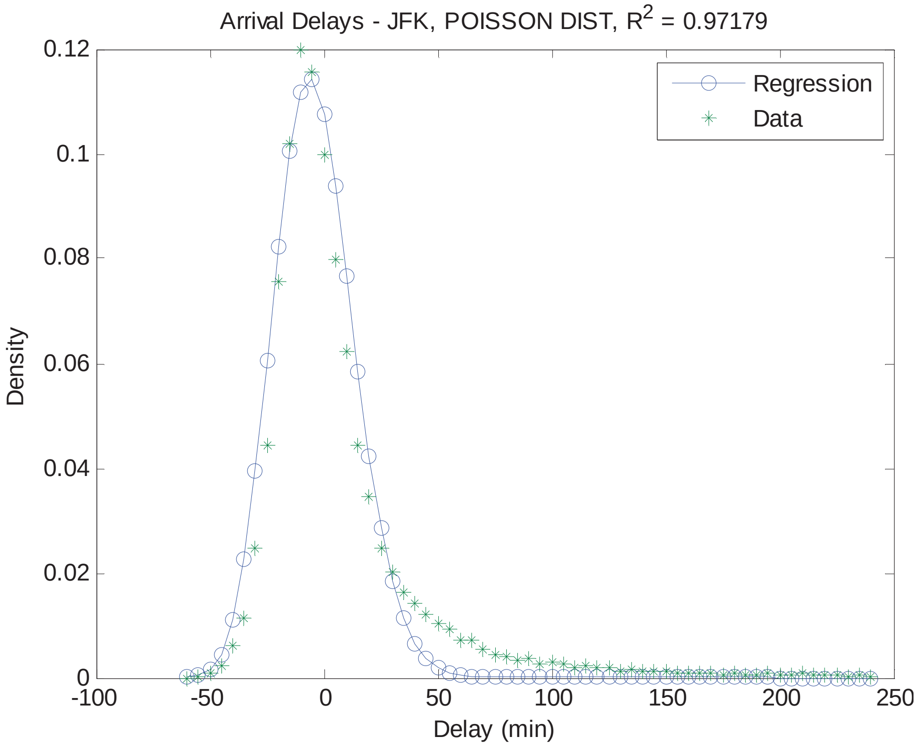


Figure 35: Poisson distribution, JFK arrival delays for 2009, Q1

4.7.6. Metroplex Markets

(Note: Equations are numbered in this sections 4.7.6 – 4.7.8 since there are several)

4.7.6.1. Schedule padding

FAA designates flights as “late” if they are delayed by 15 minutes or over. Airlines are required to report all late flights and the data is made public under T-100 On-Time performance tables. Late flights not only hurt the airline’s reputation among passengers but also increase operational costs with respect to fuel, cabin crew salaries etc. Total delay costs for U.S. Airlines for 2008 was $6.1 billion (9). Delays caused by congested airports are unavoidable; using years of experience of operating flights on the same routes, airlines deliberately over-estimate the flight duration so that most of the time they arrive at their destination at or before the scheduled arrival time. This practice is commonly referred to as schedule padding and it allows airlines to report fewer late flights, even in the presence of congestion at the arrival airports. The frequency and duration of this extra flight time remains hidden as the actual flight times are never reported to Department of Transport (DOT). With the increasing congestion at airports over the past several years, it was thought that by analyzing flights operated by the same airlines using same aircraft and same departure time, but separated by ten years, the extent of schedule padding could be estimated.

Figure 36 were generated using T-100 table for the year 1999 and 2009 with the same carrier, origin-destination and departure time. The analysis shows that there are flights where schedule padding leads to an additional 15 to 30 minutes to the total flight duration.

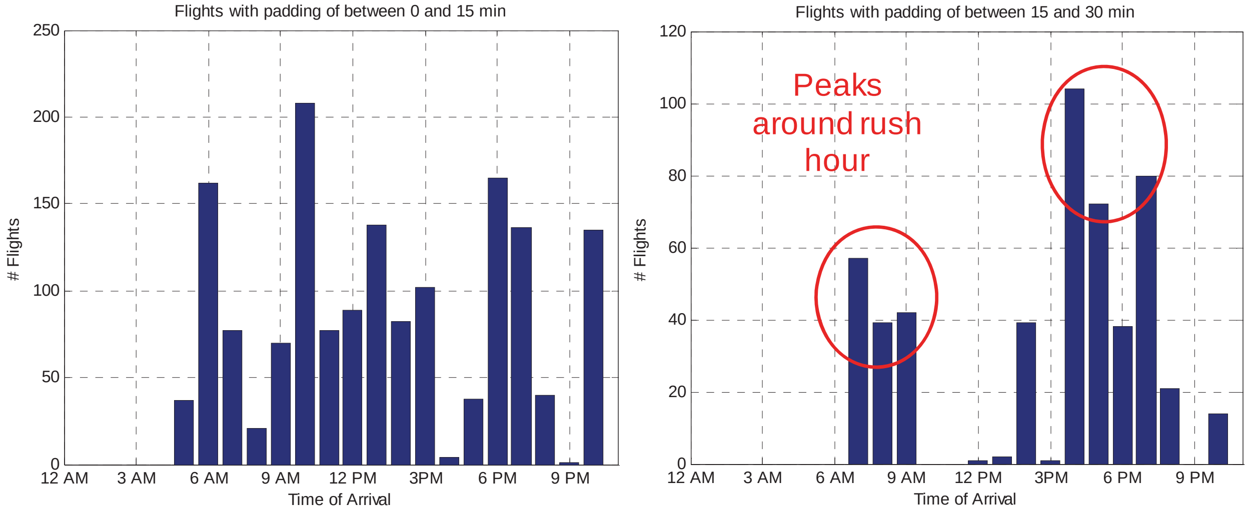


Figure 36: Schedule Padding at N90, 2009 Q1

4.7.6.2. Target Metroplex Markets

Metroplex operations could lead to lower airline delays on flight duration for all flights, irrespective of the total distance and type of aircraft. The ratio between flight delay and flight duration (Normalized Delay) is a good metric to evaluate the impact of new concepts. A higher ratio indicates more value of such operations to passengers; for example, a 20 minute delay on a 30 minute flight is worse than on a 200 minute flight. Based on this rationale, metroplex operations would have greater appeal to passengers on short duration flights.

Figure 37 shows the number of passengers arriving at N90 from around the country. The figure on the right shows the arrival market ordered with respect to their distances from N90. The figure also identifies markets that are closer than 800 miles as potential metroplex market based on Normalized Delay.

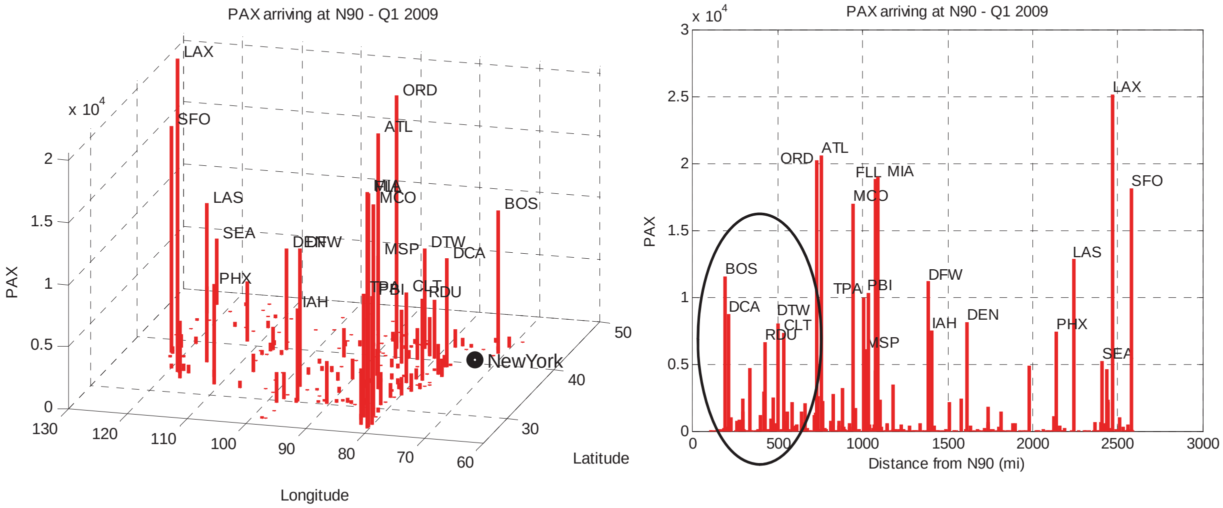


Figure 37: Passengers Arriving at N90 metroplex, Q1 2009

Normalized Delay does not consider two important features that would affect passengers' choice - purpose of travel and economic demography. Travelers who value time more than money would most likely choose to avoid any deviation from their intended travel plan at any cost and therefore would avoid metroplex flights. Others, who value money more than time, would opt for metroplex flights in return for lower ticket prices, even if their travel time would be longer, to include ground transportation. Passengers who in general are looking for a cheaper ticket would opt for metroplex flights. Parameters such as group bookings, ticket class, and travel time could estimate a passenger's level of attraction to a metroplex flight. Passengers traveling in a group and looking for a cheap ticket are assumed to be traveling for leisure, and therefore would be interested in metroplex flights. Passengers traveling on a short journey are more likely to buy a metroplex ticket, based upon higher Normalized Delays.

Using the parameters above, we can identify a new metric metroplex Index (MP_index). It is defined as follows:

$$MP\_index_{i,j} = \left(\frac{PAX_{group}}{PAX_{total}}\right)_{i,j} \left(\frac{Tickets_{coach}}{Tickets_{total}}\right)_{i,j} \left(\frac{T_{GT}}{T_{AT}}\right)_{i,j} \qquad \textbf{Eq. 1}$$

Where

i, j = Origin airport ***i***, destination airport ***j***

MP_index$_{i,j}$ = Metroplex cost metric for flights from origin ***i*** to destination ***j***

PAX_{group}, PAX_{total} = Number of traveling passengers - in group and total

$Tickets_{coach}$, $Tickets_{total}$ = Number of passengers – in coach and total

T_{GT} = Time of travel from destination airport to final destination (minutes)

T_{AT} = Time of travel in air (minutes)

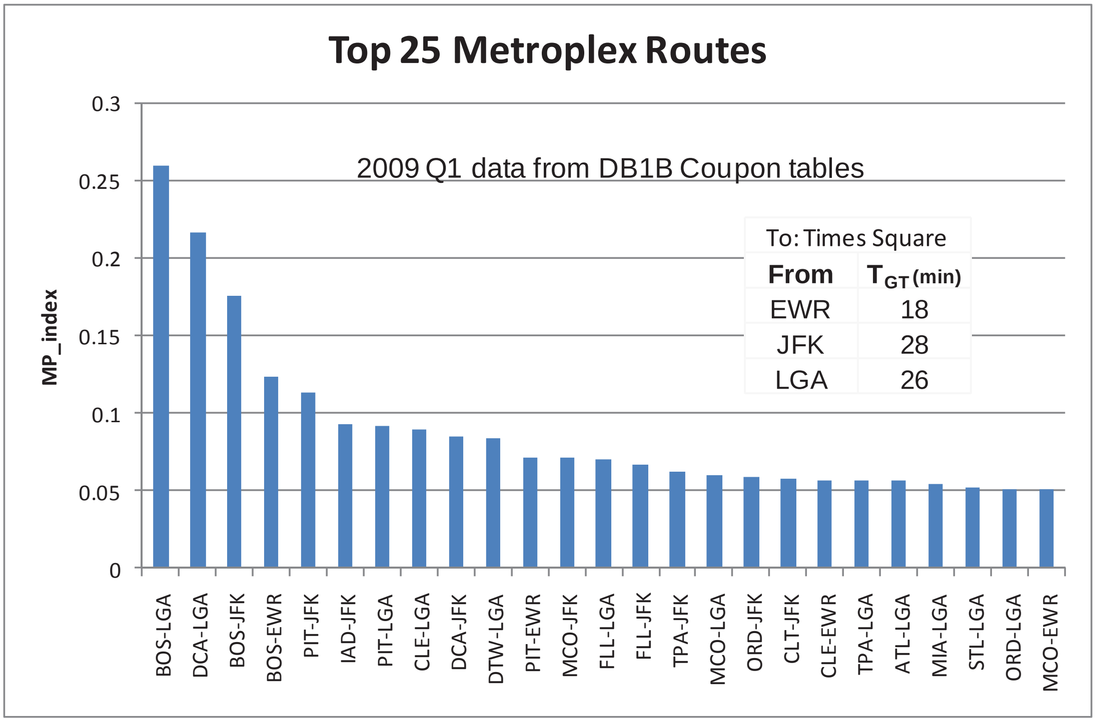
i = Origin Airport

j = Destination Airport

T_{GT} is an important parameter as it captures the effects of traffic on ground transport time from destination airport to the final in-city destination. Researchers are encouraged to use the best available estimates for this value based on the metroplex of interest.

Publicly available data from DB1B Market database is sufficient to calculate MP_index for all U.S. Domestic markets. If the assumptions are true, higher MP_index value indicates better suitability for metroplex flight operations.

Figure 38 compares markets connecting Operational Evolution Partnership (OEP) airports with N90 airports using MP_index assuming the final destination as Times Square, NY. The ground transportation time from the airport to the final destination is shown in Figure 38.



To: Times Square

From	T_{GT} (min)
EWR	18
JFK	28
LGA	26

Figure 38: Potential Metroplex Markets Comparison

The analysis shows short range markets between Boston and N90 are some of the key markets for metroplex operations. The short range markets dominate the top spots but the overall list has a mix of both short and long routes like Pittsburgh – LaGuardia. Since MP_index gives equal importance to number of passengers in a group, ticket prices, and travel time, it could lead to biased results if one of these factors is dominant. If more data is available MP_index could be scaled by adding “weights” a, b, c to the original formulation as shown in equation 2.

$$MP\_index_{i,j} = a\left(\frac{PAX_{group}}{PAX_{total}}\right)_{i,j} b\left(\frac{Tickets_{coach}}{Tickets_{total}}\right)_{i,j} c\left(\frac{T_{GT}}{T_{AT}}\right)_{i,j} \qquad \textbf{Eq. 2}$$

Where:

$MP\_index_{i,j}$ = Metroplex cost metric for flights from origin ***i*** to destination ***j***

PAX_{group}, PAX_{total} = Number of traveling passengers **-** in group and total

$Tickets_{coach}$, $Tickets_{total}$ = Number of passengers – in coach and total

T_{GT} = Time of travel from destination airport to final destination (min)

T_{AT} = Time of travel in air (min)

i = Origin Airport

j **=** Destination Airport

4.7.7. Metroplex Airline Models

A ‘Metroplex Airline model’ could be based on three existing models – Traditional airlines, On-demand airlines and restricted All-Business airline. The All-business airline model is a recent concept that redesigns the interiors of a medium sized aircraft such as Boeing 757 that now accommodates only business class passengers. One such airline in operation is *Openskies*, a British Airways subsidiary that serves Paris – Newark and Paris – Dulles markets. The airline operates only 4 aircraft twice a week. Since this is a radical shift from traditional models and does not apply to the average passenger we do not consider it for metroplex operations.

Key areas of airline modeling are network design and flight and crew scheduling. The next few sections will present the existing modeling techniques for traditional and on-demand airlines along with possible methods to implement metroplex operations within them.

4.7.7.1. Traditional Airlines

Traditional airlines typically employ hub and spoke networks to serve their markets. Hubs help in maximizing resource utilization by routing the majority of the flights through a few hub cities, thereby avoiding direct flight between airports with low demand. Hub and spoke structure helps airlines to maximize profits through the combination of cost economies and concentrated demand markets that are available at the hubs. Airlines are also able to build customer loyalty at the hubs by offering marketing devices such as frequent flyer programs, which are cost effective due to higher demand densities.

The flight scheduling problem can be broken down into a sequence of steps: itinerary identification, fleet assignment, aircraft routing, and crew scheduling. The scheduling process begins with identifying the itinerary using extensive research on historical trends in air traffic. The itinerary for each potential passenger would include the origin, destination, departure time and approximate flight duration. This data provides schedule managers at the airline with targets that they try to meet with the existing infrastructure at their disposal. Estimated demands along with the number of aircraft available provide the flight frequency necessary throughout the day.

The fleet assignment step aims at allocating aircraft on routes within performance constraints and to minimize operational costs. Some of the key operational constraints are airport runway lengths and aircraft fuel capacity. Fleet assignment for airlines based on hub and spoke network feeds several points of departure into a single hub airport from which connecting flights carry passengers to their destination. This assignment type can lead to congestion of traffic at the hub, causing further delays. At present, fleet assignment problems are formulated and solved as integer programming problems, however they turn intractable when solving large size problems (10).

Each aircraft in the fleet has its own maintenance-routing plan and all routing plans need to be coordinated to maintain smooth operation at all times. Routing plans usually spanning two to three days and take the aircraft on a loop through the passengers' demand destinations and through maintenance, stations. Certain stations are equipped with facilities and personnel to provide periodic mechanical checks which range from regular on-route service to a complete overhaul performed after every 6000 hours of service. A route planner's job is to make sure the aircraft serves demand markets while fulfilling the servicing needs on time, and minimizing dead-head (non-revenue-generating) flights. Aircraft routing is a dynamic problem, one that constantly changes based on the health of aircraft in the fleet; in the event of a mechanical failure, the available resources need to be optimized so as to minimize delays and cancellations. The routing problem is solved after the fleet has been assigned. Traditionally, aircraft are assigned to each demand segment manually.

Crew scheduling offers even more challenges than fleet scheduling because of the higher numbers of assignments and maximum hours per day, constraints that do not apply to aircraft. Crew pairing, crew rostering, and crew recovery are the main elements in crew scheduling problem. The crew pairing links two crew members with each other based on their experience and training; crew working limitations are mentioned in Federal Aviation Rules (FAR) work agreements. These FARs state that a flight crew may only work for a maximum of 40 hours during seven consecutive days. Crew rostering considers the problem of constructing monthly work schedules for each employee. Crew recovery involves rebuilding crew pairings in the event of a crew member being unavailable.

4.7.7.1.1. Traditional Airline and Robustness

Air traffic is a highly dynamic system that is prone to fluctuations throughout the day and potential disruptions due to weather, congestion and technical / mechanical failures. Operating in such conditions, an airline's ability to quickly reschedule flights in an efficient manner is most important. A robust airline schedule is flexible enough to recover in the event of unforeseen disruptions. In the event of a mechanical breakdown at the hub, the airline risks disrupting all other connecting flights, leading to a much bigger loss than the cancellation of just one flight. Clarke (11) summarizes major cause of flight delays at hubs as: weather (93%), aircraft equipment failure, runway unavailability, and excess volume. Airline schedule planning has some built-in slack to counter some of these uncertainties, but it flies against the objective of maximizing resource utilization. Excess slack would increase robustness but would also result in lower flight frequencies, which could result in lower revenues.

Flight cancellations have the biggest impact on the operations of a traditional airline based on hub and spoke network as it has the potential to cause widespread disruption to other flights and passengers downstream. In the event of a flight cancellation, the airline bears the additional cost of transporting the stranded passengers to their original intended destination, if necessary through another airline, and if no other alternatives exist, then the airline must also pay the cost of boarding.

To increase robustness, Weide (12) suggests that, when scheduling, connecting flights with short slack time should use the same flight crew and aircraft as an added constraint. These flights form the most vulnerable part of the airline network, as any delay or cancellation would leave too little time for the airline to move reserve resources to that airport. By using the same crew on such flights, the need to identify and deploy a replacement aircraft or crew is avoided. Ahmad Beygi (2008)(13) suggests optimizing the entire airline schedule to channel excess slack from other airports to the one where it is needed in case of delay or cancellation. The optimizer would reschedule the flights while trying to minimize the changes to the original schedule, by giving enough slack to the flight scheduled to depart right after the delayed or cancelled flight. Rosenberg's (2004)(14) concept involves isolating the delayed or cancelled flight from the hub traffic, thereby minimizing its effects on the rest of the network. Shan Lan (2002)(15)(16) suggests an increase in the frequency at critical airports so that even in the case of a cancellation the stranded passengers would not have to wait long for the next flight. Ageeva (2000)(17) uses constraints in the scheduling algorithm which result in routes that makes it easier for other aircraft serving adjacent airports to serve the stranded passengers at an airport. These routes also facilitate a reserve aircraft getting back in the route loop of another aircraft that is unavailable.

The literature review table shown in Table 9 shows some of the recent work on robust airline scheduling.

Table 9: Robust Airline scheduling relevant work (15)

	Objectives				
	Min Cost	Min delays/ disruptions	Ease of recovery	Isolation of disruptions	
Schedule Design		Shan Lan *et al.* (2002)			Kang & Clarke
Fleet Assignment				Rosenberger, *et al.* (2001)	
Maintenance Routing		Shan Lan *et al.* (2002)	Ageeva & Clarke (2000)		Kang & Clarke Shan Lan *et al.* (2002)
Crew Scheduling	Yen & Birge, Schaefer, *et al.* (2001)		Chebalov & Klabjan		

4.7.7.1.2. Traditional Airline Modeling for Metroplex Operations

Metroplex operations would involve flights arriving at airports that may be different from the original flight plan. Operating under a current-day traditional network, any such metroplex flight would break the scheduled chain of flights that use the same aircraft, and leave passengers at the original destination airport without any service. This scenario is identical to a flight being cancelled due to a mechanical fault, and could use some of the “robust” methods discussed in the previous section. Increased flight frequency at metroplex airports would allow stranded connecting passengers to be served without long delays. Adjacent routes with maximum commonality would allow aircraft to switch between them to service passengers stranded due to a metroplex flight arriving at an airport different from the original flight plan. Table 10 below shows an example itinerary of a metroplex bound flight within a traditional airline network. For metroplex-bound flights the destinations are shown as metroplexes (in bold) and not airports, as the final destination would not be known in advance.

Table 10: Example itinerary of a MP-bound flight operating within Traditional airline network

Traditional Itinerary					MP-Bound Itinerary				
UAL, B737					UAL, B737				
FN	**DEP**	**DTIME**	**DEST**	**ATIME**	**FN**	**DEP**	**DTIME**	**DEST**	**ATIME**
100	SFO*	1600	JFK	2100	100	SFO*	1600	**N90**	2100
101	JFK	2230	ORD	0000	101	**N90**	2230	**C90**	0000
300	ORD	1300	PDX	1630	300	**C90**	1300	PDX	1630
300	PDX	1715	SAN	1815	301	PDX	1515	SAN	1815
410	SAN	1915	ORD	2215	410	SAN	1915	**C90**	2215
901	ORD	1310	JFK	1500	901	**C90**	1310	**N90**	1500
001	JFK	1600	SFO*	2100	001	**N90**	1600	SFO*	2100
*Maintenance Base									

Modeling metroplex operations as a traditional hub and spoke airline has some drawbacks. The traditional airlines are not structured to deal well with unplanned disruptions or diversions. The techniques to handle such diversions exist, but they are used in exceptional circumstances. Metroplex flights would need these techniques on a regular basis, which would override the system. A new itinerary generation method is needed, one that is tailored for metroplex operations within a traditional airline network.

4.7.7.2. On-Demand Airlines

With the availability of small and relatively cheap aircraft, on-demand airlines provide services to travelers who call in advance to schedule a flight. Flight scheduling is the most critical objective for any on-demand airline. An effective scheduling system constructs minimum cost pilot and jet itineraries for a set of accepted transportation requests. Airlines such as DayJet(18) began providing per-seat, on-demand air transportation serves for the southeast in 2007. The flight scheduler would employ optimized algorithms with the objective of minimizing operation costs and instances of dead-head flights.

4.7.7.2.1. On-Demand Air Taxi Service Flight Generation

An example scheduler problem formulation is the 'dial-a-flight' problem (19). The key components of this problem are (a) an online accept/reject system to quickly inform passengers if their air transportation requests can be serviced and at what price, and (b) an off-line scheduling system to construct minimum cost pilot and jet itineraries for the next day once the reservation deadline has passed (20). Passengers would need to input their travel plans a couple of days before the flight date. The required inputs would include origin, destination, earliest time of departure and latest time of arrival time. The scheduler would then assign available aircraft and crew to meet passenger demands with a few operational constraints. Typically, aircraft and crew must return to home base at the end of the day or for crew switching. Flight segments can have at most one break

4.7.7.2.2. On-demand Airline Modeling for Metroplex Operations

Modeling metroplex operations based on on-demand airline would require frequent updates to the scheduler. The scheduler would aim at trying to serve all travel requests and minimize dead-head flights. The on-demand metroplex operation constraints would be similar to scheduled constraints of balancing the available aircraft and crew along with trips for regular maintenance. In addition to these constraints, on-demand airline would need the aircraft to return to its base airport to switch crew, and at the end of each day. The on-demand metroplex airline would need to re-optimize resources (aircraft, crew) allocation after a pre-defined time period (e.g. every two hours) to account for any metroplex flight diversions.

Metroplex operations needs an airline model that is robust to multiple disruptions. With small size and flexible schedule, the on-demand airline model is better prepared to handle disruptions. On-demand metroplex airlines would operate a small- to medium-range, nearly homogenous fleet of aircraft, thereby maintaining higher robustness through increased flight frequency following a metroplex flight diversion. Initial MP operations are bound to grow as a niche market with limited coverage, thus starting smaller with the On-Demand model would be the most suitable.

4.7.8. Demand / Business model

Implementation of metroplex operations by airlines would require it to be profitable. Airlines would only be able to make profits if the concept is able to attract new passengers to air travel or have passengers currently using commercial, general aviation, or air taxi, who switch to metroplex-bound flights. Typically, airlines use a variety of methods to attract passengers; these include incentives such as airline miles, free upgrades, and access to lounges at the airport.

A statistical model estimates the ticket prices offered from existing airlines.

4.7.8.1. Ticket Price Statistical Model

The model uses BTS DB1B data for the year 2009 Q1. Appendix A lists the data fields and their descriptions. The model uses multiple regression analysis to estimate the causal relationships between ticket price and the origin – destination pair with other explanatory variables. The model ignores the effects of seasonal changes to passenger demand.

4.7.8.1.1. Model Variables

Ticket Class: The ticket price depends on the ticket class. DOT defines seven ticket class categories as shown in the Table 11. Since the target market for metroplex airlines is mainly passengers that prefer cheaper tickets, the regression model uses data for restricted and unrestricted coach class only.

Trip Distance: Trip distance does not have a strong correlation with ticket price, since the end of regulation (21); however it still remains a factor as it directly impacts operating costs. Since metroplex target markets are likely to be short range the model considers only flights that are 800 miles or shorter.

Market Concentration: Market concentration impacts ticket price through level of competition. Ticket prices are lower for markets where competing airlines operate. The percentage of total seats offered by each airline measures the market concentration.

Table 11: Ticket fare class categories

Code	Ticket Class
C	Unrestricted Business
D	Restricted Business
F	Unrestricted First
G	Restricted First
U	Unknown
X	Restricted Coach
Y	Unrestricted Coach

For an OD (origin - destination) pair Herfindahl Index (HI)(22) measures the market concentration.

$$HI_{ij} = \left(p_1{}^2 + p_2{}^2 + p_3{}^2 ... + p_n{}^2\right)_{ij} \qquad \textbf{Eq. 3}$$

Where

$$T_{ij} = \sum_{1}^{A} s_a \qquad \textbf{Eq. 4}$$

$$p_{nij} = \frac{s_n}{T_{ij}} \qquad \textbf{Eq. 5}$$

i = Origin

j = Destination

$\boldsymbol{s_a}$ = Total number of seats available from *i* to *j* by airline *a*

$\boldsymbol{T_{ij}}$ **=** Total seats available from *i* to *j*

A = Total number of airlines in operation from *i* to *j*

$\boldsymbol{p_{nij}}$ = Percentage of seats from *i* to *j* offered by airline *n*

BTS T-100 table provides the total number of seats offered by each airline on each route. HI index varies from 0 to 1 where 1 indicates monopoly. Two airlines with equal market share would lead to HI value of 0.5. Any market having a Herfindahl Index greater than 0.4 is considered a highly concentrated market and less than 0.18 a less concentrated market. The higher the concentration, the more likely the fare will increase in that market segment.

Passenger Demand: Demand for air travel affects ticket price following demand and supply principal. High demand with low capacity leads to higher ticket price, while low demand generally leads to low ticket price; however this may not be true with markets having high HI index.

Low Cost carrier presence: As a general trend any presence of low cost carriers would reduce the average fare. These airlines serve passengers who travel coach and do not serve business travelers. The ticket price model identifies eight low cost carriers as reported by BTS for the year 2009.

Origin-Destination Airport Size: The model divides all airports into four groups based on their sizes as defined by the FAA (23) – Large Hub, Medium Hub, Small Hub, and Non Hub. Those airports enplaning 1 percent or more of the total are classified as large hubs; airports enplaning between 0.25 percent and 0.99 percent of the total are classified as medium hubs; airports enplaning 0.05 percent to 0.24 percent of the total are small hubs; and airports enplaning less than 0.05 percent of the total are non-hub.

Delay: One of the main benefits of metroplex flights is that they avoid arrivals at congested airports, thus reducing delays. Reduced delay would lead to lower flight operating costs and could also lead to cheaper fares. BTS On-time performance table provides the delay data.

4.7.8.1.2. Ticket Price Regression Model

The general regression model is shown below:

$$\ln(f_{ij}) = \beta_0 + \beta_1 \ln(d_{ij}) + \beta_2 \ln(p_{ij}) + \beta_3 \ln(h_{ij}) + \beta_4 (lc_{ij}) + \beta_5 (s_i) + \beta_6 (s_j) + \beta_7 (del_{ij}) + r_{ij} \qquad \textbf{Eq. 6}$$

Where

$f_{ij} = \text{fare from airport i to j}$

$i, j = \text{origin and destination}$

$d_{ij} = \text{distance from i to j}$

$p_{ij} = \text{number of coach PAX from i to j}$

$h_{ij} = HI \text{ index of segment ij}$

$lc_{ij} = \text{Low cost airline presence (0 or 1)}$

$s_i = \text{Origin airport size (1,2,3,4)}$

$s_j = \text{Destination airport size (1,2,3,4)}$

$del_{ij} = \text{Normalized average arrival delays with flight duration}$

$r_{ij} = \text{Residue value}$

$\beta_0, \beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6, \beta_7$ are regression coefficients

Table 12 below shows the variables sources and the conditioning steps taken to combine data from DB1B coupon and market tables with T-100 tables. The price model uses the data entries shown in bold font. To ignore outliers and promotional ticket sales, the regression model ignores any trip with ticket price cheaper than $50.

Table 12: Regression Model Data Conditioning

Step	Database	PAX	OD Pair	MP Market Criteria	Variable
1	DB1B (Coupon + Market)	9,657,090	7,709	-	fare, PAX, s
2	T-100	14,5673,377	13,776	-	HI, LC
3	**DB1B (Coupon + Market)**	**3,652,072**	**4,815**	**Dist < 800mi Fare > $50**	**fare, PAX, s**
4	T-100	81,587,282	8,838	Dist < 800mi	HI, LC
5	**T-100 (Step 4) ϵ DB1B (Step 3)**	**2,659,455**	**3,251**	**Dist < 800mi Fare > $50**	**HI, LC**
6	**OnTime**	**-**	**2,445**	**Dist < 800mi**	**delay**

The results for the ordinary least square regression analysis are shown in Table 13. The trip distance parameter *d* has a positive sign indicating a direct correlation with fare; i.e., fare increases as distance increases. The passenger demand parameter p has a positive coefficient as well. As passenger demand increases, congestion increases, which leads to increased indirect costs that result in increased fares. The *HI* index has a negative coefficient indicating decreasing fare prices with increasing competition. The negative coefficient indicates that the presence of any low cost carriers drives the ticket prices down. The airport size parameters have negative coefficients, which show that if the origin or destination is a hub, then the fare would go down. This is primarily due to increased competition between airlines at larger airports; with more options to choose from, passengers opt for the cheaper flights, in turn driving airlines to reduce ticket prices as well. The strong positive delay parameter shows that higher delays lead to higher ticket prices. Thus if metroplex flights reduce delays, the model would be able to estimate the new lower ticket price. The statistical analysis shows R squared value of 0.59 with low errors for all parameters. All parameters are statistically significant with p-value less than 1%.

Table 13: Regression model results

Variable	**Coefficient**	**Standard Error**
Intercept	0.7865	0.0700
$\ln(d_{ij})$	0.7111	0.0112
$\ln(p_{ij})$	0.0248	0.0038
$\ln(h_{ij})$	-0.0252	0.0081
lc_{ij}	-0.7223	0.0321
s_i	-0.0558	0.0075
s_j	-0.0685	0.0074
del_{ij}	0.2100	0.0535

R squared	**0.5931**	
# Observations	1,527,600	

Before applying the regression model to predict ticket prices it is important note that due to the three different data sources – DB1B, T-100 and On-time performance tables complete data on only 2,445 OD pairs out of the total 4,815 for which only fare data is available. With better, more homogenous data sources, this regression model would be able to predict with increased confidence than what is possible at present.

5. Results

5.1. Results from ACES Experiments (N90 and SCT, On-demand/GA and Commercial)

5.1.1. Introduction

In this section we present a series of ACES experiments to test the hypothesis that metroplex-bound flights will either have a neutral or beneficial effect on overall system performance. Certainly, if they have a detrimental effect on performance, then the likelihood of their adoption is unlikely.

In conducting these experiments, which occurred early in the project's timeline, the modelers assumed a *random* selection of flights as metroplex-bound, and for each metroplex-bound flight selected, the modelers chose the destination airport *at random.* No attempt was made, in these experiments, to optimize the choice of destination airport to minimize aircraft delay or to optimize system performance. The reason these experiments were conducted was that the project needed a "quick look" to determine metroplex-bound flight performance. Because random variables are used in these experiments, the experiments were repeated a number of times to generate a sample from an underlying population, and then the "bootstrapping" method, explained later, is used to generate confidence intervals for the actual location of the mean performance parameter for each case.

The metric used is the average delay at each of the target airports. Some of the experiments considered N90 metroplex only, while others considered both N90 and SCT. Some of the experiments targeted the "on demand" and general aviation market exclusively, while other experiments targeted only commercial users. The overall goal of these experiments is to gain a quick look into the performance of the system when the metroplex-bound flight option is used by different markets, different user classes, and at different percentages of total operations.

The design of these experiments allow analysis of the entire performance sweep of the concept for different flight operators for both N90 and SCT metroplex Bootstrapping provides the statistical analysis of the experiments that allows us to quantify the performance results using metrics such as 95% confidence interval, mean, and the delay distribution.

Bootstrapping (24) is a nonparametric technique for statistical inference. It is a computer-intensive method that needs a large dataset to work with. The Bootstrapping approach uses the large dataset as a population from which small samples are drawn repeatedly. Unlike other parametric statistical methods, Bootstrap estimates the sampling distribution of a statistic empirically without making any assumptions about the population explicitly. To estimate the statistic of interest a small sample (bootstrap sample) from the population is drawn with replacement by randomly choosing values *n* number of times. The bootstrap sample then estimates the population and any statistics on it would be applicable to the population as well. The main sources of error are: 1) The error introduced by picking a particular sample from the population and 2) sampling error from not using all possible bootstrap samples. Higher values of *n* would reduce the latter error.

5.1.2. Air Taxi and GA Flight Analysis

Metroplex Airline modeling study suggested Air Taxi airlines are better suited to handle the routine disruptions expected in a metroplex operation therefore this analysis focuses on air taxi and GA operations while leaving commercial airline flights unchanged. To map these benefits of the concept, the first set of ACES experiments focus on Air Taxi and GA flights while leaving commercial flights unmodified. Aircraft Situation Display to Industry (ASDI) database provides the baseline Flight Data Set that includes the origin, destination, time of departure and waypoints for each flight on 07 November 2008. Running this unmodified flight data set in ACES provides the baseline delay results.

Table 14 below breaks down the original flight data set into operations (arrival or departure) and flight operators (Commercial, Air Taxi and GA).

Table 14: Original Flight Data Set

	N90		SCT		
Flight Operation	**Arrivals**	**Departure**	**Arrivals**	**Departure**	**Total**
Commercial	1,549	1,545	1,049	1,043	5,090
Air Taxi	292	288	58	64	696
General Aviation	159	202	129	162	643
Total	2,000	2,035	1,236	1,269	6,429

Commercial flights dominate the flight operations with 80% flights out of the total 6429 flights.

The aim of the experiments is twofold – to assess the impact of metroplex operations on Air Taxi and GA separately and to investigate the impact of increasing the number of metroplex bound flights on total delays. Table 15 below shows the experiment design.

Table 15: ACES Experiment Design – GA and Air Taxi

	Flight Operators					
	Air Taxi		GA		Both	
Case	% MP Flights	# Runs	% MP Flights	# Runs	% MP Flights	# Runs
1	25	10	25	10	25	10
2	50	10	50	10	50	10
3	75	10	75	10	75	10
4	100	10	100	10	100	10

The first case investigates the total arrival delays with 25% of all arrivals designated as metroplex bound for Air Taxi, GA and the combination of the two ("both") flights. The other cases are similar with 50%, 75% and 100% of all arrivals designated as metroplex-bound. Metroplex bound flights are identified randomly from the original flight data set and each such flight is assigned a random destination airport from within the metroplex to which the original destination airport belonged. To capture the effects of random assignments each case for each flight operator is run 10 times; including the baseline, this takes the total number of ACES runs to be 121 (4*3*10 + 1).

Figure 39 to Figure 42 below show the results of the four experiment cases. The baseline delay of 4043 minutes, as measured from the ACES experiment run with the original unmodified flight data set, is shown in red while the Air Taxi, GA and "Both" cases are shown in blue and green, respectively. Figure 39 shows the case with 25% of all arrival flights designated as metroplex-bound. All the ACES runs for in this category perform better than the baseline, with the best case reducing delays by 11% and the worst case reducing delays by 3% over the baseline run. Figure 40, Figure 41, and Figure 42 show that increase in metroplex-bound flights results in increased delays for GA flights, while delays from Air Taxi and "Both" flights remain less than the baseline case.

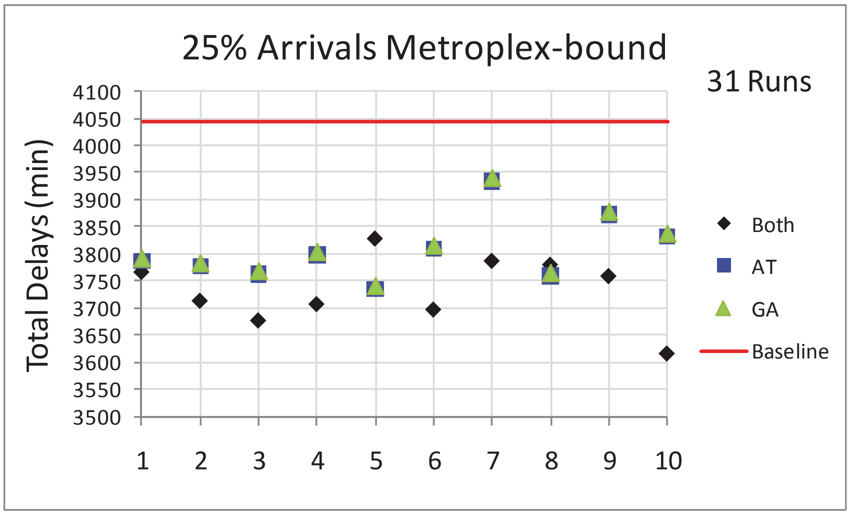


Figure 39: Air Taxi and GA results 25% metroplex-bound flights

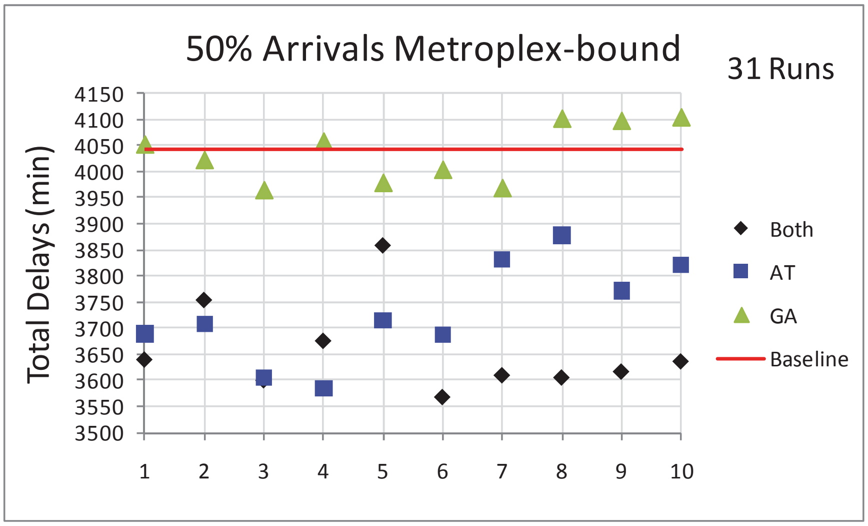


Figure 40: Air Taxi and GA results 50% metroplex-bound flights

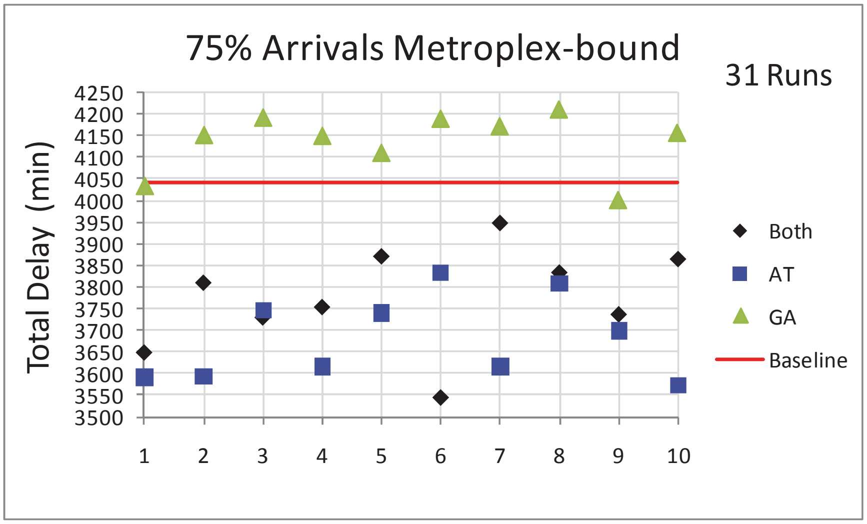


Figure 41: Air Taxi and GA results 75% metroplex-bound flights

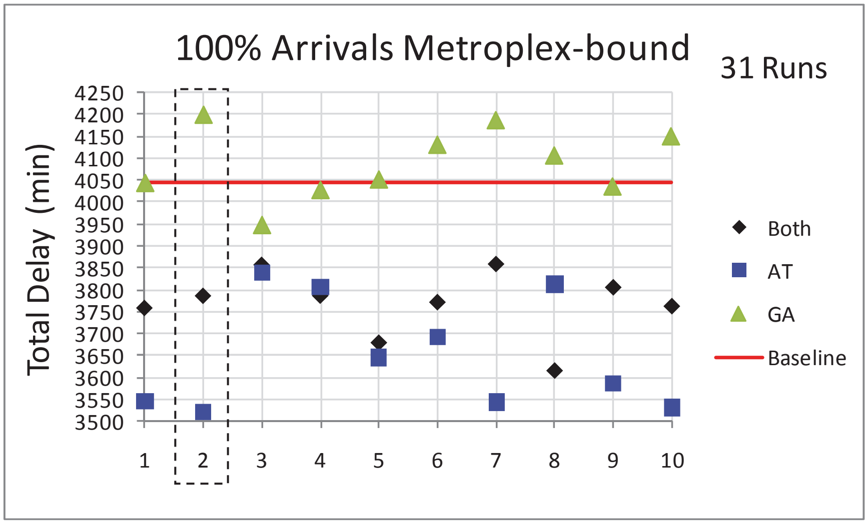


Figure 42: Air Taxi and GA results 100% metroplex-bound flights

The results from the ACES experiments show that GA, “Both” and Air Taxi cases result in delays of 4199, 3787 and 3522 minutes respectively. To investigate the underlying causes of differences in delays for GA, Air Taxi and “Both” cases a set of runs from the case 4 (100% Arrivals as metroplex-bound flights) are chosen. These runs are highlighted in Figure 42. A comparison of the total number of flight arrivals for all airports within the N90 and SCT metroplexes is shown in Figure 43. In the case of LaGuardia (KLGA), the number of arrivals for GA case is much more than the Air Taxi and “Both”. KLGA has 100 more arrivals than Air Taxi and 93 more than “Both” runs and 12 more than the Baseline case.

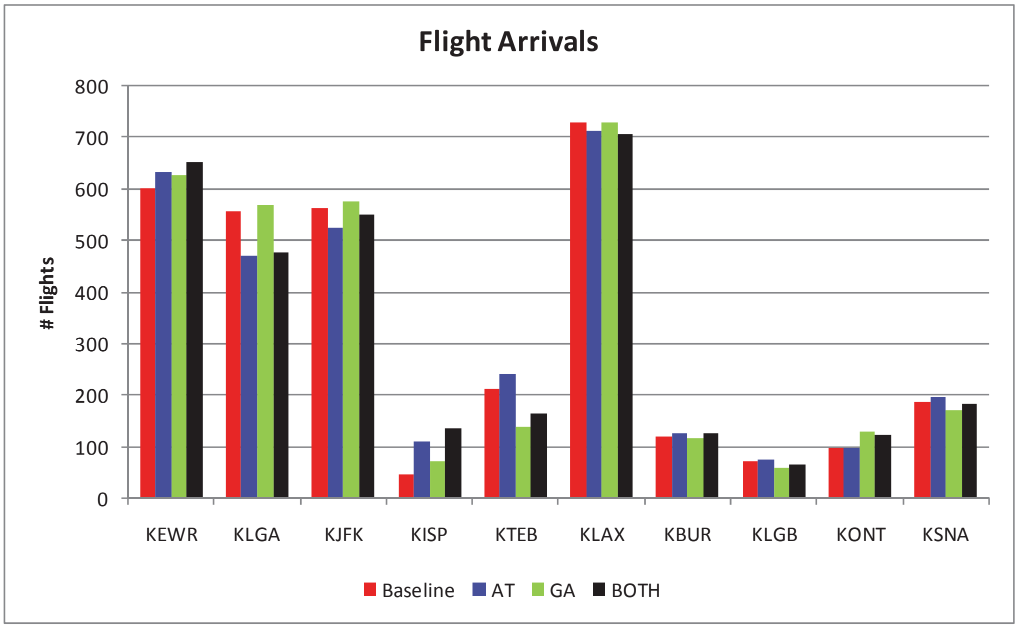


Figure 43: Flight arrivals for ACES runs highlighted in Figure 42

Large number of arrivals would lead to increased delays if the airport capacity constraint is exceeded. Flights that are scheduled to arrive at an airport when the arrival capacity has been exceeded would experience delays. Any increase in the number of such flights would lead to an increase in total arrival delays for that airport. Table 16 below shows the hourly Airport Arrival Rates for all the airports within N90 and SCT metroplexes.

Table 16: Airport Arrival and Departure Rates being used for ACES experiments[3]

ACES Default	
Airport	**AAR**
KEWR	59
KLGA	**43**
KJFK	67
KISP	31
KTEB	43
KLAX	86
KBUR	43
KSNA	31
KONT	59
KLGB	31

---

[3] FAA Airport Capacity Enhancement (ACE) Plan 2000', 'FAA Advisory Circular (AC) 150/5060-5' and 'The FAA ACE Plan 2001'

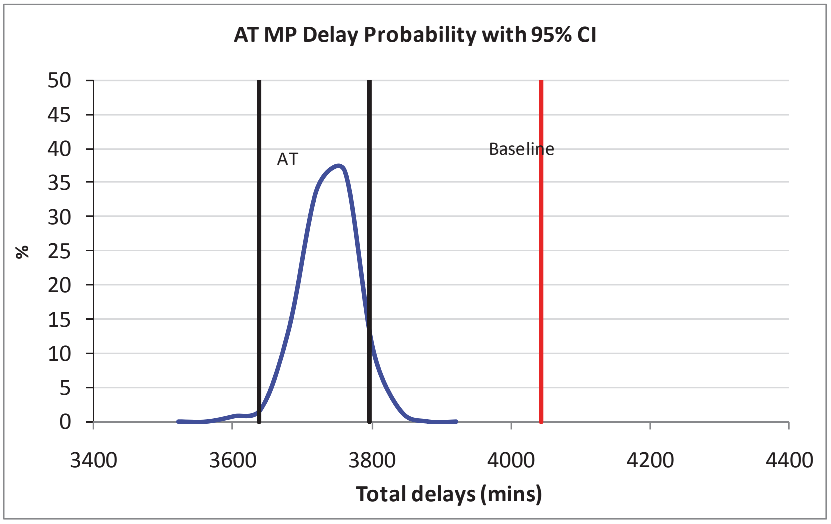
The AAR value of 43 is lowest among the three most busy N90 airports, others being KJFK and KEWR. Table 17 below shows the total number of arrivals at the airports of N90 and SCT metroplexes. The analysis above shows that the low AAR at KLGA combined with the high number of arrivals at KLGA is responsible for increased total delays for GA operations during these random ACES experiments.

Table 17: 100% Arrivals metroplex-bound

	# Flight Arrivals									
	KEWR	KLGA	KJFK	KISP	KTEB	KLAX	KBUR	KLGB	KONT	KSNA
Baseline	601	558	564	47	212	729	119	73	98	187
BOTH	653	477	550	136	166	706	126	66	124	185
AT	634	470	526	110	242	712	127	74	96	197
GA	626	**570**	577	71	138	729	116	60	130	171

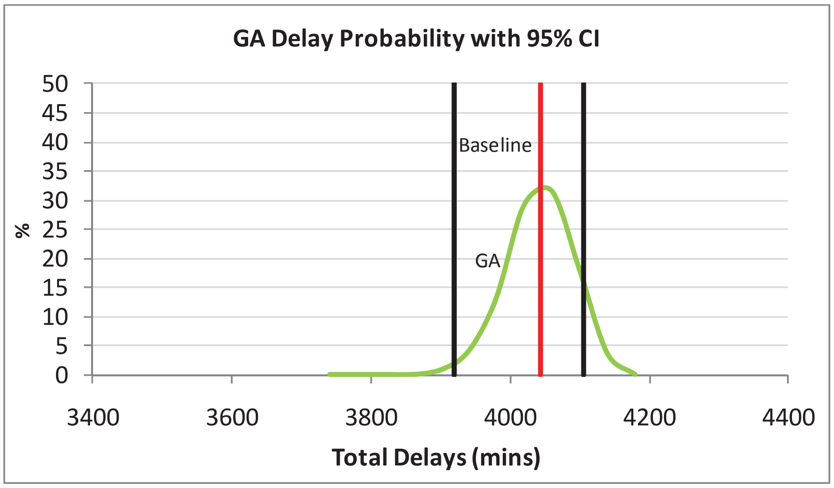
5.1.2.1. Statistical Analysis

Due to the random nature of this set of metroplex experiments it is important to be able to estimate the confidence interval for the delay results generated. There are potentially millions of flight combinations possible by varying the number and destination of metroplex bound flights. Bootstrapping provides the confidence interval estimates from a smaller subset of such flights. As shown in Table 15, there are a total of 40 ACES runs for each flight operator. From this population of 40 results, bootstrap uses 251(25) random samples. This bootstrap sample then provides other important metrics such as 95% Confidence interval bounds, the standard deviations and the standard error. Figure 44 to Figure 46 show the delay distribution for the three operator cases. Similar to the trends from the actual data shown in Figure 39 to Figure 42, delay distribution shows the GA case to perform worse than AT and "Both" cases. Comparing the mean delay values with baseline, Air Taxi case reduces delay by 8% and "Both" by 7%. Mean delay for GA case is just 25 minutes less than baseline.



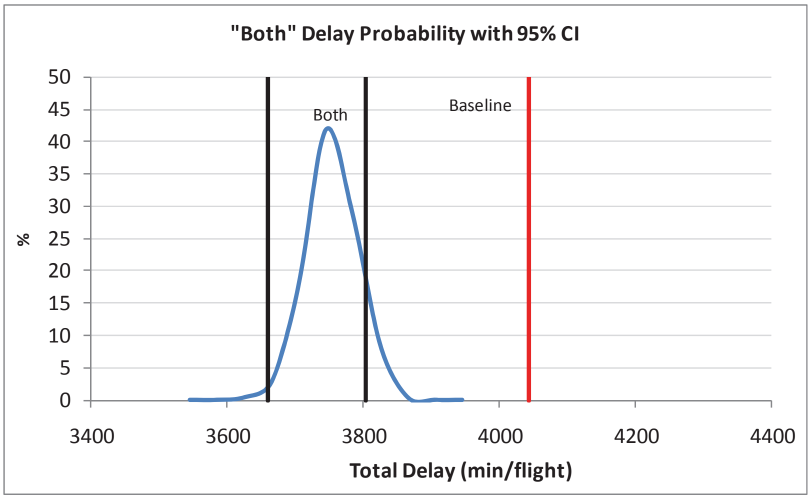
Air Taxi	
Total Sample (N)	251
confidence level %	95
Lower Bound (min)	3637
Upper Bound (min)	3797
Mean (min)	3717
Std. Deviation (min)	108
Std. Error (min)	34

Figure 44: Arrival delay probability for Air Taxi case



GA	
Total Sample (N)	251
confidence level%	95
Lower Bound (min)	3920
Upper Bound (min)	4106
Mean (min)	4017
Std. Deviation (min)	134
Std. Error (min)	42

Figure 45: Arrival delay probability for GA case



"Both"	
Total Sample (N)	251
confidence level%	95
Lower Bound (min)	3660
Upper Bound (min)	3804
Mean (min)	3733
Std. Deviation (min)	93
Std. Error (min)	30

Figure 46: Arrival delay probability for "Both" case

These ACES runs with their statistic analyses provide an estimate of the performance envelope of the metroplex concept when applied to Air Taxi, GA and a combination of the two. The final results show that the concept does reduce total delays at airports given that the capacity constraints are not violated. However, the underlying assumption that any aircraft can arrive at any airport within a metroplex is unrealistic. Within a metroplex the airports differ in terms of demand-to-capacity ratios, which could be a significant factor in the assignment of the destination airport for a metroplex-bound flight. The next set of ACES runs investigates the metroplex concept while addressing more realistic constraints.

5.1.3. ACES Smart Case Analysis

The previous ACES experiments allowed non-commercial flights to arrive at a random airport within the metroplex without any regard to the facilities and congestion levels. Under such a scenario, a small passenger aircraft such as a Beechcraft Bonanza originally flying to Teterboro (KTEB) could be assigned to land at KJFK. This switch from a small airport to a large, busy international airport is unrealistic. Even if there are marginal delays to be saved here, the pilot would likely prefer a small airport with fewer wide-body aircraft and less congestion. These "smart" experiments restrict the destination airport assignment to airports that are of similar size and have comparable facilities as compared to the original destination airport in the baseline flight data set. Previous results point out that N90 airports operate at close to their capacity and experienced maximum delays for the unconstrained metroplex operations. These airports would therefore serve as excellent test cases for the experiments with more realistic constraints. To simulate this "smart" concept, ACES was setup so that flights to big three (KEWR, KJFK, KLGA) airports are randomly assigned to one of the big three, while flights to the small three (KTEB, KISP, KFRG) are randomly assigned to one of them. These experiments designate all GA and Air Taxi flights as metroplex-bound i.e. 100% Air Taxi and GA flights are metroplex bound. The experiment design is shown in Table 18 below. The 40 ACES runs provide the initial population for Bootstrap.

Table 18: ACES Experiment Design – "Smart" case

	Flight Operator	
	Both	
Case	% MP Flights	# Runs
1	100	40

Analysis of ten such ACES runs helps in understanding the underlying reasons for differences in delays among these experiments. Figure 47 below plots the total arrival delays at N90 airports from 10 ACES runs. The results show that all the "smart" case runs result in lower delays than the baseline. Although variation in the delays for each run is evident, it is quite small computed as minutes per flight.

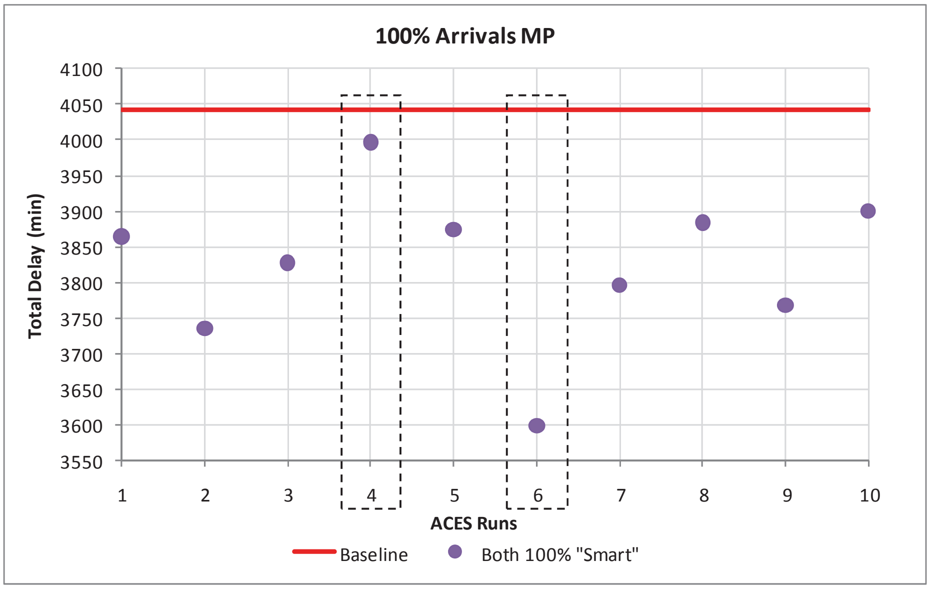


Figure 47: ACES Smart case sample results

The delays range from 0.56 minutes per flight to 0.61 minutes per flight. It is important to note that these delays are results of flight operations at the N90 and SCT metroplex only. It is likely that experiments that include all the other flights would result in much higher delays; therefore it is important to identify key reasons for these delay variations. In Figure 47, ACES runs 4 and 6 result in the highest and lowest delays respectively. The Air Taxi and GA results presented in the previous section identified airport arrival capacity constraint as the primary reason for arrival delays; the current analysis starts with the same approach. Figure 48 compares the number of flight arrivals and total delays at each N90 airport.

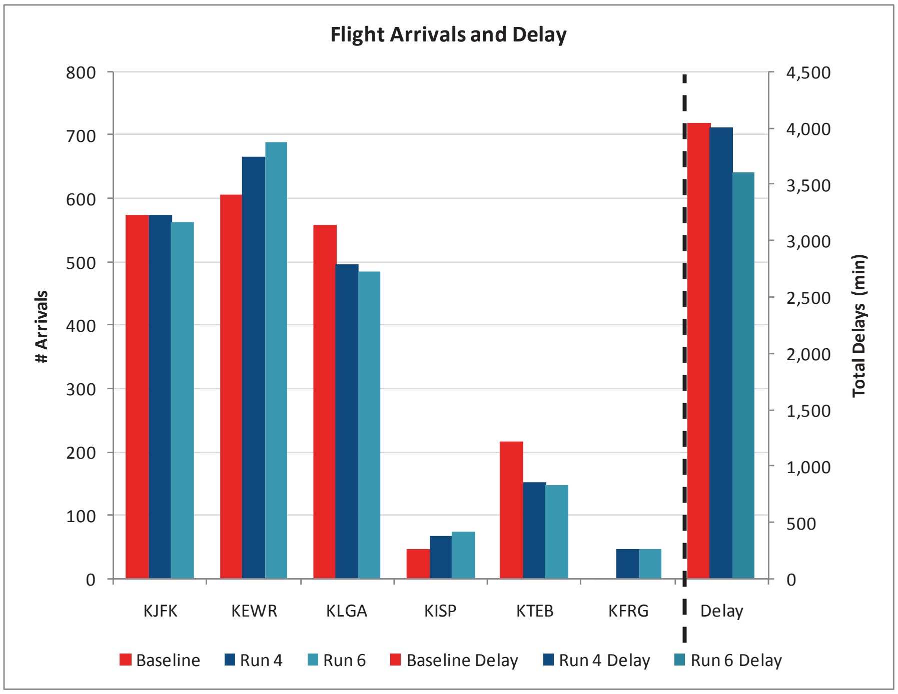


Figure 48: Arrivals and Delay comparison – ACES run 4 and 6 from Figure 47

Among the three busiest airports, KLGA and KEWR experience the most variation in number of arrivals from baseline, to Run 4 and 6. Figure 49 shows the total Air Taxi and GA arrivals for the baseline case.

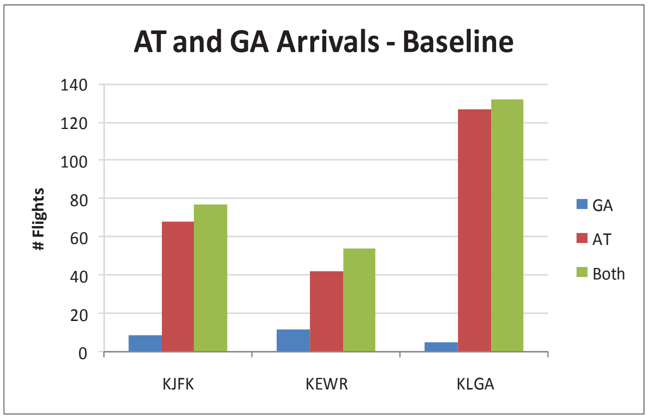


Figure 49: Baseline Air Taxi and GA arrivals at KJFK, KEWR and KLGA airports

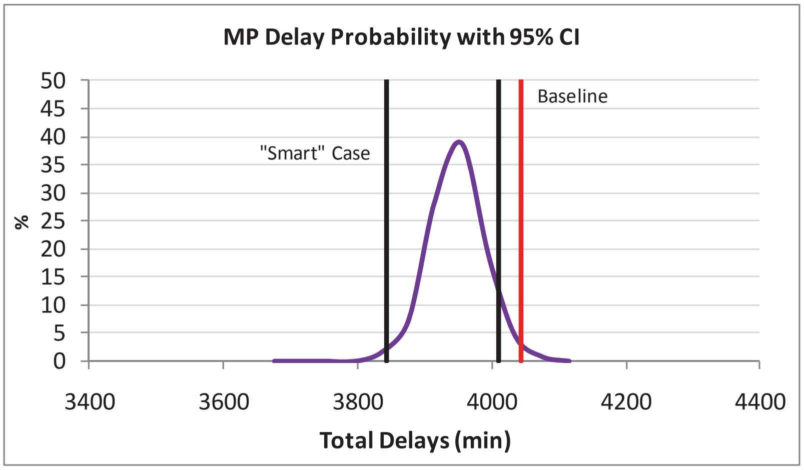
KLGA experiences the majority of Air Taxi traffic therefore for any random metroplex assignment, it is more likely that Air Taxi flights are distributed away from KLGA. This is true for the ACES runs 4 and 6 and in both these cases the number of arrivals is less than the baseline case. As the number of arrivals at KLGA, which is the first of the big airports to reach arrival capacity, decreases so do the total delays. Table 19 shows the arrival delays for runs 4 and 6.

Table 19: Arrival Delays for ACES runs 4 and 6 from Figure 47

	Baseline	Run 4	Run 6
KLGA	791	456	402
KWER	297	404	469
KJFK	711	905	511
Total	1799	1765	1382

5.1.3.1. Statistical Analysis

A Bootstrap analysis further investigates this behavior. A total of 40 ACES runs for the Smart case provide the initial Bootstrap population. Choosing random samples with replacement expands the sample size to 251. 95% Confidence Interval bounds, mean, and errors for this sample estimates these statistics for the entire population.



"Smart"	
Total Sample (N)	251
confidence level %	95
Lower Bound (min)	3843
Upper Bound (min)	4011
Mean (min)	3928
Std. Deviation (min)	120
Std. Error (min)	38

Figure 50: Arrival delay probability for "Smart" case

The bootstrap results show that smart runs for N90 perform better than the baseline. By comparing the mean delays with the baseline shows that the realistically constrained "smart" ACES runs reduced the total delay by 3%. Due to more stringent constraints, this delay saving of 3% is lower than the 7% and 8% provided by Air Taxi and "Both" cases.

Previous experiments deal exclusively with non-commercial flights however commercial flights account for 80% of all operations at N90 and SCT metroplexes. The next set of experiments analyzes the effects of metroplex operation using commercial flights.

5.1.4. Commercial Only Smart Case Analysis

Since majority of the flying public use commercial flights it is important to investigate the effects of metroplex operations on delays for such flights. To identify performance trends by using commercial we run Air Taxi and GA flights as they were in the original flight data set. Purdue University's Flexible Flight Selection model identifies N90 bound 478 flights from the original flight data set as metroplex bound. It uses historical data to identify flights that are most likely to have fewer than five connecting passengers. As with previous experiments we run SCT metroplex flights that were in the original flight data set. For each ACES run these 478 flights are assigned a random destination airport from within the N90 metroplex. The destination airport assignment follows the realistic constraint that ensures the flight arrives at an airport that is similar in size and facilities to the one at which it was originally scheduled to arrive. 40 such runs provide the results for analysis. Table 20 shows the experiment design.

Table 20: ACES Experiment Design – "Commercial Smart" case

	Flight Operator	
	Commercial	
Case	% MP Flights	# Runs
1	100	40

Figure 51 shows the delay results from the 40 ACES runs. The delays vary from 3994 (Run_MIN) minutes to 4735 (Run_MAX) minutes. Of all the 40 experiments only four produced delays lower than the baseline.

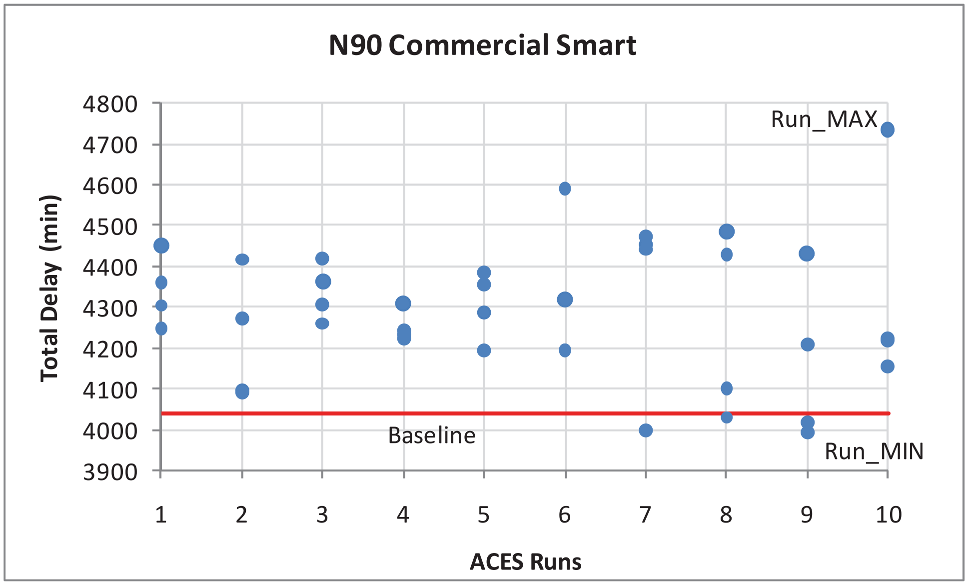


Figure 51: ACES Commercial Smart case results

Table 21 shows the number of arrivals for the baseline, Run_MAX and Run_MIN cases at the three N90 airports.

Table 21: Flight arrivals at N90 airports for Commercial Smart case

	# Flights Arrivals				
	KJFK	**KEWR**	**KLGA**	**Total**	**KJFK + KLGA**
Baseline	564	601	558	1723	1122
Run_MAX	683	587	453	1723	1136
Run_MIN	678	631	414	1723	1092

Since this is a smart run where metroplex flights only arrive at airports that are similar to the ones they were originally assigned to, all three runs result in the same total flight arrivals for the big airports at N90. Comparison of the total number of flights arriving at JFK and LGA shows that the Run_MAX case has the maximum number, followed by the baseline case, followed by the Run_MIN case. The number of arrivals at KJFK and KLGA fall in the same order as the total delays for these runs. Table 22 shows the total delays at KJFK, KLGA and KEWR for the three runs. The Run_MAX case results in the highest total delays, followed by the baseline and Run_MIN cases. This further establishes the relationship between large number of arrivals and greater total delays at KJFK and KLGA. This is likely to be the effect of violation of the arrival capacity constraints at KJFK and KLGA.

Table 22: Arrival delays at N90 airports for Commercial Smart case

	Arrival Delays (min)				
	KJFK	**KEWR**	**KLGA**	**Total**	**KJFK + KLGA**
Baseline	712	297	791	1800	1502
Run_MAX	1430	388	446	2264	1876
Run_MIN	909	334	301	1544	1209

The total number of arrivals over capacity at these airports is shown in Table 23. The 'Run_MAX' case has the maximum number of arrivals over capacity while the 'Run_MIN' case has the minimum; this is in line with the delay trends of Table 22 proving that the congestion at KJFK and KLGA is the main cause of increased delays seen in ACES runs that involve flying commercial flights as metroplex-bound.

Table 23: Arrivals over capacity at KJFK and KLGA for Commercial Smart case

Arrivals Over Capacity			
	KJFK	**KLGA**	**KJFK + KLGA**
Baseline	56	71	127
MAX	110	22	132
MIN	101	14	115

5.1.5. Commercial only distinct N90 and SCT Analysis

For all previous ACES experiments, the original flight data set was modified to estimate the effects of metroplex operations by assigning certain flights a random destination airport while leaving all other flights as they were. These analyses showed that N90 airports experienced higher delays due to their congested airspace that exceeded the airports' capacities. In order to rule out effects of traffic at SCT on N90 results and vice-versa, the next ACES experiments use two distinct flight data sets, one each for the N90 and the SCT analysis. The flight data set for N90 (FDS_N90) consists of only those flights whose origin or destination was an airport in the N90 metroplex. The flight data set for SCT (FDS_SCT) contains only flights whose origin or destination was an airport in the SCT metroplex. Table 24 shows the number of flights in each flight data set by flight operator.

Table 24: Flights by operators - Flight Data Sets FDS_90 and FDS_SCT

Metroplex	N90	SCT
FDS	FDS_N90	FDS_SCT
Commercial Flights	3093	2091
Air Taxi Flights	578	119
GA Flights	358	288
Total	4029	2498

Table 25 and Table 26 show number of flight arrivals and departures for N90 and SCT metroplexes respectively.

Table 25: Flights by operations - Flight Data Set FDS_N90

FDS_N90 Flights		
	Departure	**Arrivals**
KJFK	584	573
KEWR	592	605
KLGA	552	558
KTEB	257	216
KFRG	4	2
KISP	50	48
N90 Total	**2039**	**2002**

Table 26: Flights by operations – Flight Data Set FDS_SCT

FDS_SCT Flights		
	Departure	**Arrivals**
KLAX	737	740
KBUR	116	123
KSNA	239	195
KONT	111	99
KLGB	66	79
SCT Total	**1269**	**1236**

From these flight data sets, the Flexible Flight Selection lists 30% and 50% commercial flights as metroplex bound for N90 and SCT metroplexes. Each such list forms one set of ACES experiments as shown in Table 27 below.

Table 27: ACES Experiment Design – Commercial only distinct N90 and SCT case

Experiments	**Metroplex**	**%Flexible Flights**	**No. of ACES Run**
1	**N90**	**0 (Baseline)**	**1**
2	N90	30	40
3	N90	50	40
4	**SCT**	**0 (Baseline)**	**1**
5	SCT	30	40
6	SCT	50	40

The first and fourth experiments represent the baseline case for N90 and SCT metroplexes consisting of one ACES run each. As with previous experiments, 40 ACES runs provide the population for statistical analysis using Bootstrap approach. The second and fifth experiments involve 40 ACES runs with 30% commercial flights designated as metroplex-bound. Similarly, third and sixth experiments involve 40 ACES runs with 50% commercial flights as metroplex-bound. Figure 52 and Figure 53 show the results for SCT metroplex with 30% and 50% commercial flights selected as metroplex bound.

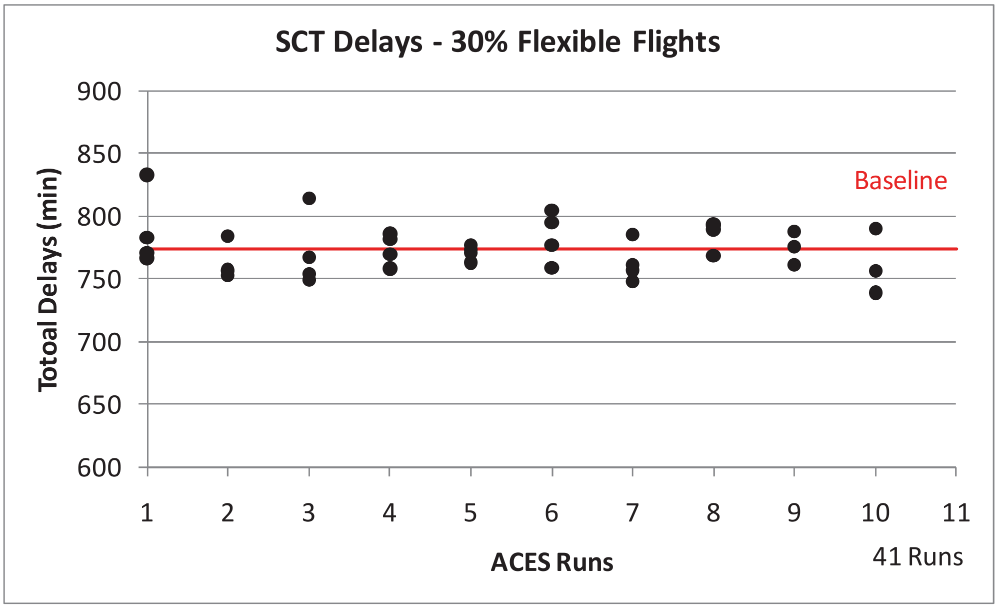


Figure 52: ACES Commercial only distinct SCT case – 30% flight metroplex bound

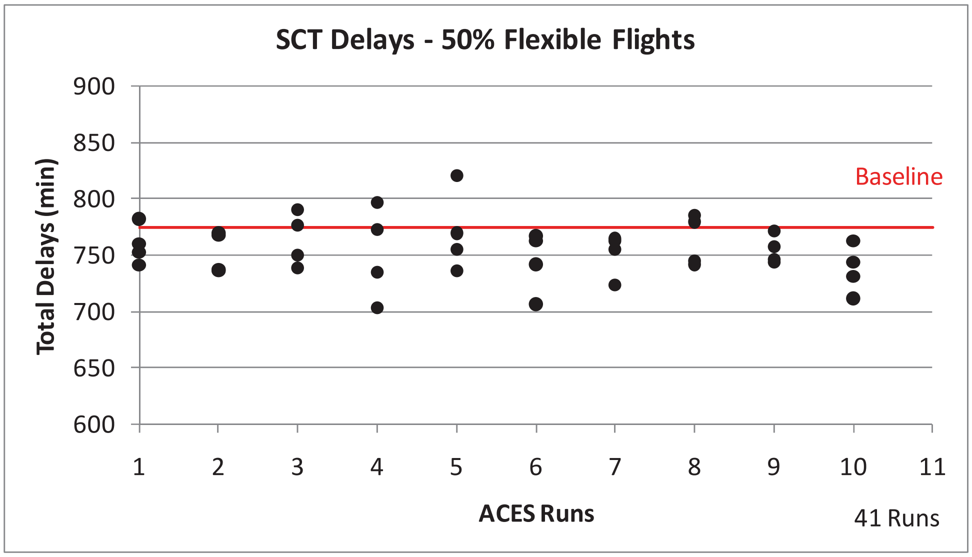
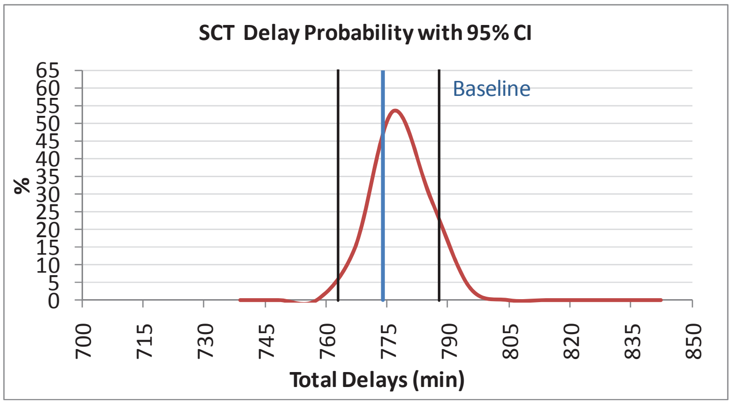


Figure 53: Commercial only distinct SCT case – 50% flight metroplex bound

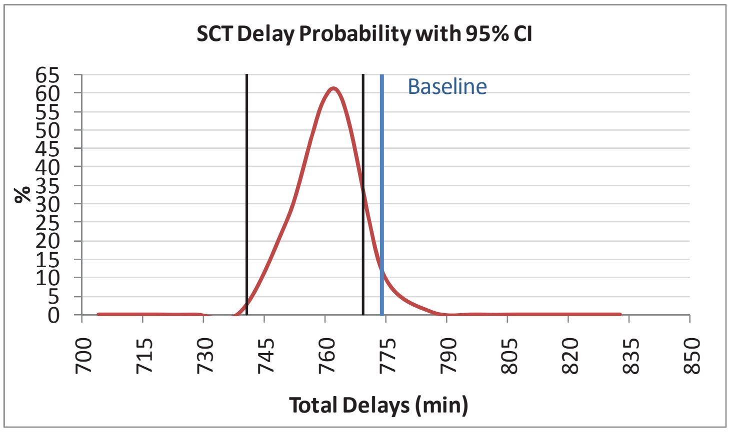
The SCT results in Figure 52 show that with 30% commercial flights as metroplex bound, the delays are comparable with the baseline run. The delays range from 739 minutes (4.5% reduction over baseline) to 833 minutes (increase of 8% over baseline). With 50% commercial flights operating as metroplex bound, only five runs exceed baseline delays and the rest reporting lower delays. The delays range from 704 minutes (9% reduction over baseline) to 820 minutes (increase of 6% over baseline).

Bootstrap uses these 40 ACES runs to estimate the delay probability of a flight operating in the SCT metroplex where 30% or 50% commercial flights are metroplex bound. Figure 54 and Figure 55 show the boot strap results for distinct SCT cases.



SCT 30% Flexible Flights	
Total Sample (N)	251
confidence level %	95
Lower Bound (min)	763
Upper Bound (min)	788
Mean (min)	774
Std. Deviation (min)	18
Std. Error (min)	5.75

Figure 54: Arrival delay probability for distinct SCT case with 30% flexible flights



SCT 50% Flexible Flights	
Total Sample (N)	251
confidence level %	95
Lower Bound (min)	740
Upper Bound (min)	769
Mean (min)	755
Std. Deviation (min)	22
Std. Error (min)	7

Figure 55: Arrival delay probability for distinct SCT case with 50% flexible flights

The bootstrap results show that in case of SCT, an increase in the number of metroplex flights leads to a decrease in delays.

Figure 56 and Figure 57 show the results for N90 metroplex with 30% and 50% commercial flights as metroplex bound. A majority of runs result in delays greater than the baseline case, with only three out of 40 runs performing better. The delays range from 1882 minutes (3% delay reduction over baseline) to 2416 (increase of 24% over baseline). With 50% commercial flights as metroplex-bound all the ACES runs report delays exceeding baseline run. The delays range from 1974 minutes (increase of 2% over baseline) to 2480 minutes (increase of 28% over baseline). Bootstrap results for distinct N90 metroplex with 30% and 50% are shown in Figure 58 and Figure 59, respectively.

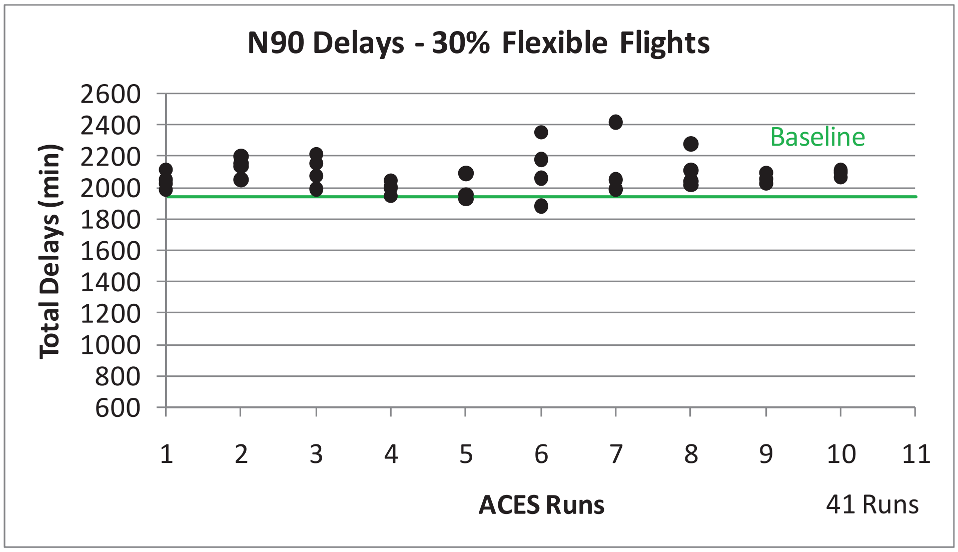


Figure 56: ACES Commercial only distinct N90 case – 30% flight metroplex bound

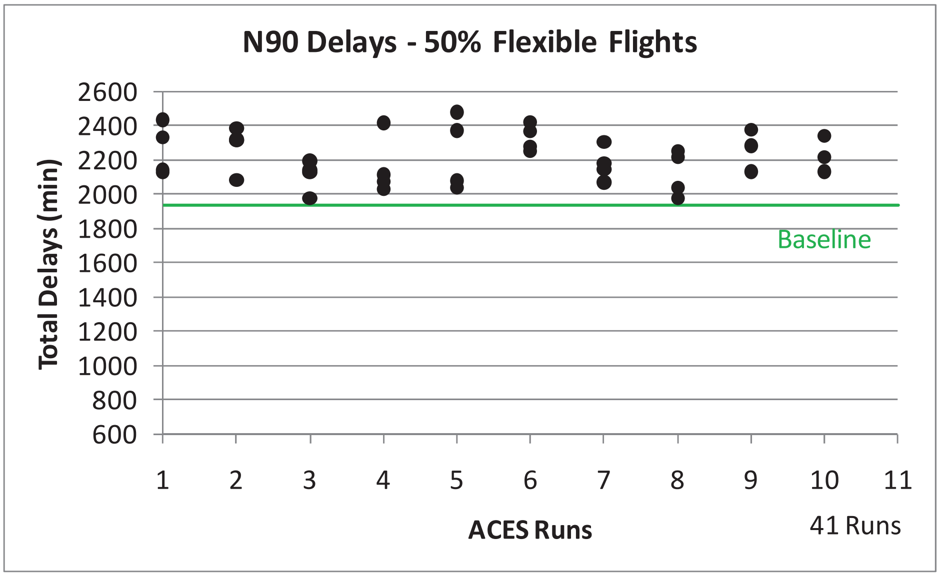
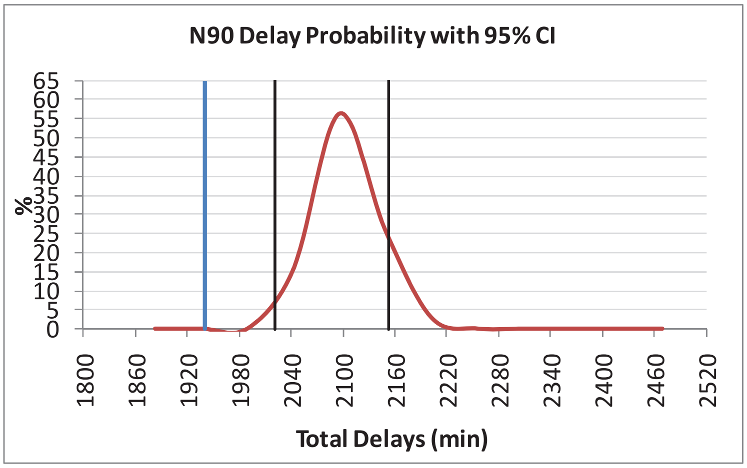
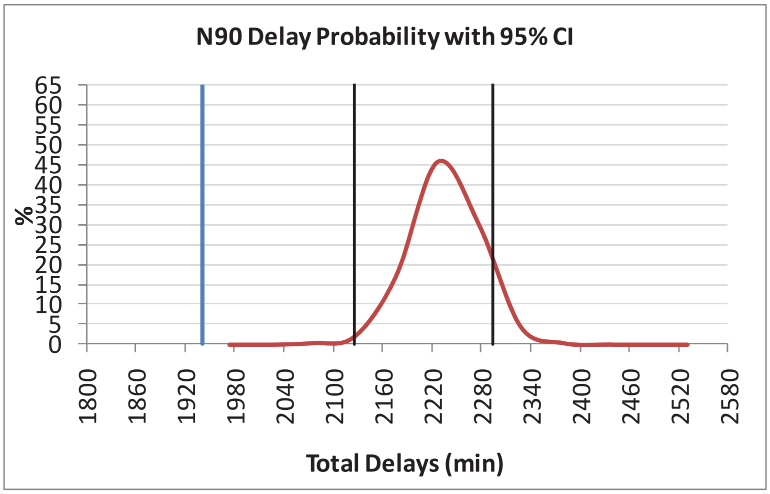


Figure 57: ACES Commercial only distinct N90 case – 50% flight metroplex bound



N90 30% Flexible Flights	
Total Sample (N)	251
confidence level %	95
Lower Bound (min)	2021
Upper Bound (min)	2152
Mean (min)	2076
Std. Deviation (min)	103
Std. Error (min)	32

Figure 58: Arrival delay probability for distinct N90 case with 30% flexible flights



N90 50% Flexible Flights	
Total Sample (N)	251
confidence level %	95
Lower Bound (min)	2126
Upper Bound (min)	2295
Mean (min)	2212
Std. Deviation (min)	133
Std. Error (min)	42

Figure 59: Arrival delay probability for distinct N90 case with 50% flexible flights

N90 metroplex bound flights result in delays higher than the baseline runs. This result agrees with those from previous studies – "Smart" case and Commercial only smart case. Results from those studies point out the constricted arrival capacities at KJFK and KLGA as the main reason for higher delays at these airports. Table 28 shows the arrival delays at each N90 airport. This data would help in estimating the effects of arrival capacity and congestion on N90 airport delays. KJFK and KLGA account for 79%, 75% and 88% of total delays for N90_Baseline, N90_Min and N90_Max runs. They also account for 56%, 54% and 59% of all arrivals for N90_Baseline, N90_Min and N90_Max runs. Further analysis would show that the number of arrivals could justify the delay trends for N90 airports.

Table 28: Arrival delay analysis –Distinct N90 case

N90 Delay Analysis (min)						
	N90_Baseline		**N90_Min Delay**		**N90_Max Delay**	
	# Arrivals	**Arrival Delay**	**# Arrivals**	**Arrival Delay**	**# Arrivals**	**Arrival Delay**
KJFK	397	423	490	564	497	1030
KEWR	450	217	465	229	398	157
KLGA	423	577	315	254	375	465
KTEB	158	38	158	35	158	35
KFRG	2	4	2	4	2	4
KISP	34	2	34	2	34	2
N90 Total	1464	**1261**	1464	**1088**	1464	**1693**

Table 29 shows the landing delays at KJFK, KLGA and KEWR due to arrival constraint violations.

Table 29: AAR landing delay comparisons – Distinct N90 case

	N90_Baseline (min)		**N90_Min Delay (min)**		**N90_Max Delay (min)**	
	AAR Landing	ADR Takeoff	**AAR Landing**	ADR Takeoff	**AAR Landing**	ADR Takeoff
KJFK	250	305	368	422	635	415
KEWR	165	104	178	104	134	104
KLGA	372	183	171	183	308	183

Comparison between N90_Max and N90_Min runs on AAR Landing delays and number of arrivals shows that a difference of seven arrivals results in an increase of 247 minutes of delay. This analysis shows that the difference in number of arrivals alone does not lead to proportionate differences in delays. Comparison between the two flight schedules would help in identifying the differences between the two runs and the time of their occurrence. In Figure 60, flight operation for N90_Max run is shown in red. The difference between N90_Min and N90_Max are shown in black. The periods of positive black columns coincides with periods of high traffic volume for the N90_Max run. This means that for N90_Max run the additional metroplex bound flights arrive at times of peak traffic thus resulting in larger delays even with comparable number of total flight arrivals than in the N90_Min run.

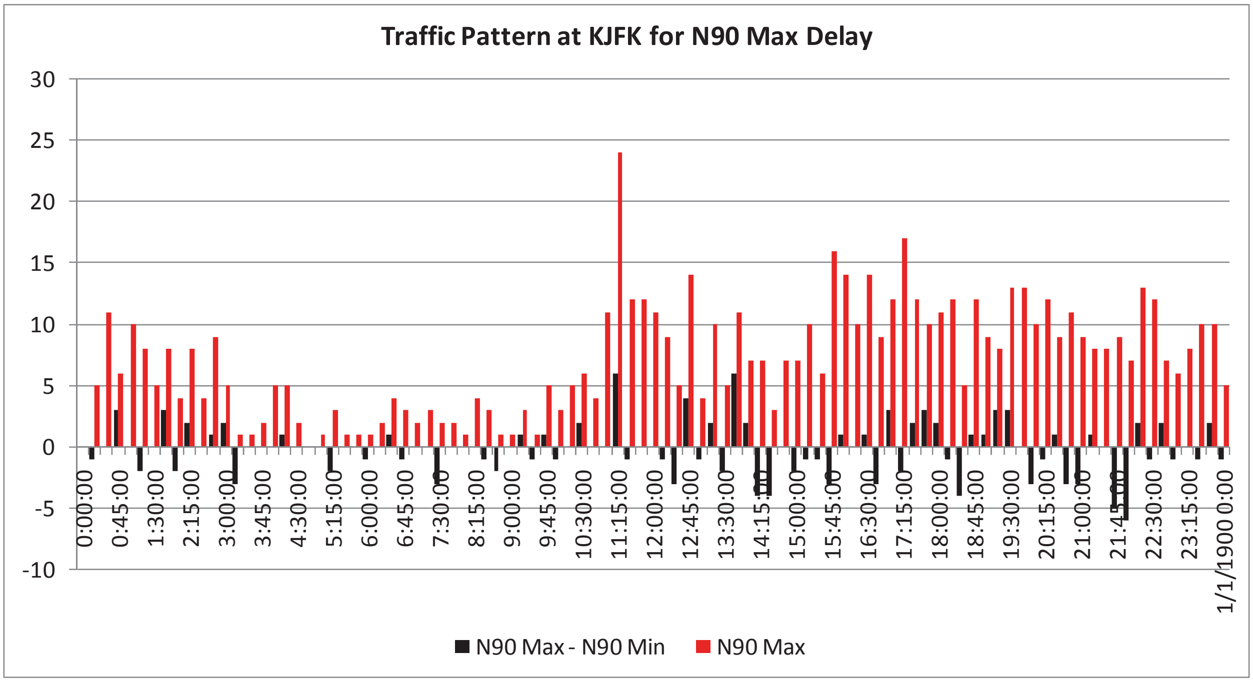


Figure 60: Flight operation comparison – N90_max and N90_Min runs

5.2. Results from LTV – McTMA model

To evaluate the benefit of flexible operations and the integrated model on the metroplex regions, actual flight data into N90 Metroplex was utilized to test the integrated LTV-McTMA model. Figure 61 shows the stacked ETA distribution of the historical data for three major airports (EWR, JFK, LGA) on N90. An interesting demand characteristic is that traffic demand at JFK between 1:00 and 5:00 is much less than that at either LGA or EWR. On the other hand, demand at JFK from 16:00 to 23:00 increases steeply and overall demand among three airports seems to be evenly distributed compared to those at earlier time periods.

Given all ETAs, McTMA determines the required time of arrival (RTA) for each flight at every meter fix and airport while considering critical operational constraints. Delay for each flight at meter points and the airport is defined as the difference between the unimpeded ETA and RTA.

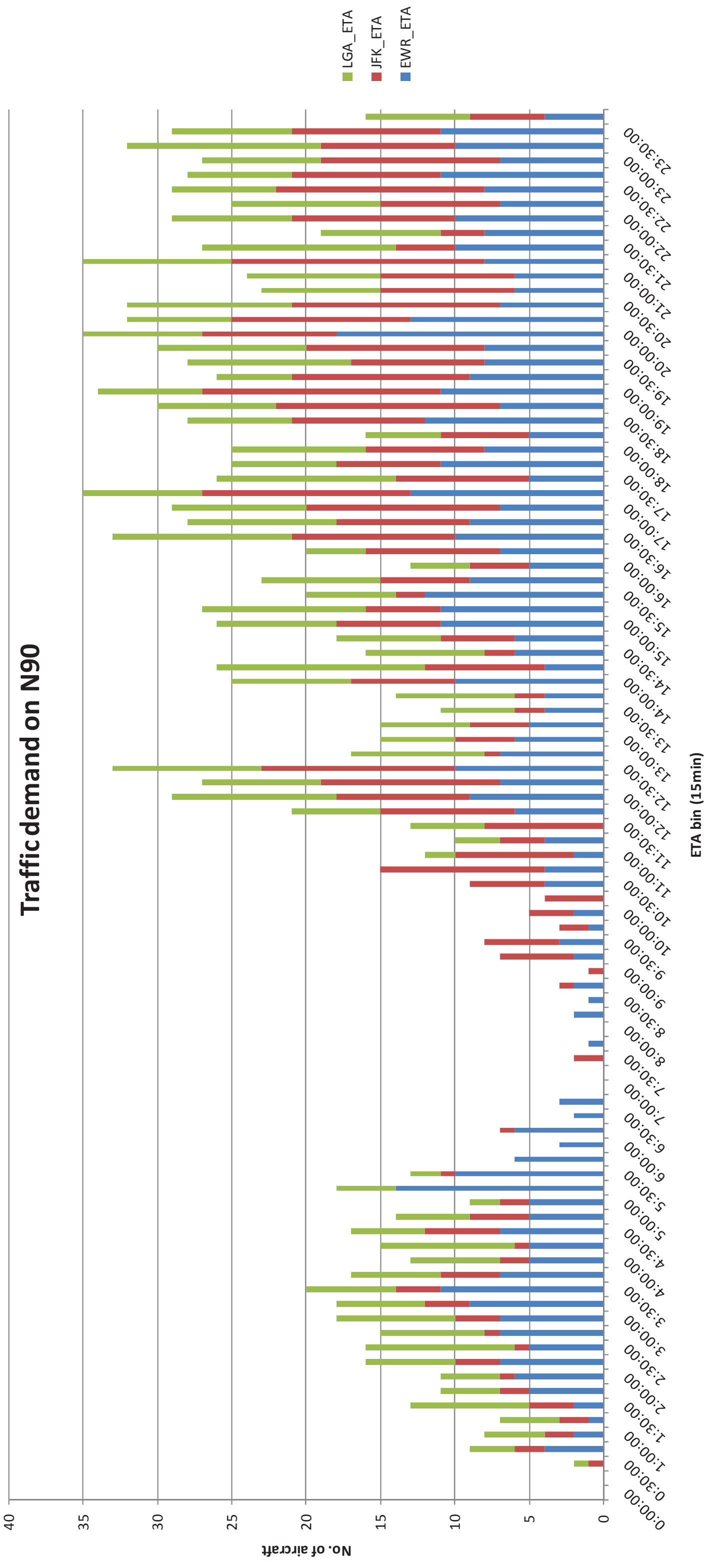


Figure 61: Traffic demand on N90

Table 30 shows an example of the McTMA scheduling result for the major airports in N90. A total of 1524 flights on November 7, 2008 were tested and scheduled at 14 arrival fixes and 3 major airports. As indicated in the highlighted area, the McTMA scheduler schedules aircraft by assigning the necessary delay to keep aircraft separated based on wake vortex separation and proper separation at the meter fixes. No additional arrival rates are set in this analysis.

One possible limitation of this scheduling analysis is to approximate the computation of wake vortex separation by using speeds at five minutes before touchdown, because no detailed runway configuration exists in the current data.

Table 30: Scheduling example output

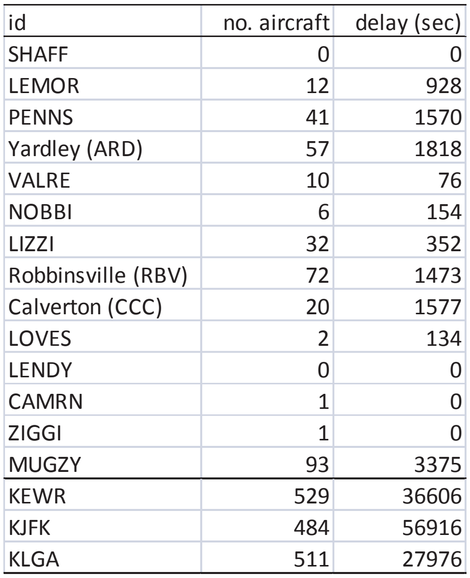
EWR	ETA	STA
JBU540	20:03:00	20:04:28
BTA2852	20:08:00	20:08:00
COA1580	20:08:00	20:09:17
COA1177	20:09:00	20:10:34
COA85	20:10:00	20:11:33
AVI1	20:10:00	20:13:13
BTA2864	20:11:00	20:14:33
COA111	20:11:00	20:15:55
COA1134	20:11:00	20:17:12
UCA8640	20:13:00	20:18:29
COA769	20:13:00	20:19:44
DLH402	20:14:00	20:20:40
COA1403	20:14:00	20:22:17
CJC3406	20:15:00	20:23:34
BTA2342	20:16:00	20:24:51
TRS577	20:17:00	20:26:08
CJC3253	20:19:00	20:27:25
BTA2939	20:21:00	20:28:46
COA55	20:21:00	20:29:48
COA171	20:21:00	20:31:28
COA186	20:24:00	20:32:45
COA71	20:24:00	20:33:43
JBU554	20:25:00	20:35:20
BTA2533	20:29:00	20:36:38

JFK	ETA	STA
FIN5	20:04:00	20:05:25
AFR6	20:09:00	20:09:00
AMX402	20:11:00	20:11:00
SWR14H	20:12:00	20:12:00
JBU1086	20:13:00	20:13:40
EGF4656	20:16:00	20:16:00
DAL99	20:16:00	20:16:57
NWA895	20:17:00	20:18:35
JBU832	20:18:00	20:19:49
EIN111	20:18:00	20:20:44
DAL30	20:20:00	20:22:27
FRL214	20:21:00	20:23:49
UAL6	20:22:00	20:25:04
JBU94	20:23:00	20:26:17
JBU605	20:26:00	20:27:30
EGF4750	20:27:00	20:28:43
COM727	20:29:00	20:29:56
CPA94	20:30:00	20:30:53

LGA	ETA	STA
AWE2174	20:01:00	20:02:34
AAL1030	20:04:00	20:04:00
PDT4203	20:04:00	20:05:17
EGF4838	20:06:00	20:06:27
DAL1354	20:12:00	20:12:00
EGF4921	20:14:00	20:14:00
DAL1356	20:17:00	20:17:00
AWE2131	20:18:00	20:18:17
NWA508	20:18:00	20:19:33
ACA714	20:24:00	20:24:00
TRS207	20:31:00	20:31:00

Table 31 indicates the computed total delays for nominal flights (non-optimized) at the 14 meter fixes and 3 major airports. JFK incurred about twice as much delay as the other two airports, even when it had the smallest number of arriving aircraft. That is possibly because the traffic demand to JFK is not evenly distributed over an entire day. Among 14 meter fixes, MUGZY, which is shared by EWR and JFK, had the largest delay.

Table 31: Delays for Nominal Flights at 14 meter fixes and 3 airports (Non-optimized)



id	no. aircraft	delay (sec)
SHAFF	0	0
LEMOR	12	928
PENNS	41	1570
Yardley (ARD)	57	1818
VALRE	10	76
NOBBI	6	154
LIZZI	32	352
Robbinsville (RBV)	72	1473
Calverton (CCC)	20	1577
LOVES	2	134
LENDY	0	0
CAMRN	1	0
ZIGGI	1	0
MUGZY	93	3375
KEWR	529	36606
KJFK	484	56916
KLGA	511	27976

5.2.1. Scheduling results

Before testing the flexible operation concept, we attempted to identify the benefit of just the optimization performed by the LTV when there were no flexible flights. ETAs based on the November 7, 2008 traffic file were input to McTMA, without optimization, and scheduled. (This traffic file is considered the "nominal" traffic file.) The same traffic file then had their ETAs modified by the LTV as discussed above, and the resulting traffic file was input to McTMA. (Again, none of these flights were considered flexible.)

Figure 62 shows the comparison of total delay for nominal flights with that of the LTV-optimized flights. Using the LTV optimizer, the total sum of delays at the three airports was reduced to 1,830 minutes (9.5 % reduction) as compared to the 2,025 minutes for the nominal traffic file. The LTV optimizer seems to condition the flows to reduce arrival peaks at JFK.

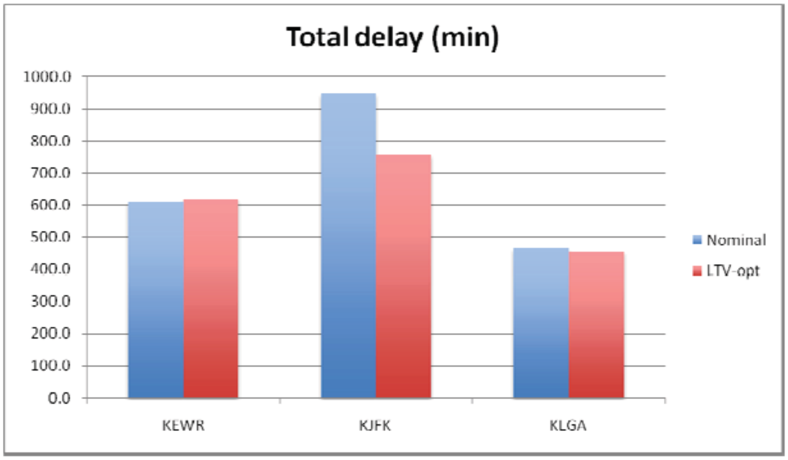


Figure 62: Total delay for 3 airports at N90 for nominal vs. LTV-optimized flights

More detailed delay statistics for both nominal and LTV-optimize flights are shown in Table 32. Overall, the LTV optimizer has a positive effect on delay reduction even though the main function of LTV optimizer is not to decrease total delay.

Table 32: Delay Statistics for 3 airports at N90 for nominal vs. LTV-optimized flights

Delay on N90	EWR		JFK		LGA	
	non-opt	opt	non-opt	opt	non-opt	opt
Mean (min)	1.15	1.17	1.96	1.56	0.91	0.89
Median (min)	0.33	0.55	0.95	0.74	0.40	0.38
SD (min)	1.71	1.49	2.70	2.18	1.09	1.09
Max (min)	9.70	9.13	12.88	10.28	4.88	5.85
3rd quartile (min)	1.65	1.90	2.85	2.26	1.53	1.53

Next, different combinations of flexible flights, with and without LTV-optimization are compared. Specifically, under conditions with and without LTV-optimization, different percentages of flexible flights were compared – 0%, 10%, 20%, 30%, 40%, and 50%. (The 0% cases are discussed above – the “nominal” and “optimized” cases whose results are shown in Figure 62: Total delay for 3 airports at N90 for nominal vs. LTV-optimized flights and Table 32.)

Figure 63 and Table 33 show how total delay changes depending on the percentage of flexible flights. As the percentage of flexible flights increase, the total sum of delay for the three major airports decreases almost linearly. This suggests that McTMA and ARB reduce overall delay by reassigning flexible flights to less congested slots. Compared to the nominal case, the benefit of delay reduction reaches 29.4% at 50% flexible flights.

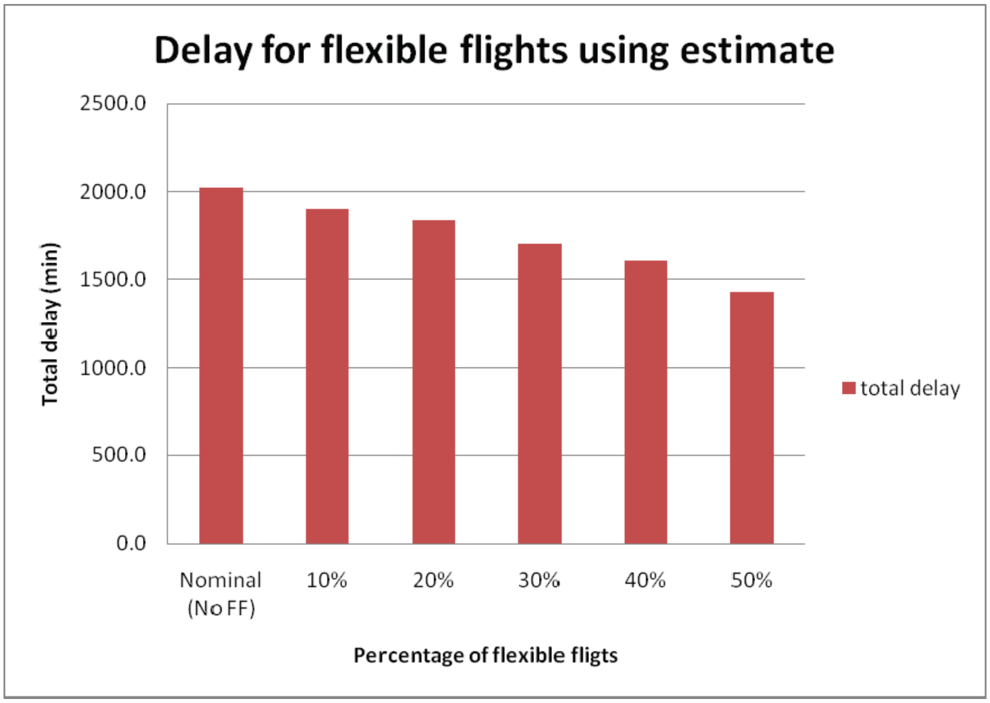


Figure 63: Total delays for various flexible flight percentages into N90 for November 7, 2008

Table 33: Delay reduction for various flexible flight percentages into N90 for November 7, 2008

	KEWR	KJFK	KLGA	Total	Reduction
Nominal (No FF)	610.1	948.6	466.3	2025.0	
10%	586.6	1001.4	316.2	1904.2	-6.0%
20%	547.9	975.3	313.3	1836.5	-9.3%
30%	414.7	967.0	322.4	1704.2	-15.8%
40%	377.4	825.5	406.2	1609.1	-20.5%
50%	389.3	586.4	453.4	1429.1	-29.4%

Next, the same percentage of flexible flights was used in conjunction with LTV optimization. The results are shown in Figure 64 and Table 34. The results exhibit similar behavior to the non-optimized case, but with a somewhat larger benefit in terms of delay reduction. Combining the integrated model with 50% flexible flights chosen resulted in a reduction in total delay of 40.8%.

In Figure 64, it is observed that delay with 20% flexible flights the delay slightly increases over the 10% case, which is a deviation from the otherwise-linear decreasing trends of delay reduction. While the reason for this is unknown, there is likely some variability in the benefits obtained due to the particular traffic file.

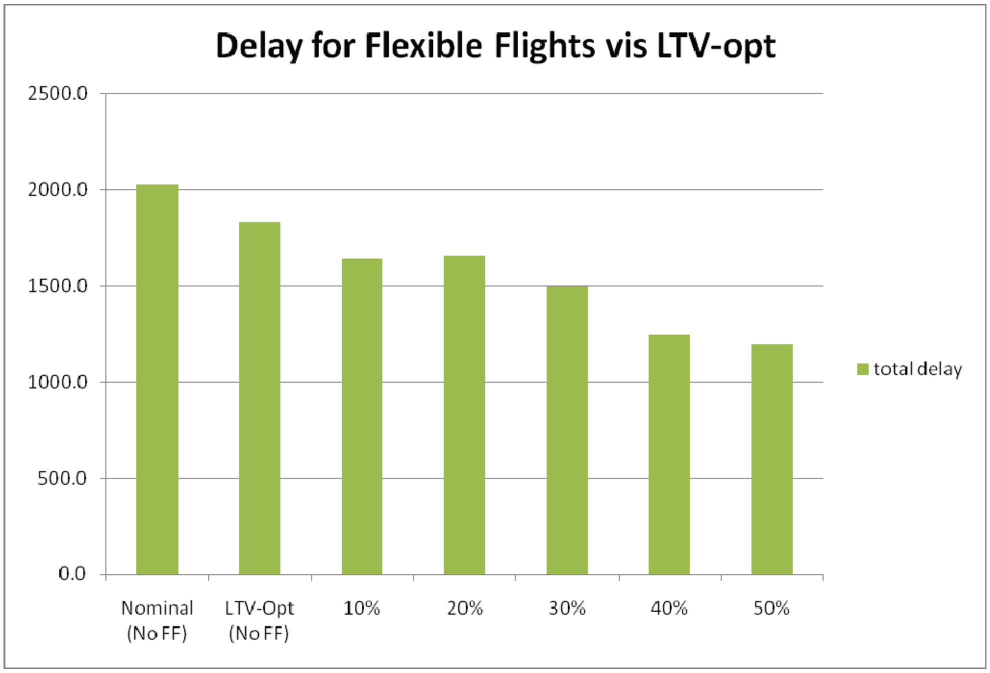


Figure 64: Total delay for various flexible flight percentages into N90 for November 7, 2008

Table 34: Delay reduction for various flexible flight percentages into N90 for November 7, 2008

	KEWR	KJFK	KLGA	Total	Reduction
Nominal (No FF)	610.1	948.6	466.3	2025.0	0.0%
LTV-Opt (No FF)	619.0	755.3	456.4	1830.8	-9.6%
10%	583.0	778.6	279.6	1641.2	-19.0%
20%	547.1	761.8	349.7	1658.6	-18.1%
30%	414.5	731.6	353.2	1499.3	-26.0%
40%	369.2	552.4	321.2	1242.8	-38.6%
50%	352.2	485.8	360.3	1198.2	-40.8%

A comparison of the total delay for the four different approaches is shown in Figure 65. Level of flexible operations is assigned to be 30%. LTV-optimization makes relatively small saving (about 10%) by providing McTMA scheduler with better ETAs. However, we can see that combing LTV optimized flows with flexible operations produces much larger reduction of delay. This is because the integrated model (LTV+McTMA) with flexible flights off-loads the congested airports (i.e., balances runway operations) resulting in reduced delay.

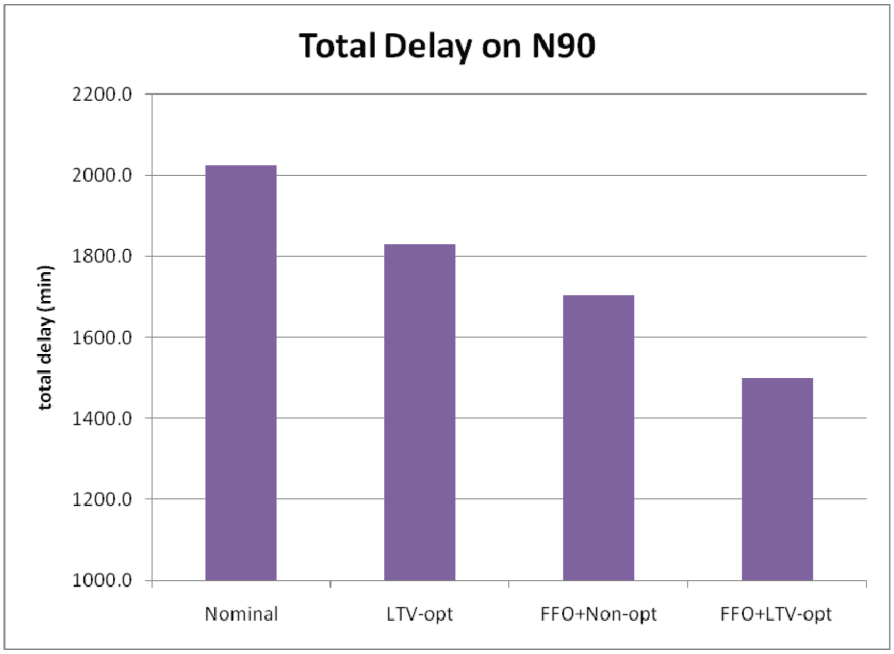


Figure 65: Total delay comparison for the four approaches for the November 7, 2008 data file

5.2.2. Cost of delay for N90

The cost of total delay at N90 for nominal and flexible flights was estimated using cost figures generated for NASA and described in a report by Ferguson et al. (2011). Specifically, the “air cost” of delay, identified in the report in aggregate form, was adjusted for differences in the cost of delay by airport. The results are shown in Table 35, which shows the cost of delay for the nominal traffic file, and in Table 36, which shows the cost of delay for LTV-optimized flights with 30% flexible flights. The difference between these delays, $22,509, is an estimate of the savings obtained by using 30% flexible flights and the LTV optimizer for this metroplex on this day. (There are numerous limitations to this result that warrant caution in its interpretation, including the use of only one traffic file, one metroplex, and numerous simplifying assumptions such as having all delay taken enroute.)

Table 35: Estimate of the cost of delay at N90 for the nominal traffic file

	$ per min	Air cost per min	# delay min	Total air delay cost	# flights	$ per flight
EWR	$ 12.15	$ 48.60	610.1	$ 29,651	529	$ 56.05
JFK	$ 9.51	$ 38.04	948.6	$ 36,085	484	$ 74.56
LGA	$ 10.49	$ 41.96	466.3	$ 19,565	511	$ 38.29
Total				$ 85,300		

Table 36: Estimate of the cost of delay for LTV-optimized flights and 30% flexible flights at N90 for November 7, 2008

	$ per min	Air cost per min	# delay min	Total air delay cost	# flights	$ per flight
EWR	$ 12.15	$ 48.60	414.5	$ 20,143	514	$ 39.19
JFK	$ 9.51	$ 38.04	731.6	$ 27,831	540	$ 51.54
LGA	$ 10.49	$ 41.96	353.2	$ 14,819	470	$ 31.53
Total				$ 62,793	1524	

Table 37 shows the cost savings derived from different percentages of flexible flights into N90. The savings are the difference between the cost of delay for nominal flights and the cost of delay for that level of flexible flights. Also shown in Table 37 is the amount saved per flight, obtained by dividing the total benefit by the number of flexible flights. This is an estimate of the amount the ticket prices could be reduced, in aggregate form, if the savings were applied to the flexible flights without profit taken by the airlines. (The savings per flight would have to be divided by the number of seats on the flight to obtain the average reduction for each fare.) Alternately, this amount could be saved by the airlines on each flight.

Figure 66 depicts the savings per flight graphically. After 10% flexible flights, the savings stays relatively constant.

Table 37: Savings by percentage of flexible flights

	Total cost benefit	# flexible flights	$ per flight
10% FF	$ 15,618	152	$ 102.48
20% FF	$ 15,060	305	$ 49.41
30% FF	$ 22,507	457	$ 49.23
40% FF	$ 32,866	610	$ 53.91
50% FF	$ 34,589	762	$ 45.39

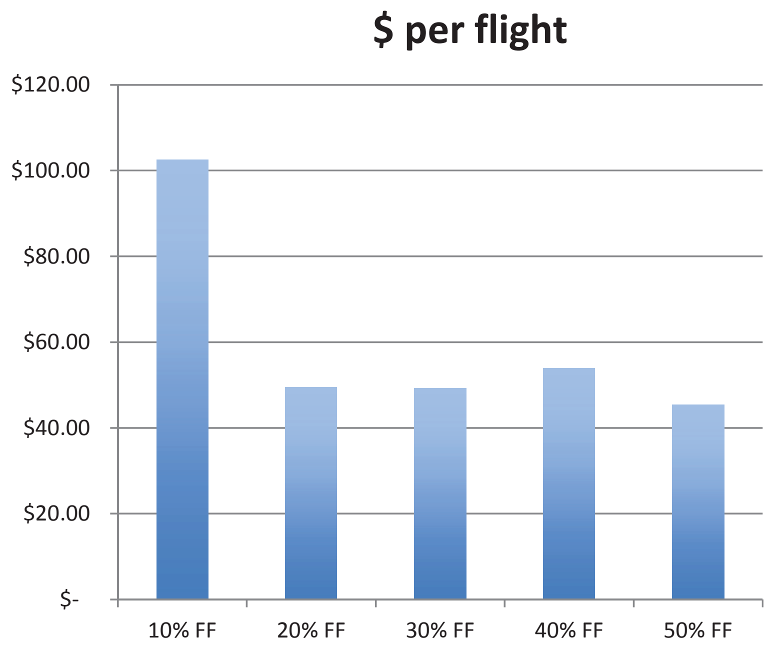


Figure 66: Savings in dollars per flight by percentage of flexible flights

5.2.3. Scheduling Results on SCT Metroplex data

In order to test the proposed integrated model and flexible concept on a different metroplex, SCT flights data have been also tested. In the SCT metroplex, 5 major airports (BUR, LAX, LGB, ONT, SNA) and 4 meter fixes are considered for scheduling purposes.

The SCT metroplex is dominate by LAX in terms of demand and delay. As shown in Table 38 and Figure 67, LAX has over 90% of the SCT delay. Since flexible operations reduce arrival peaks by reassigning flexible flights into less congested airports, one would expect that the benefits of the concept in SCT would be substantially greater than found for N90, where the delay is more balanced across the airports in the metroplex.

As shown in Figure 68 and Figure 69, the delay savings is substantially greater than for N90. The delay savings exceeds 70% when the LTV-optimizer is used and 50% flexible flights are available. (The ARB did not constrain aircraft to landing at compatible airfields and therefore may allow for greater rescheduling flexibility than really exists.)

Table 38: Demand and delay for SCT traffic file

	Non-opt & No FF		LTV-opt & 30% FF	
	# aircraft	delay (min)	# aircraft	delay (min)
KBUR	109	15.7	118	19.8
KLAX	577	1309.3	531	722.6
KLGB	50	0.3	84	2.2
KONT	92	13.5	102	14.9
KSNA	154	39.2	147	23.0
Total	982	1377.8	982	782.4

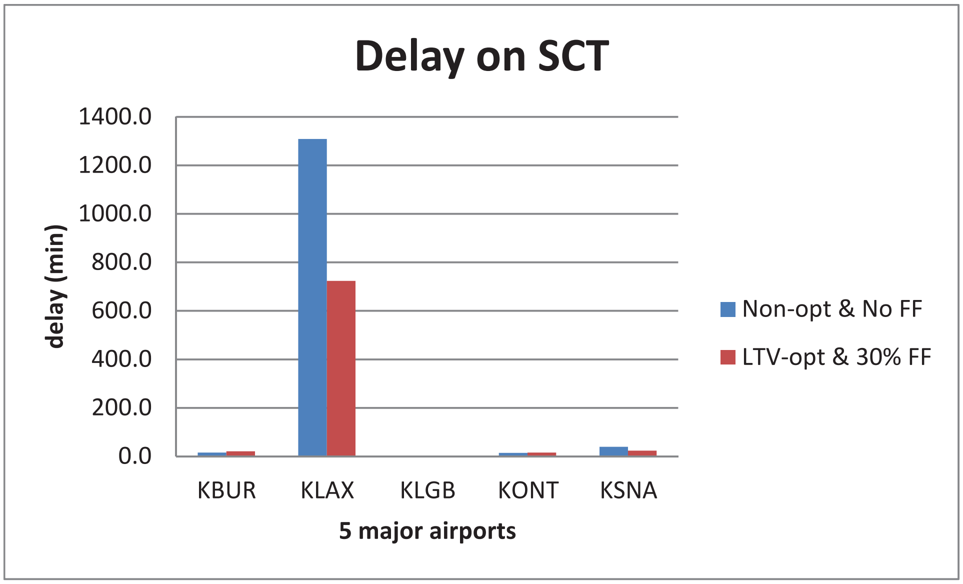


Figure 67: Delay distribution for the SCT metroplex airports for the nominal case vs. LTV-optimized case with 30% flexible flights

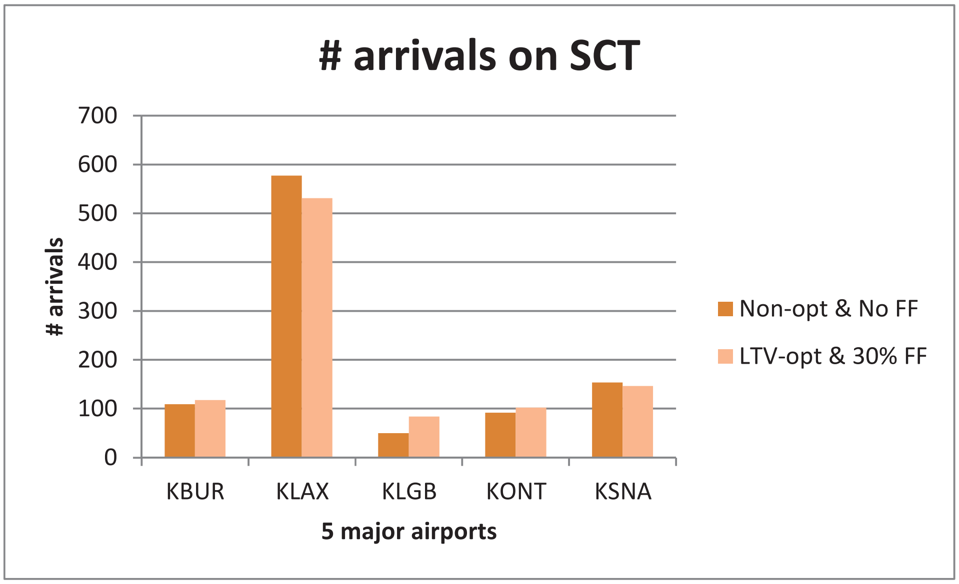


Figure 68: Nominal vs. LTV-optimized/30% flexible flight demand on the airports in the SCT metroplex

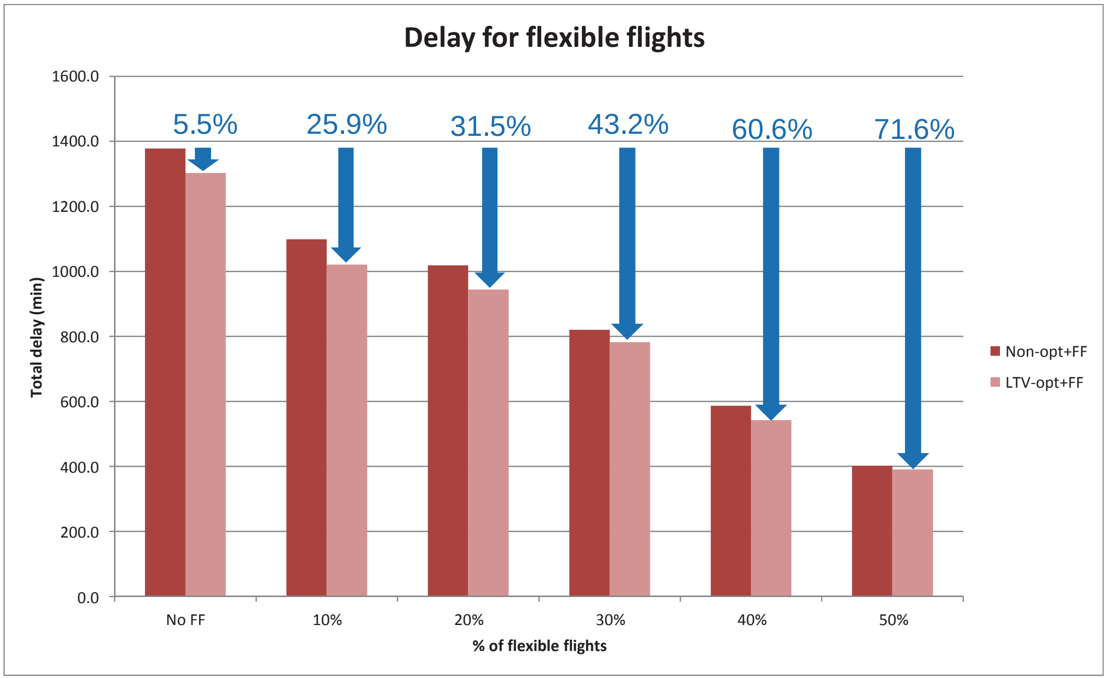


Figure 69: Total delay reduction in SCT with and without LTV-optimization, and at various percentages of flexible flights

5.3. Best Case Results from a Simple Flight Allocation

What is the best case scenario in reducing arrival delays at congested airports? If it is possible to shift any flight landing at a congested airport to a less congested airport without any consideration of constraints (e.g. vortex separation, proper separation between flights, etc.), arrival delay can be reduced significantly. However, it is not realistically possible. One of the major reasons to analyze the best case is to have a lower boundary of delay reduction. These results, a form of best case, can be compared to ACES and LTV+McTMA results. Figure 70 depicts traffic demands and airport arrival rate (AAR) for N90 airports. X axis represents 15 min. time intervals and Y axis represents the number of flights within the time interval. The goal of the best case is to minimize the number of flights landing at an over-capacitated airport by shifting flights (called flexible flight operations) between airports. In order to calculate total arrival delays, flights in the overcapacity interval shift to next time interval, and along with that a 15 min. delay for each shifting flight is added to total delays. As expected, there are cons and pros to this analysis. Since this method uses a simple flight allocation, costs involved in writing and running computer codes are low. But a striking con is that this simple method makes errors of total delays because the smallest unit for delay is assumed to be 15 min.

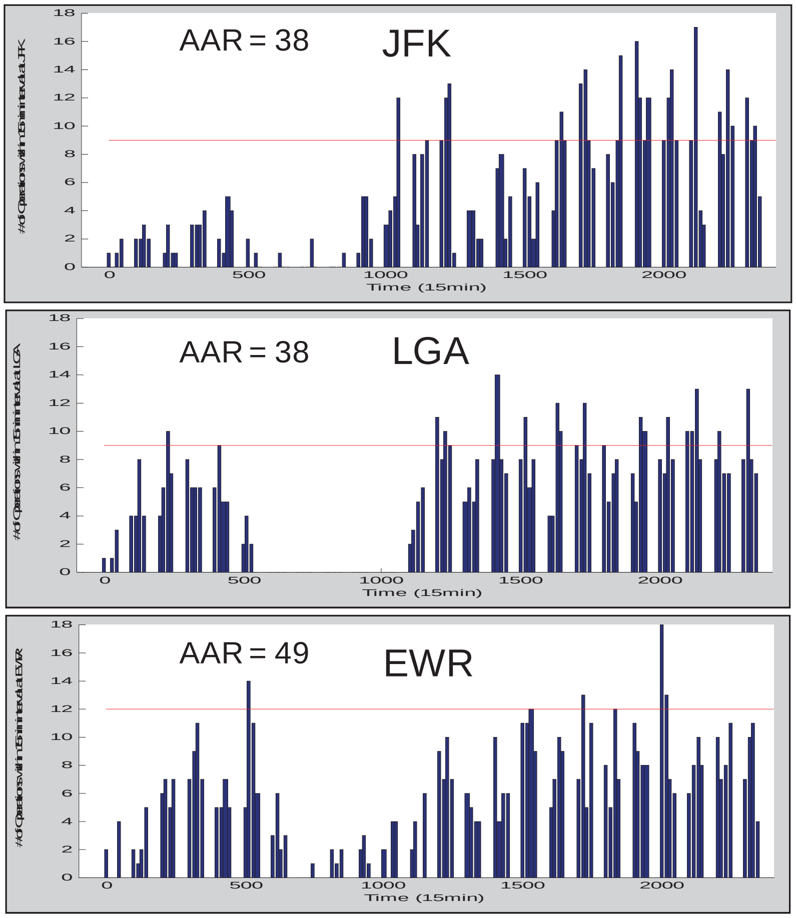
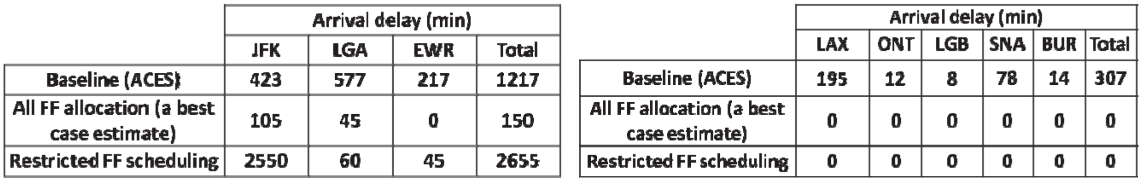


Figure 70: Traffic demand and AAR (Airport Arrival Rate) for N90 airports on November 7th in 2008

In this analysis, two cases are run: unrestricted flexible flight allocation (a best case estimate) and restricted flexible flight scheduling. In the unrestricted flexible flight allocation case, all flights have a possibility to be a flexible flight, but in restricted flexible flight scheduling; only 30% of the flights chosen by the FFS model can be considered as flexible flights. Even though a flight is at an overcapacity airport, if the flight is not in the candidate flexible flight list, it cannot be moved to another airport. Table 39 shows the results of a best case estimate and restricted flexible flight scheduling for N90 and SCT. These two cases are compared to baseline results from ACES. At N90, total arrival delays of best case estimates reduce dramatically compared to baseline case, but total delays from restricted scheduling case are much higher than baseline results because this model assumes 15 min. delays, which is an important limitation of this model. For SCT, there are no delays because there are no traffic demands over capacity. In other words, ample capacity across all SCT airports meant allocation never resulted in any delay.

Table 39: Arrival delays from a simple flight allocation method for N90 and SCT



	Arrival delay (min)			
	JFK	LGA	EWR	Total
Baseline (ACES)	423	577	217	1217
All FF allocation (a best case estimate)	105	45	0	150
Restricted FF scheduling	2550	60	45	2655

	Arrival delay (min)					
	LAX	ONT	LGB	SNA	BUR	Total
Baseline (ACES)	195	12	8	78	14	307
All FF allocation (a best case estimate)	0	0	0	0	0	0
Restricted FF scheduling	0	0	0	0	0	0

5.4. Comparison of results between all cases

In this section, we show a brief delay comparison at N90 for ACES's simulation, integrated LTV-McTMA model with flexible operation concept, and the best-case estimate described in the previous section. For the comparison of flexible operation concept, 30% of flexible flights are selected. As described in the previous section, if more flexible flights are chosen, more savings of delay reduction would be obtained. Table 40 summarizes the ACES runs (min and max savings) as compared to the baseline from the ACES simulation. The "All FF allocation" is the best possible savings achievable, using essentially manual rescheduling with maximum, perhaps unrealistic, flexibility, although the delay incurred comes in chunks of a minimum of 15 minutes. The "restricted FF" scheduling shows the savings achievable when only the 30% of the flights designated as flexible could be moved to a different airport. The remainder of the rows shows the effect of different scheduling options, again with 30% flexible flights, as compared to the McTMA baseline. (The differences in baseline delay reflect very different methods for scheduling aircraft between ACES and McTMA.)

Table 40: Total delay comparison between the ACES simulation, the best case scenario, and the LTV-optimized/30% flexible flight case

	Arrival Delay Minutes Total
Baseline (ACES)	1,940
Random FF (ACES)-min	1,882
Random FF (ACES)-max	2,416
All FF allocation (a best case estimate)	150
Restricted FF scheduling	2,655
McTMA	2,025
LTV-opt + McTMA	1,830
FFS+McTMA	1,704
FFS+LTV-opt + McTMA	1,500

The savings for the ACES runs is, at best, approximately 3%. The savings for McTMA is 26%. The substantially greater savings indicates that the scheduler is choosing flights to move much more intelligently than the random selection used in ACES. Figure 71 compares these estimates graphically.

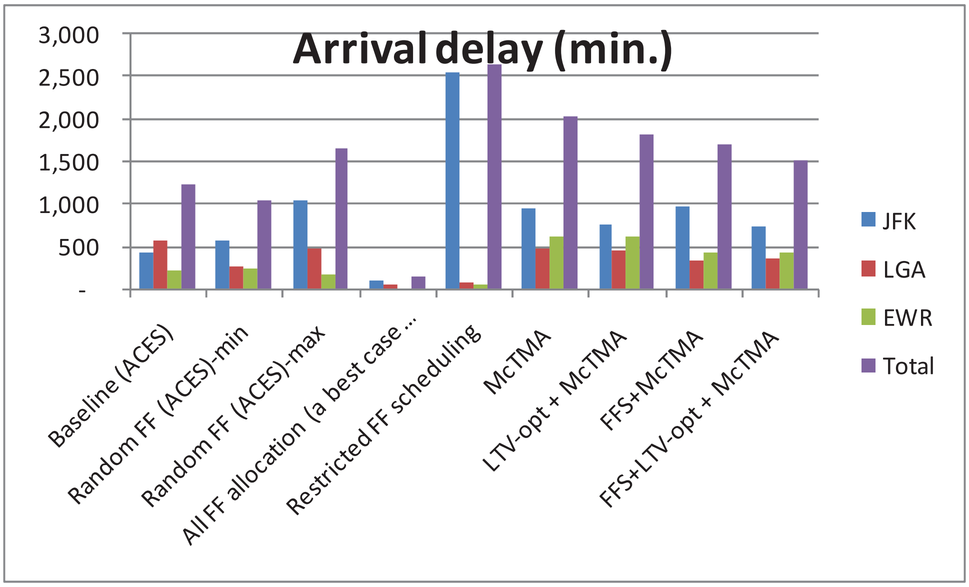


Figure 71: Arrival delay for the ACES simulation, best case estimate, and the LTV-optimized/30% flexible flight case

At SCT, the comparison is shown in Table 41. ACES showed an improvement of 24%, while the LTV-optimized/30% flexible flight case showed an improvement of 43%, again indicating that the scheduler is choosing flights to reschedule intelligently.

Table 41: Total delay comparison between ACES, a best case estimate, and the LTV-optimized/30% flexible flight case for SCT

	Arrival delay (min)					
	LAX	ONT	LGB	SNA	BUR	Total
Baseline (ACES)	195	12	8	78	14	307
Random FF (ACES)-min	103	13	42	55	20	233
Random FF (ACES)-max	137	14	71	117	11	350
All FF allocation (a best case estimate)	0	0	0	0	0	0
Restricted FF scheduling	0	0	0	0	0	0
McTMA	1309.3	13.5	0.3	39.2	15.7	1378
LTV-opt + McTMA	1242	14.4	2.8	34.9	8.7	1302.8
FFS+McTMA	784.5	6.6	1.1	12.6	15.8	820.6
FFS+LTV-opt + McTMA	722.6	14.9	2.2	23	19.8	782.5

5.5. Intermodal study results

Passengers traveling on metroplex bound flights could arrive at any one of the metroplex airports; in such a scenario they must be aware of the ground transportation options available at all the airports, to go to the final destination in the city or to another airport to board a connecting flight. The loss / benefit analysis in terms of time and cost of travel from the airport to the final destination would have a big impact on the marketability of metroplex tickets.

Ideally, metroplex airports should be equidistant from each other and the city center such that it would take the same amount of time and money to get from any metroplex airport to a downtown location. Since in reality the airport locations are not ideal, it is important to estimate the best and worst case scenarios that a passenger may face when opting for a metroplex flight. Returning passengers who have a parked car at an airport are likely to opt for a standard commercial flight that guarantees their return to the airport of their choice. Metroplex flight customers have the option to take on public transportation or use a cab to reach their final destination.

We analyzed data on trip times for the options that travelers have to move between the major airports in both N90 and SCT. Table 42 shows the codes used in the subsequent tables. Table 43 and Table 44 show the inter-metroplex travel itinerary for passengers using public transport for the SCT and N90 metroplex respectively. Google maps[4] provide the data source for public transport itinerary. The distance is shown in miles and the total time “TIME” and total walk time “WALK” are in minutes. Walk time can be a metric to compare itineraries on passenger preference; itineraries with high walk time are more likely to be avoided. 3:00 A.M. and 9:00 A.M. were chosen as non-rush hour and rush hour times, respectively.

Table 42: Public transport codes

Code	Description
W	Walk
B	Bus
LR	Light Rail
T	Train
S	Subway
C	Cab / Drive

---

[4] Google Maps, http:\\www.maps.google.com

Table 43: SCT Inter-Metroplex travel using public transport at non-rush hour and rush hour

	DESTINATION													
	SNA							LAX						
		3:00 AM			9:00 AM				3:00 AM			9:00 AM		
ORIGIN	DISTANCE (miles)	METHOD	TIME (min)	WALK (min)	METHOD	TIME (min)	WALK (min)	DISTANCE (miles)	METHOD	TIME (min)	WALK (min)	METHOD	TIME (min)	WALK (min)
SNA								42.1	W-B-B-B-B-W	221	45	W-B-B-B-B-W	265	27
LAX	41.2	W-B-LR-B-B-B-W	206	19	W-B-LR-B-B-B-B-W	228	19							
ONT	42.6	W-B-B-B-T-B-W	259	8	W-B-T-T-B-W	319	36	57.1	W-B-T-S-LR-B-W	223	30	W-B-T-S-B-W	223	45
BUR	52.5	W-B-S-T-B-B-W	227	5	W-B-S-T-B-W	237	22	29.4	B-B-W	124	23	B-B-B-W	131	24
LGB	27.8	W-B-B-B-W	141	27	W-B-B-B-W	167	27	26.2	W-B-LR-LR-B-W	132	49	W-B-B-LR-B-W	134	27
	ONT							BUR						
		3:00 AM			9:00 AM				3:00 AM			9:00 AM		
ORIGIN	DISTANCE (miles)	METHOD	TIME (min)	WALK (min)	METHOD	TIME (min)	WALK (min)	DISTANCE (miles)	METHOD	TIME (min)	WALK (min)	METHOD	TIME (min)	WALK (min)
SNA	45.6	W-B-T-T-T-B-B-W	249	22	W-B-B-B-B-T-B-W	300	22	52.7	W-B-T-W	205	26	W-B-T-T-W	210	30
LAX	56.6	W-B-B-T-B-W	222	43	W-B-B-T-B-W	212	33	32	W-B-B-W	120	16	W-B-B-W	153	26
ONT								51.9	W-B-T-T-W	151	16	W-B-T-T-B-W	180	20
BUR	48.5	B-T-T-B-W	172	18	B-T-T-B-W	172	18							
LGB	50.6	W-B-LR-S-T-B-W	272	10	W-B-LR-S-T-B-B-W	216	22	39.4	W-B-LR-S-T-W	149	35	W-B-B-LR-S-B-W	154	4
	LGB													
		3:00 AM			9:00 AM									
ORIGIN	DISTANCE (miles)	METHOD	TIME (min)	WALK (min)	METHOD	TIME (min)	WALK (min)							
SNA	22.6	W-B-B-B-B-W	156	24	W-B-B-B-B-W	155	7							
LAX	22.4	W-B-LR-B-B-W	90	18	W-B-LR-LR-B-B-W	101	18							
ONT	53.3	W-B-T-S-LR-B-B-W	204	10	W-B-T-B-B-B-W	238	22							
BUR	39	W-B-S-LR-B-B-W	132	4	W-B-T-S-LR-B-B-W	154	4							
LGB														

Table 44: N90 Inter-Metroplex travel using public transport at non-rush hour and rush hour

	DESTINATION													
	EWR							JFK						
		3:00 AM			9:00 AM				3:00 AM			9:00 AM		
ORIGIN	DISTANCE (miles)	METHOD	TIME (min)	WALK (min)	METHOD	TIME (min)	WALK (min)	DISTANCE (miles)	METHOD	TIME (min)	WALK (min)	METHOD	TIME (min)	WALK (min)
EWR								36.3	W-B-T-S-LRW	126	8	W-B-S-T-T-LR-W	97	8
JFK	30	W-LR-T-T-B-W	105	8	W-LR-T-T-B-W	101	8							
LGA	22.7	W-B-S-T-B-W	134	5	B-S-T-T-B-W	94	1	12.3	B-S-LR-W	79	7	B-S-T-LR-W	74	7
ISP	65.2	C-T-T-B-W	150	1	C-T-T-B-W	146	1	44.2	C-T-R-W	96	7	C-T-R-W	96	7
	LGA							ISP						
		3:00 AM			9:00 AM				3:00 AM			9:00 AM		
ORIGIN	DISTANCE (miles)	METHOD	TIME (min)	WALK (min)	METHOD	TIME (min)	WALK (min)	DISTANCE (miles)	METHOD	TIME (min)	WALK (min)	METHOD	TIME (min)	WALK (min)
EWR	24.2	W-B-T-S-B-W	132	9	W-B-B-S-B	109	1		W-B-T-T-T-C	192	1	W-B-S-T-T-T-C	157	1
JFK	12.2	W-LR-T-S-B	87	7	W-LR-S-S-B	82	7		W-R-T-C	97	1	W-R-T-T-C	104	7
LGA									B-S-T-C	139	0	B-S-T-T-C	129	0
ISP	45.7	C-T-S-B	132	0	C-T-B-B	127	0							

Table 45 and Table 46 show the travel method and time from airport to the city center for SCT (Downtown, LA) and N90 (Times Square, NY) during rush-hour and non-rush hours.

Table 45: Public transport travel time estimates to Downtown, LA

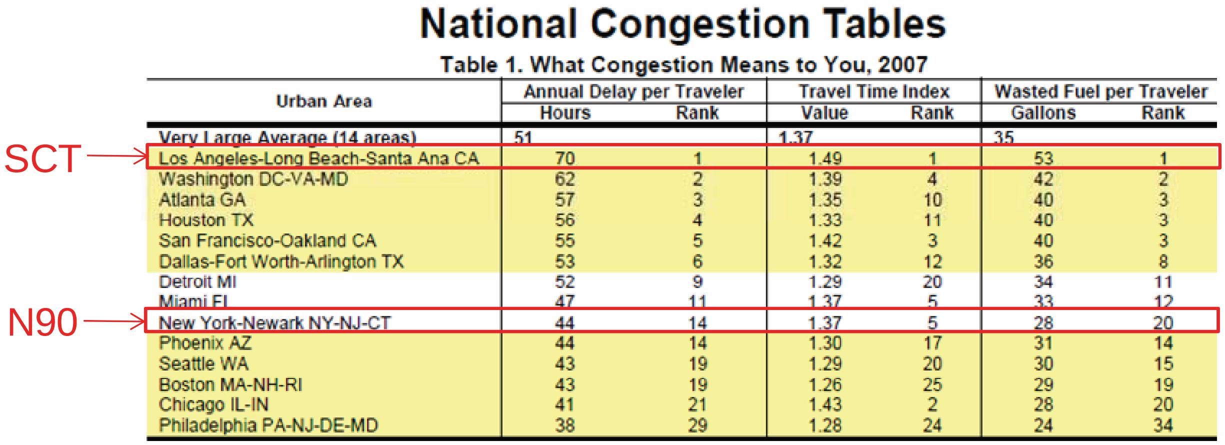
	SCT - Downtown, LA						
		3:00 AM			9:00 AM		
ORIGIN	DISTANCE (miles)	METHOD	TIME (min)	WALK (min)	METHOD	TIME (min)	WALK (min)
SNA	40.7	W-B-W-T-W-S-W	121	29	W-B-W-T-W-B	181	55
LAX	18.8	W-B	72	15	W-B-W-LR-W-S-W	80	28
ONT	40.4	W-B-W-B-W	145	16	W-B-W-B-W	135	16
BUR	17.5	W-B-W-S-W	95	52	W-B-W-S-W	70	14
LGB	25	W-B-W-S-W-S-W	105	42	W-B-W-S-W-S-W	98	30

Table 46: Public transport travel time estimates to Times Square, NY

	N90 - Time Square, NY						
		3:00 AM			9:00 AM		
ORIGIN	DISTANCE (miles)	METHOD	TIME (min)	WALK (min)	METHOD	TIME (min)	WALK (min)
EWR	16.9	W-B-W-T-W-S-W	84	14	LR-W-T-W-S-W	54	12
JFK	17.8	LR-W-S-W	66	11	LR-W-ST-W-S-W	63	15
LGA	9.5	W-B-W-S-W	58	3	W-B-W-S-W	56	13
ISP	51.6	C-T-W-S-W	112	12	C-T-W-S-W	95	12

Public transport may be the most cost effective option available but the frequent changes from bus to train to subway makes it less comfortable than using a cab. But travel by taxi is subject to road congestion. Texas Transportation Institute's Urban Mobility Report (26) predicts the general congestion on highways and urban areas around the country. The analysis uses data on travel speed and incident-related travel delays. The report presents the results in the form of Travel Time Index (TTI) which is the ratio of travel time in peak period to travel time at free-flow conditions. As an example, TTI of 1.35 indicates a 20 minute free-flow trip would take 27 (20 x 1.35) minutes at rush hour. The Texas Transportation Institute defines rush hour as 6 A.M. to 9 A.M. and 4 P.M. to 7 P.M. Table 47 presents TTI values for some of the most congested urban areas in the country.

Table 47: Texas Transportation Institute's Nation Congestion Tables



National Congestion Tables

Table 1. What Congestion Means to You, 2007

Urban Area	Annual Delay per Traveler		Travel Time Index		Wasted Fuel per Traveler	
	Hours	Rank	Value	Rank	Gallons	Rank
Very Large Average (14 areas)	51		1.37		35	
Los Angeles-Long Beach-Santa Ana CA	70	1	1.49	1	53	1
Washington DC-VA-MD	62	2	1.39	4	42	2
Atlanta GA	57	3	1.35	10	40	3
Houston TX	56	4	1.33	11	40	3
San Francisco-Oakland CA	55	5	1.42	3	40	3
Dallas-Fort Worth-Arlington TX	53	6	1.32	12	36	8
Detroit MI	52	9	1.29	20	34	11
Miami FL	47	11	1.37	5	33	12
New York-Newark NY-NJ-CT	44	14	1.37	5	28	20
Phoenix AZ	44	14	1.30	17	31	14
Seattle WA	43	19	1.29	20	30	15
Boston MA-NH-RI	43	19	1.26	25	29	19
Chicago IL-IN	41	21	1.43	2	28	20
Philadelphia PA-NJ-DE-MD	38	29	1.28	24	24	34

Using TTI with non-rush hour travel time estimates from Google Maps gives the travel time estimates during rush hour. Table 48 and Table 49 below show the travel time estimates for SCT and N90 metroplexes respectively.

Table 48: SCT Inter Metroplex travel time estimates using a cab at non-rush hour and rush hour

SCT					
Non Rush Hour – Google Maps, Mins					
ORIGIN	SNA	LAX	ONT	BUR	LGB
SNA		48	51	63	28
LAX	45		62	39	27
ONT	48	61		59	57
BUR	57	39	60		46
LGB	28	26	56	44	
TTI Rush Hour, Mins					
ORIGIN	SNA	LAX	ONT	BUR	LGB
SNA		72	76	94	42
LAX	67		92	58	40
ONT	72	91		88	85
BUR	85	58	89		69
LGB	42	39	83	66	

Table 49: N90 Inter Metroplex travel time estimates using a cab at non-rush hour and rush hour

N90					
Travel Time (mins) Non Rush Hour (3:00 A.M)					
	DESTINATION				
ORIGIN	LGA	EWR	JFK	ISP	Times Sq
LGA		37	16	62	17
EWR	39		46	92	27
JFK	20	47		60	28
ISP	58	87	53		64
Travel Time (mins) Rush Hour (9:00 A.M)					
ORIGIN	LGA	EWR	JFK	ISP	Times Sq
LGA		51	22	85	23
EWR	53		63	126	37
JFK	27	64		82	38
ISP	79	119	73		88

Based on travel time and comfort alone, passengers would choose cab over public transport for almost every trip. To assess the impact of costs of travel the next tables show the estimated cab fare for trips to city center from the metroplex airports in dollars. The fare calculations are based on government guidelines (27) and include the effects of extra time spent in the cab due to traffic.

Table 50: SCT cab fares to metroplex airports and Downtown, LA

SCT						
FARE ($) Non Rush Hour (3:00 A.M)						
ORIGIN	**SNA**	**LAX**	**ONT**	**BUR**	**LGB**	**Downtown**
SNA		108	118	136	59	104
LAX	107		144	86	61	51
ONT	116	146		134	136	104
BUR	136	89	135		98	45
LGB	59	60	120	98		66
FARE ($) Rush Hour (9:00 A.M)						
ORIGIN	**SNA**	**LAX**	**ONT**	**BUR**	**LGB**	**Downtown**
SNA		119	129	149	65	115
LAX	116		158	94	67	56
ONT	126	159		147	148	115
BUR	148	97	148		107	51
LGB	65	65	132	107		73

Table 51: N90 cab fares to metroplex airports and Times Square, NY

N90					
FARE ($) Non Rush Hour (3:00 A.M)					
ORIGIN	**LGA**	**EWR**	**JFK**	**ISP**	**Times Sq.**
LGA		55	30	98	25
EWR	56		80	142	41
JFK	31	89		101	45
ISP	97	138	104		110
FARE ($) Rush Hour (9:00 A.M)					
ORIGIN	**LGA**	**EWR**	**JFK**	**ISP**	**Times Sq.**
LGA		60	32	107	28
EWR	62		87	156	45
JFK	34	96		110	45
ISP	106	151	111		120

Cost of travel is an important consideration for passengers opting for metroplex flights. For these passengers the cost of surface transport would be as important as the airline ticket price. For this reason, any cost comparison between a traditional commercial flight and a metroplex flight must include the cost of ground transport as well. Table 52 compares the total costs of a business and coach passenger to get from Boston to Times Square, NY using public transport and taxi. The table lists two options (taxi and public transport) for coach and business passengers. The total costs are sum of the ticket price, and the taxi fare or public transport costs[5].

---

[5] Based on recommended Hourly Values of Intercity Surface Mode Travel Time Savings by Department of Transportations

Table 52: BOS-N90 travel cost comparisons

	Ticket Class							
Transport by	**Coach**				**Business**			
Taxi	**Destination Airport**	**Coach FARE ($)**	**Taxi Fare to Times Sq ($)**	**Total Cost ($)**	**Destination Airport**	**Business FARE [1]($)**	**Taxi Fare to Times Sq ($)**	**Total Cost ($)**
	LGA	174	28	202	LGA	259	28	**287**
	EWR	183	45	228	EWR	241	45	**286**
	JFK	100	45	145	JFK	148	45	**193**
Public Transport	**Destination Airport**	**Coach FARE ($)**	**Public Transport Fare to Times Sq[2] ($)**	**Total Cost ($)**	**Destination Airport**	**Business FARE[1] ($)**	**Public Transport Fare to Times Sq[2] ($)**	**Total Cost ($)**
	LGA	174	14	**188**	LGA	259	20	279
	EWR	183	13	**196**	EWR	241	19	260
	JFK	100	16	**116**	JFK	148	22	170

The coach fares are the average fares paid by passengers in 2009 Q1. Rush hour cab fares are from table 19. To target Coach and Business PAX, metroplex airline would need to aim at ticket prices of $100 and $113 respectively.

6. Conclusions

The primary objectives of this project were to articulate, model, and evaluate a concept for flexible operations at a metroplex as a means to optimize the use of metroplex resources. In particular, the quantification of best-case benefits from the concept was pursued in order to establish whether further research is warranted. A flexible flight is one whose destination airport is not assigned until a threshold is reached near the arrival area at which time the runway which reduces overall delay is assigned to that flight. The concept seeks to make best use of available metroplex resources via this flexibility.

In summary, the modeling objectives have been met and the resulting quantitative evaluation indicate that indeed the concept has potential for significant reductions in delay (and cost due to delay) in the N90 (New York/New Jersey) and SCT (Southern California) metroplexes. Delay reductions on the order of 26% are possible in N90 when 30% of the commercial airline flights (smartly selected by their low probability of having many connecting passengers), and nearly 41% when 50% of the flights are flexible. In the SCT metroplex, the delay reductions are estimated to be even greater (43% with 30% flexible flights, 71% with 50% flexible flights). The higher reductions at SCT are due to the fact that this metroplex is less constrained currently than N90; thus, there is “more room” to take advantage of flexibility. These findings, using an integrated model consisting of enroute optimization, terminal area scheduling and runway balancing, were bounded by sets of simulation runs of the concept in ACES under several scenarios. In particular, ACES was used to examine the potential impact of using the flexible operations concept for on-demand/air taxi and General Aviation (GA) flights; the benefits in NYNJ were especially attractive in these scenarios, indicating the flexible operations concepts may be useful to a wide variety of users.

Finally, a set of supporting analyses that examined economic considerations of the concept were presented. In particular, a preliminary intermodal analysis illustrated how the flexible operations concept, when integrated with information systems that make clear the ground mode options, could be attractive to travelers in reaching their destination. These aspects represent a fruitful area of research to more fully flesh out the potential workings of the concept.

7. One Potential Future Work Item

While numerous areas of future work were highlighted in the body of this report, one area in particular that could leverage recent NASA sponsored research is the use of metroplex dependency functions in runway scheduling. Currently, McTMA does not consider internal dependencies in a metroplex before allocating flights to runways. It is of utmost importance to consider such dependencies in a metroplex if minimizing congestion or increasing throughput is the prime objective. Metroplex dependencies occur across different dimensions between the constituent airports. A few example attributes of these dimensions are airport proximities, runway configurations, airport operations etc. Purdue, over the past three years, have developed a metroplex runway dependency metric based on data collected from sources such as Aviation Systems Performance Metrics (ASPM) and Performance Data Analysis and Reporting System (PDARS). The purpose of the metric is to point out if the use of a particular runway or a particular combination of runways increase or decrease the runway dependencies at a metroplex. As dependencies increase, the throughput and thereby the capacity of the metroplex decreases (2). It is therefore essential to choose the right combination of runways from available ones at a given time before allocating flights.

A capacity diagram of a metroplex is constructed in order to determine the observed capacity at a metroplex for a specific period. This diagram was partially used to validate the metric. In addition to that, information from the capacity diagrams is used to develop a Capacity Coverage Chart (CCC). A CCC helps to identify those runway configurations at a metroplex that have the highest the capacities and also those configurations that are used most frequently at a metroplex. The CCC can therefore be used to choose the best configurations. Figure 72 shows the CCC of NYNJ for 2007.

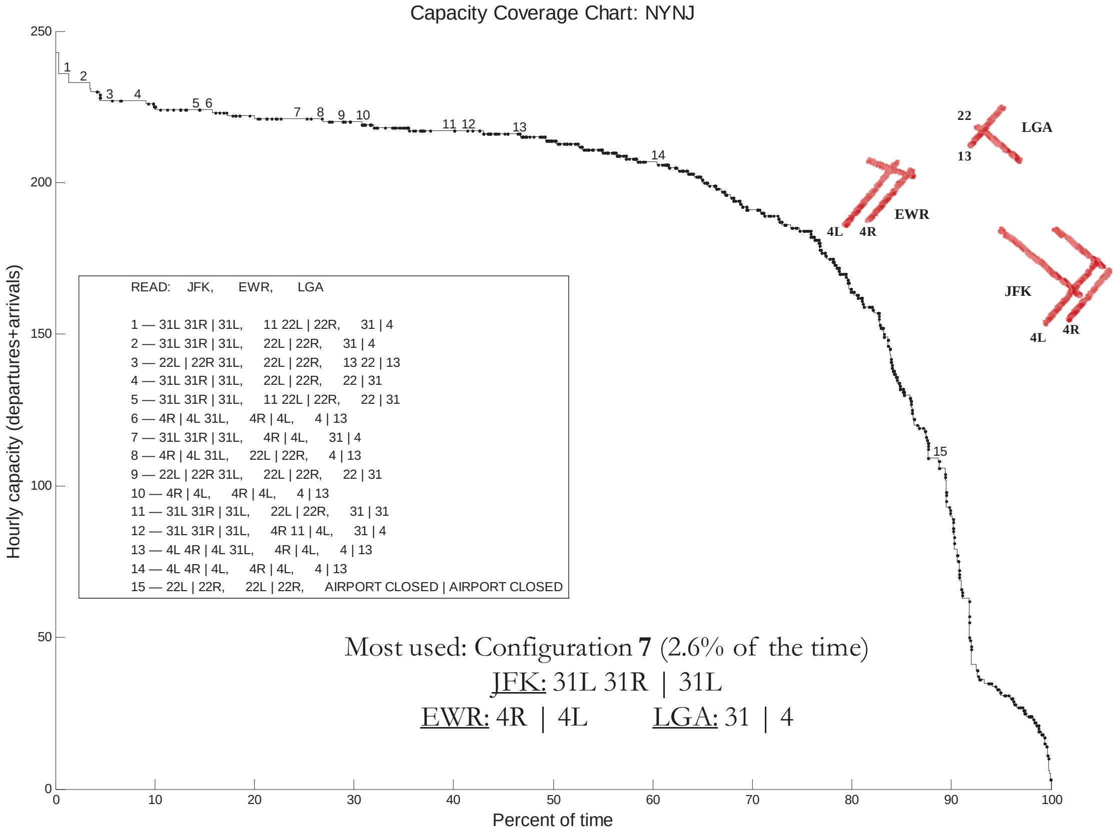


Figure 72: Capacity coverage chart of NYNJ in 2007. Note that only configurations that are used at least 1% of the time in the given year is marked in the figure

The CCC shows the most used metroplex runway configuration and the configuration that produces the maximum capacity can be estimated. Based on the runway dependency metric and the capacity coverage chart, a technique is proposed (Figure 73) for optimizing runway dependency so that operations can be allocated optimally across available metroplex runways. This practice would be beneficial to the flexible operations concept as it allows flights to be re-arranged, and thereby potentially creating opportunities to minimize runway dependencies.

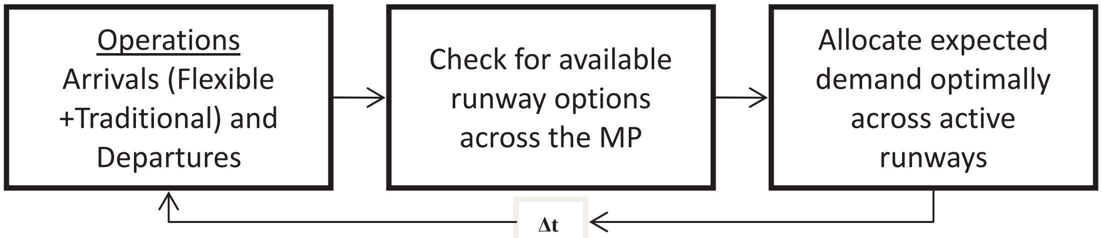


Figure 73: Runway dependency optimization process

8. References and Citations

1. Federal Aviation Administration, “FAA Aerospace Forecasts FY 2008-2025,” http://www.faa.gov/data_research/aviation/aerospace_forecasts/2008-2025/ [retrieved 20 December 2010].
2. Ayyalasomayajula, S. and DeLaurentis, D., “Developing Strategies for Improved Management of Airport Metroplex Resouces,” 9th AIAA Aviation Technology, Integration, and Operations Conference (ATIO) and Aircraft Noise and Emissions Reduction Symposium (ANERS), Hilton Head, SC, AIAA Paper 2009-7043, Sep. 2009.
3. Donaldson, A. and Hansman, R., “Capacity Improvement Potential for the New York Metroplex System,” 10th AIAA Aviation Technology, Integration and Operations (ATIO) Conference and AIAA/ISSMO Multidisciplinary Analysis Optimization (MAO), Fort Worth, TX, AIAA Paper 2010-9218, Sep. 2010.
4. Ganesan, R. and Sherry, L., “Adaptive Control of Multistage Airport Departure Planning Process using Approximate Dynamic Programming,” [online resource] http://catsr.ite.gmu.edu/pubs/GanesanIIEQC.pdf [retreived 20 December 2010].
5. Clarke, J.-P. et al., “Characterization of and Concepts for Metroplex Operations,” NASA/CR-2011-216414, http://www.aviationsystemsdivision.arc.nasa.gov/publications/2011/NASA-CR-2011-216414.pdf [retrieved July 2011].
6. Expedia Inc., http://www.expedia.com/Home.htm [retrieved August 2010].
7. Sun, D., Sridhar, B., and Grabbe, S., “Disaggregation Method for an Aggregate Traffic Flow Management Model,” *AIAA Journal of Guidance, Control and Dynamics*, Vol. 33, No. 3, pp. 666–676.
8. Landry, S. J., “The Design of a Distributed Scheduling System for Multi-center Time-based Metering of Air Traffic into Congested Resources,” *Air Traffic Control Quarterly*, Vol. 16, No. 1, pp. 69–97.
9. Meyn, L. et al., “Build 4 of the Airspace Concept Evaluation System,” AIAA Modeling and Simulation Technologies Conference and Exhibit, Keystone,CO, AIAA Paper 2006-6110, Aug. 2006.
10. Bureau of Transportation Statistics, “Data Directory: List of Databases,” [online database], http://www.transtats.bts.gov/DataIndex.asp [retrieved 21 July 2010].
11. Air Transportation Association, “Annual and Per-Minute Cost of Delays to U.S. Airlines,” http://www.airlines.org/Economics/DataAnalysis/Pages/CostofDelays.aspx [retrieved 7 July 2010].
12. Castelli, L., Ukovich, W., and Pesenti, R., “An Airline-based Mutilevel Analysis of Airfare Elasticity for Passenger Demand,” Air Transport Research Society World Conference, Toulouse, France, Jul. 2003.
13. Clake, M. D. D., “Irregular Airline Operations: A Review of the State-of-the Practice in Airline Operation Control Centers,” *Journal of Air Transport Management*, Vol. 4, No. 2, pp. 67–76.
14. Weide, O., Ryan, D., and Ehrgott, M., “Iterative Airline Scheduling,” Technical Report 645, Department of Engineering Science, The University of Auckland, New Zealand, 2007.
15. AhmadBeygi, S., Cohn, A., and Lapp, M., “Decreasing Airline Delay Propagation By Re-Allocating Scheduled Slack,” Technical report, AGIFORS, http://www.agifors.org/award/submissions2008/Ahmadbeygi_paper.pdf [retireved March 2009].
16. Rosenberger, J. M., Johnson, E. L., and Nemhauser, G. L., “A Robust Fleet-Assignment Model with Hub Isolation and Short Cycles,” *Transportation Science*, Vol. 38, No. 3, pp. 357–368.
17. Lan, S., Barnhart, C., and Clarke, J.-P., “New Approaches to Add Robustness into Airline Schedules,” MIT, Course Lecture Notes, 2002.
18. Lan, S., Clarke, J.-P., and Barnhart, C., “Planning for Robust Airline Operations: Optimizing Aircraft Routings and Flight Departure Times to Minimize Passenger Disruptions,” *Transportation Science*, Vol. 40, No. 1, pp. 15–28.
19. Ageeva, Y., and Clarke, J.-P., “Approaches to Incorporating Robustness into Airline Scheduling,” Report No. ICAT-2000-8, MIT International Center for Air Transportation, Massachusetts Institue of Technology, Cambridge, MA, Aug. 2000.
20. Personal Communication, Bruce Holmes. [Cited: 2 15, 2011.].
21. Cordeau, J.-F., Laporte, G., Potvin, J.-Y., and Savelsbergh, M. W. P., “Transportation on Demand,” *Handbook in Operations Research & Management Science*, Vol. 14, pp. 429–466.
22. Espinoza, D., Garcia, R., Goycoolea, M., Nemhauser, G. L., and Savelsbergh, M. W. P., “Per-Seat, On-Demand Air Transportation Part I: Problem Description and an Integer Multi-Commodity Flow Model,” *Transportation Science*, Vol. 42. No. 3, pp. 263–278.

23. Rama-Murthy, K., “Modeling of United States Airlines Fares Using Official Airline Guide (OAG) and Airline Origin and Destination Survey (DB1B),” Masters Thesis, Department of Civil Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA, Jun. 2006.
24. Gowrisankaran, G., “Competition and Regulation in the Airline Industry,” FRBSF Economic Letter, No. 2002-01, Jan. 2002.
25. Federal Aviation Administration, “Airport Categories,” http://www.faa.gov/airports/planning_capacity/passenger_allcargo_stats/categories/ [retrieved 20 September 2010].
26. Fox, J., and Weisburg, S., “An R and S-PLUS Companion to Applied Regression: A Web Appendix to the Book,” Sage Publications, Thousand Oaks, CA, 2002.
27. Haukoos, J., and Lewis, R., “Advanced Statistics: Bootstrapping Confidence Intervals for Statistics with “Difficult” Distributions,” *Academic Emergency Medecine*, Vol. 12, No. 4, pp. 360–365.
28. Schrank, D., and Lomax, T., “2009 Urban Mobility Report,” Report Prepared by the Texas Trasportation Institute for University Transportation Center for Mobility, College Station, TX, 2009.
29. New York City & Limousine Commision, “Passenger Information: Rate of Fare,” http://www.nyc.gov/html/tlc/html/passenger/taxicab_rate.shtml [retrieved 9 September 2010].
30. Yen, J. W., and Birge, J. R., “A Stochastic Programming Approach to the Airline Crew Scheduling Problem,” *Transportation Sciences*, Vol. 40, No. 1, 3–14.
31. Sridhar, B., Soni, T., Sheth, K., and Chatterji, G. B., “An Aggregate Flow Model for Air-Traffic Management,” *Journal of Guidance, Control and Dynamics*, Vol. 29, No. 4, pp. 992–997.
32. Muller E. R., and Chatterji, G. B., “Analysis of Aircraft Arrival and Departure Delay Characteristics,” AIAA's Aircraft Technology, Integration, and Operations (ATIO) 2002 Technical, Los Angeles, CA, AIAA Paper 2002-5866, Oct. 2002.
33. Geslin, C., “Pricing and Competition in US Airline Markets: Changes in Air Travel Demand Since 2000,” Masters Thesis, Dept. of Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, MA, 2006.
34. Kara, A. Q., Ferguson, J., Hoffman, K., and Sherry, L., “Estimating Domestic U.S. Airline Cost of Delay Based on European Model,” Proceedings of the 4th International Conference on Research in Air Transportation - ICRAT 2010, Budapest, Hungary, Jun. 2010.
35. Dunbar, M., Froyland, G., and Wu, C.-L., “Robust Airline Schedule Planning: Minimizing Propagated Delay in an Integrated Routing and Crewing Framework,” Report, University of New South Wales, Sydney, NSW, Australia, http://www.optimization-online.org/DB_HTML/2010/03/2578.html [retrieved August 2010].
36. Bhadra, D., Gentry, J., Hogan, B., and Wells, M., “CAASD’s Future Air Traffic Timetable Estimator: A Micro-Econometric Approach,” MITRE Technical Papers, http://www.mitre.org/work/tech_papers/tech_papers_03/bhadra_estimator/index.html [retrieved March 2010].
37. Siek, J. G., Lee. L.-Q., and Lumsdaine, A., “The Boost Graph Library: The User Guide and Reference Manual,” Addison-Wesley Professional, Upper Saddle River, NJ, Dec. 2001.
38. Ganesan, R. and Sherry, L., “Adaptive Control of Multistage Airport Departure Planning Process using Approximate Dynamic Programming,” [online resource] http://catsr.ite.gmu.edu/pubs/GanesanIIEQC.pdf [retreived 20 December 2010].

9. Appendix A

DB1B Coupon Columns[6]:

Column	Description	Notes
ItinID	Itinerary ID	Foreign key to DB1BTicket
MktID	Market ID	Foreign key to DB1BMarket
SeqNum	Coupon Sequence Number	Itinerary-level
Coupons	Number of Coupons in the Itinerary	Also in DB1BTicket
Year	Year	Also in DB1BTicket
Quarter	Quarter (1-4)	Also in DB1BTicket
Origin	Origin Airport Code	IATA Airport Code
OriginAptInd	Origin Airport, Multiple Airports Indicator	-
OriginCityNum	Origin Airport, City Code	-
OriginCountry	Origin Airport, Country Code	-
OriginStateFips	Origin Airport, State FIPS Code	-
OriginState	Origin Airport, State Code	-
OriginStateName	Origin State Name	-
OriginWac	Origin Airport, World Area Code	-
Dest	Destination Airport Code	IATA Airport Code
DestAptInd	Destination Airport, Multiple Airports Indicator	-
DestCityNum	Destination Airport, City Code	-
DestCountry	Destination Airport, Country Code	-
DestStateFips	Destination Airport, State FIPS Code	-
DestState	Destination Airport, State Code	-
DestStateName	Destination State Name	-
DestWac	Destination Airport, World Area Code	-
Break	Trip Break Code	-
CouponType	Coupon Type Code	-
TkCarrier	Ticketing Carrier Code	-
OpCarrier	Operating Carrier Code	-
RPCarrier	Reporting Carrier Code	-
Passengers	Number of Passengers	-
FareClass	Fare Class Code	-
Distance	Coupon Distance	-
DistanceGroup	Distance Group, in 500 Mile Intervals	-
Gateway	Gateway Indicator (1=Yes)	-
ItinGeoType	Itinerary Geography Type	-
CouponGeoType	Coupon Geography Type	-

---

[6] http://www.transtats.bts.gov/Fields.asp?Table_ID=289.

DB1B Market Columns[7]:

Number	Column	Description	Notes
1	**ItinID**	Itinerary ID	Foreign key to DB1BTicket
2	**MktID**	Market ID	Primary key
3	**MktCoupons**	Number of Coupons in the Market	-
4	**Year**	Year	-
5	**Quarter**	Quarter (1-4)	-
6	**Origin**	Origin Airport Code	-
7	**OriginAptInd**	Origin Airport, Multiple Airports Indicator	-
8	**OriginCityNum**	Origin Airport, City Code	-
9	**OriginCountry**	Origin Airport, Country Code	-
10	**OriginStateFips**	Origin Airport, State FIPS Code	-
11	**OriginState**	Origin Airport, State Code	-
12	**OriginStateName**	Origin State Name	-
13	**OriginWac**	Origin Airport, World Area Code	-
14	**Dest**	Destination Airport Code	-
15	**DestAptInd**	Destination Airport, Multiple Airports Indicator	-
16	**DestCityNum**	Destination Airport, City Code	-
17	**DestCountry**	Destination Airport, Country Code	-
18	**DestStateFips**	Destination Airport, State FIPS Code	-
19	**DestState**	Destination Airport, State Code	-
20	**DestStateName**	Destination State Name	-
21	**DestWac**	Destination Airport, World Area Code	-
22	**AirportGroup**	Airport Group	-
23	**WacGroup**	World Area Code Group	-
24	**TkCarrierChange**	Ticketing Carrier Change Indicator	-
25	**TkCarrierGroup**	Ticketing Carrier Group	-
26	**OpCarrierChange**	Operating Carrier Change Indicator	-
27	**OpCarrierGroup**	Operating Carrier Group	-
28	**RPCarrier**	Reporting carrier code	-
29	**TkCarrier**	Ticketing carrier code	-
30	**OpCarrier**	Operating carrier code	-
31	**BulkFare**	Bulk fare indicator	-
32	**Passengers**	Number of passengers	-
33	**MktFare**	Market fare (ItinYield*MktMilesFlown)	-
34	**MktDistance**	Market distance	Includes ground transport
35	**MktDistanceGroup**	Distance group, in 500 mile intervals	-
36	**MktMilesFlown**	Market miles flown (track miles)	-
37	**NonStopMiles**	Non-Stop Market Miles (Radian Measure)	-
38	**ItinGeoType**	Itinerary Geography Type	-
39	**MktGeoType**	Market geography type	-

---

[7] http://www.transtats.bts.gov/Fields.asp?Table_ID=247

T-100 Columns[8]:

Number	Column	Description
1	**Year**	Year
2	**Quarter**	Quarter (1-4)
3	**Month**	Month
4	**AirlineID**	US DOT ID number
5	**UniqueCarrier**	Unique carrier code
6	**Carrier**	IATA carrier code
7	**FlightDate**	Flight date (yyyymmdd)
8	**DayofMonth**	Day of month
9	**DayOfWeek**	Day of week
10	**Flights**	Number of flights
11	**FlightNum**	Flight number
12	**TailNum**	Tail number
13	**AirTime**	Flight time (minutes)
14	**ArrDel15**	Arrival delay indicator, 15+ min.
15	**ArrDel30**	Arrival delay indicator, 30+ min.
16	**ArrDelSys15**	Arrival delay indicator, 15+ min.
17	**ArrDelSys30**	Arrival delay indicator, 30+ min.
18	**ArrDelay**	Arrival delay (minutes)
19	**ArrTime**	Actual arrival time (hhmm)
20	**ArrTimeBlk**	CRS arrival time block, hourly intervals
21	**CRSArrTime**	CRS arrival time (hhmm)
22	**DepDel15**	Departure delay indicator, 15+ min.
23	**DepDel30**	Departure delay indicator, 30+ min.
24	**DepDelSys15**	Departure delay indicator, 15+ min.
25	**DepDelSys30**	Departure delay indicator, 30+ min.
26	**DepDelay**	Departure Delay (minutes)
27	**DepTime**	Actual departure time (hhmm)
28	**DepTimeBlk**	CRS departure time block, hourly intervals
29	**CRSDepTime**	CRS departure time (hhmm)
30	**Origin**	Origin airport
31	**OriginCityName**	Origin airport, city name
32	**OriginState**	Origin airport, state code
33	**OriginStateFips**	Origin airport, state fips
34	**OriginStateName**	Origin airport, state name
35	**OriginWac**	Origin airport, world area code
36	**Dest**	Destination airport
37	**DestCityName**	Destination airport, city name
38	**DestState**	Destination airport, state code
39	**DestStateFips**	Destination airport, state fips
40	**DestStateName**	Destination airport, state name
41	**DestWac**	Destination airport, world area code
42	**Distance**	Non-stop distance (using radian measure)

---

[8] http://www.transtats.bts.gov/Tables.asp?DB_ID=120

43	**DistanceGroup**	Distance intervals (250 miles)
44	**TaxiIn**	Taxi in time (minutes)
45	**TaxiOut**	Taxi out time (minutes)
46	**Off**	Off time (hhmm)
47	**On**	On time (hhmm)
48	**Cancelled**	Cancelled flight indicator
49	**CancellationCode**	Reason for cancellation
50	**Diverted**	Diverted flight indicator
51	**CarrierDelay**	Carrier delay (minutes)
52	**WeatherDelay**	Weather delay (minutes)
53	**NASDelay**	NAS delay (minutes)
54	**SecurityDelay**	Security delay (minutes)
55	**LateAircraftDelay**	Late aircraft delay (minutes)

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
01- 12 - 2011	Contractor Report	June 25, 2010 to June 24, 2011

4. TITLE AND SUBTITLE
A Concept for Flexible Operations and Optimized Traffic into Metroplex Regions

5a. CONTRACT NUMBER
NNL10AA15C

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
DeLaurentis, Daniel; Landry, Steve; Sun, Dengfeng; Wieland, Fred; Tyagi, Ankit

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
305295.02.07.07.02

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, VA 23681-2199

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSOR/MONITOR'S ACRONYM(S)
NASA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
NASA/CR-2011-217302

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category 01
Availability: NASA CASI (443) 757-5802

13. SUPPLEMENTARY NOTES
Langley Technical Monitor: Michael R. Sorokach

14. ABSTRACT

A "Flexible Flight Operations" concept for airport metroplexes was studied. A flexible flight is one whose destination airport is not assigned until a threshold is reached near the arrival area at which time the runway which reduces overall delay is assigned. The concept seeks to increase throughput by exploiting flexibility. The quantification of best-case benefits from the concept was pursued to establish whether further concept research is warranted. Findings indicate that indeed the concept has potential for significant reductions in delay (and cost due to delay) in the N90 (NY/NJ) and SCT (Southern California) metroplexes. Delay reductions of nearly 26% are possible in N90 when 30% of the commercial airline flights are flexible (smartly selected by their low probability of connecting passengers); nearly 41% delay reduction is found when 50% of the flights are flexible. In the SCT metroplex, delay reductions estimates are greater. Greater reductions result at SCT since it is less constrained currently than N90, providing "more room" to take advantage of flexibility. Using the flexible operations concept for on-demand/air taxi and General Aviation flights were found to be beneficial at NYNJ, indicating the flexible operations concepts may be useful to a wide variety of users.

15. SUBJECT TERMS
Airspace Systems; Flexible Operations; Ground Transportation; Metroplex; NextGen Applications; Optimized Air Traffic Flow; Runway Management

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES
U	U	U	UU	110

19a. NAME OF RESPONSIBLE PERSON
STI Help Desk (email: help@sti.nasa.gov)

19b. TELEPHONE NUMBER *(Include area code)*
(443) 757-5802