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Characterization of and Concepts for Metroplex Operations

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TABLE OF CONTENTS

TABLE OF CONTENTS (cont.)

TABLE OF CONTENTS (cont.)

TABLE OF CONTENTS (cont.)

LIST OF FIGURES

LIST OF FIGURES (cont.)

LIST OF TABLES

LIST OF TABLES (cont.)

ACRONYMS AND GLOSSARY

3-D	three-dimensional
3X	three times
4-D	four-dimensional
4-DT	four-dimensional trajectory
AC	aircraft
ACES	Airspace Concept Evaluation System
ADIZ	Air Defense Identification Zone
ADS-B	Automatic Dependent Surveillance – Broadcast
ADT	Airspace Design Tool (Metron Aviation)
AFP	Airspace Flow Programs
AGL	above ground level
a.m.	ante meridiem
ANSP	Air Navigation Service Provider
APREQ	Approval Request
ARMT	Airport Resource Management Tool
ARTCC	air route traffic control center
ARTS	Automated Radar Terminal Systems
ASDE-X	Airport Surface Detection Equipment, Model X
ATA	arrival transition area
ATAC	ATAC Corporation, Sunnyvale, California
ATC	air traffic control
ATCSCC	Air Traffic Control System Command Center (FAA)
ATCT	air traffic control tower
ATG	Airspace Traffic Generator
ATM	air traffic management
ATT	along-track tolerance
BADA	Base of Aircraft Data
CASSIS	CTA-ATM System Integration Studies
CAVS	cockpit-based all weather merging and spacing
CDA	continuous-descent arrival
CDR	coded departure route
CIWS	corridor integrated weather system
CO	carbon monoxide
CO_2	carbon dioxide
ConOps	concept of operations
CTA	controlled time of arrival
CTAS	Center/TRACON Automation System
CW	convective weather
D10	Dallas-Fort Worth TRACON
dBA	A-weighted sound level in decibels
DC	Washington, D.C.
DFM	Departure Flow Manager
DME	distance-measuring equipment
DNL	day-night average sound level
DSP	Departure Spacing Program
DTA	departure transition area
EDCT	expected departure clearance time
EDMS	Emissions and Dispersion Modeling System
EDP	expedite departure path
EMS	Environmental Management System
EPA	Environmental Protection Agency
ERAM	en-route automation modernization
ETA	estimated time of arrival
ETMS	enhanced traffic management system
EVO	equivalent visual operations
FAA	Federal Aviation Administration
FACT-2	Capacity Needs in the National Airspace System
FCM	flow contingency management
FEIS	New York/New Jersey/Philadelphia Final Environmental Impact Statement
FFC	Future Flight Central
FIFO	first in, first out
FMS	flight management system
GA	general aviation
GaTech	Georgia Institute of Technology, Atlanta, Georgia
GDP	Ground Delay Programs

GMU	George Mason University, Fairfax, Virginia
HC	hydrocarbon
IADS	Interactive Analysis and Display System
IADSTMM	Integrated Arrival/Departure and Surface Traffic Management for Metroplex
IAP	instrument approach procedure
ICAO	International Civil Aviation Organization
ID	identification
IFR	instrument flight rules
IID	independent and identically distributed
ILS	instrument landing system
IMC	instrument meteorological conditions
ITWS	integrated terminal weather system
IWP	(JPDO) Integrated Work Plan
JPDO	Joint Planning and Development Office
LA	Los Angeles, California
LAT	look-ahead time
LNAV	lateral navigation
LOA	letter of agreement
MACS	Airspace Traffic Generator
MAMS	Military Airspace Management System
MATLAB	A computational tool developed by Mathworks
MBA	mean time between arrivals
MC-TMA	Multi-Center Traffic Management Advisor
Metron	Metron Aviation, Inc., Dulles, Virginia
MIT	mile in trail
MITRE	MITRE Corporation, McLean, Virginia
MLE	maximum-likelihood estimator
MSL	mean sea level
MVA	minimum vectoring altitude
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NASEIM	NAS-wide Environmental Impact Model
NextGen	Next-Generation Air Transportation System
NFDC	National Flight Data Center
nm	nautical mile
NO_x	nitrogen oxide
NRA	NASA Research Announcement
NTC	North Texas Commission
NTX	North Texas Research Station for CTAS
NY	New York City, New York
OEP	Operational Evolution Partnership (FAA initiative)
PBS	performance-based operations and services
PDARS	performance data analysis and reporting system
PDF	probability density function
PM	particulate matter
p.m.	post meridiem
PNT	positioning, navigation, and timing
PTP	point to point
RAPT	Route Availability Planning Tool
RNAV	area navigation system
RNP	required navigation performance
ROA	research opportunities in aeronautics
ROC	required obstruction clearance
RTA	required time of arrival
RTT	research transition team
SDO	super-density arrival/departure operations
SEL	sound exposure level
Sensis	Sensis Corporation, Campbell, California
SF	San Francisco, California
SID	standard instrument departure
SIMMOD	Airport and Airspace Delay Simulation Model
SME	subject-matter expert
SMS	surface management system
SMS-ATG	Surface Management System-Airspace Traffic Generator
SO_x	sulfur dioxide

SOP	standard operating procedure
STAR	standard terminal arrival route
SUA	special-use airspace
SWAP	Severe Weather Avoidance Plan
TACEC	Terminal Area Capacity-Enhancing Concept
TAF	terminal-area forecast
TASAT	Tool for Analysis of Separation and Throughput
TBO	trajectory-based operations
TDMA	time-division multiple access
TFM	traffic flow management
TFMS	traffic flow management system
TMA	Traffic Management Advisor
TMU	Traffic Management Unit
TRAC	Test of Reaction and Adaptation Capabilities
TRACON	terminal radar approach control facilities
TRL	technology readiness level
URET	User Request Evaluation Tool
VACAPES	Virginia Capes Operating Area
VAMS	Virtual Airspace Modeling and Simulation (NASA project)
VLJ	very light jet
VMC	visual meteorological conditions
VNAV	vertical navigation
V/STOL	vertical/short takeoff and landing
XTT	cross-track tolerance

ATC FACILITY IDENTIFICATIONS

21D	Lake Elmo, St. Paul, Minnesota
A80	Atlanta Large TRACON
ABE	Lehigh Valley International Airport, Allentown, Pennsylvania
ACY	Atlantic City International Airport, Atlantic City, New Jersey
AHN	Athens/Ben Epps, Athens, Georgia
ANE	Anoka County, Minneapolis, Minnesota
ARR	Aurora Municipal Airport, Chicago, Illinois
ATL	Atlanta Hartsfield International Airport, Atlanta, Georgia
AXH	Houston Southwest, Houston, Texas
BFI	Boeing Field, Seattle, Washington
BOS	Logan International Airport, Boston, Massachusetts
BUR	Bob Hope, Burbank, California
BWI	Baltimore - Washington International Airport, Baltimore, Maryland
C90	Chicago TRACON
CANUK	entry fix southeast of ATL
CCR	Buchanan Field, Concord, California
CDW	Essex County, Caldwell, New Jersey
CHD	Chandler Municipal, Chandler, Arizona
CLT	Charlotte/Douglas International Airport, Charlotte, North Carolina
CNO	Chino, Chino, California
CRQ	McClellan-Palomar, Carlsbad, California
CSG	Columbus Metropolitan, Columbus, Georgia
CXO	Lone Star Executive, Houston, Texas
D10	Dallas - Fort Worth TRACON
DAL	Dallas Love Field, Dallas, Texas
DCA	Ronald Reagan National Airport, Washington, D.C.
DFW	Dallas/Fort Worth International Airport, Dallas-Fort Worth, Texas
DIRTY	Entry fix northeast of ATL
DMW	Carroll County Regional, Westminster, Virginia
DPA	DuPage, Chicago/West Chicago, Illinois
DTW	Detroit Metropolitan Wayne County, Detroit, Michigan
DVT	Phoenix Deer Valley, Phoenix, Arizona

DWH	David Wayne Hooks, Houston, Texas
EFD	Ellington Field, Houston, Texas
ELIOT	exit fix west of EWR
ENW	Kenosha Regional, Kenosha, Wisconsin
ERLIN	entry fix northwest of ATL
EWR	Newark International Airport, Newark, New Jersey
FCM	Flying Cloud, Minneapolis, Minnesota
FDK	Frederick Municipal, Frederick, Maryland
FFZ	Falcon Field, Mesa, Arizona
FLL	Fort Lauderdale-Hollywood International Airport, Fort Lauderdale, Florida
FRG	Republic, Farmingdale, New York
FTY	Fulton County - Brown Field, Atlanta, Georgia
FXE	Fort Lauderdale Executive, Fort Lauderdale, Florida
GEU	Glendale Municipal, Glendale, Arizona
GMN	Gorman VORTAC, Gorman, California
GORMAN	Gorman VORTAC (GMN), Gorman, California
GYY	Gary/Chicago International Airport, Gary, Indiana
HEF	Manassas Regional/Harry P. Davis Field, Manassas, Virginia
HND	Henderson Executive, Las Vegas, Nevada
HONIE	entry fix southwest of ATL
HOU	Houston Hobby, Houston, Texas
HPN	Westchester County, White Plains, New York
HWD	Hayward Executive, Hayward, California
I90	Houston TRACON
IAD	Washington Dulles International Airport, Dulles, Virginia
IAH	George Bush International Airport, Houston, Texas
IGQ	Lansing Municipal, Chicago/Lansing, Illinois
ILG	New Castle, Wilmington, Delaware
ISP	Long Island - MacArthur, Islip, New York
IWS	West Houston, Houston, Texas
JAX	Jacksonville International Airport, Jacksonville, Florida
JFK	J. F. Kennedy International Airport, New York, New York
JQF	Concord Regional, Concord, North Carolina
JYO	Leesburg Executive, Leesburg, Virginia
L30	Las Vegas TRACON
LAS	Las Vegas McCarran International Airport, Las Vegas, Nevada
LAX	Los Angeles International Airport, Los Angeles, California
LGA	LaGuardia, New York, New York
LGB	Long Beach/Daugherty Field, Long Beach, California
LNA	Palm Beach County Park, West Palm Beach, Florida
LOM	Wings Field, Philadelphia, Pennsylvania
LOT	Lewis University Airport, Chicago/Romeoville, Illinois
LVJ	Pearland Regional, Houston, Texas
LVK	Livermore Municipal, Livermore, California
LVN	Airlake, Minneapolis, Minnesota
M98	Minneapolis TRACON
MCN	Middle Georgia Regional, Macon, Georgia
MDW	Chicago Midway, Chicago, Illinois
MEM	Memphis International Airport, Memphis, Tennessee
MIA	Miami International Airport, Miami, Florida
MIA	Miami Tower/TRACON
MIC	Crystal, Minneapolis, Minnesota

MKE	General Mitchell International, Milwaukee, Wisconsin
MMU	Morristown Municipal Airport, Morristown, New Jersey
MSP	Minneapolis-St Paul International, Minneapolis, Minnesota
MTN	Martin State, Baltimore, Maryland
MYF	Montgomery Field, San Diego, California
N90	New York TRACON
NCT	North California TRACON
NKX	Miramar Marine Corps Air Station, San Diego, California
OAK	Metropolitan Oakland International Airport, Oakland, California
ONT	Ontario International Airport, Ontario, California
OPF	Opa Locka, Miami, Florida
ORD	Chicago O'Hare International Airport, Chicago, Illinois
P50	Phoenix TRACON
PAE	Snohomish Co (Paine Field), Everett, Washington
PAO	Palo Alto, Palo Alto, California
PBI	Palm Beach International Airport, West Palm Beach, Florida
PBI	Palm Beach TRACON
PCT	Potomac TRACON
PDK	Dekalb-Peachtree, Atlanta, Georgia
PHL	Philadelphia International Airport, Philadelphia, Pennsylvania
PHX	Phoenix Sky Harbor International Airport, Phoenix, Arizona
PNE	Northeast Philadelphia, Philadelphia, Pennsylvania
POC	Brackett Field, La Verne, California
PSP	Palm Springs International Airport, Palm Springs, California
PWK	Chicago Executive, Chicago/Wheeling, Illinois
RFD	Chicago/Rockford International Airport, Rockford, Illinois
RHV	Reid-Hillview of Santa Clara County, San Jose, California
RIV	March Air Reserve Base, Riverside, California
RYY	Cobb County - McCollum Field, Atlanta, Georgia
S43	Harvey Field, Snohomish, Washington
S46	Seattle TRACON
S50	Auburn Municipal, Auburn, Washington
SAN	San Diego International, San Diego, California
SCT	Southern California TRACON
SDF	Louisville International Airport - Standiford Field, Louisville, Kentucky
SDL	Scottsdale, Scottsdale, Arizona
SDM	Brown Field Municipal, San Diego, California
SEA	Seattle-Tacoma International Airport, Seattle, Washington
SEE	Gillespie Field, San Diego/El Cajon, California
SFO	San Francisco International Airport, San Francisco, California
SGR	Sugar Land, Houston, Texas
SGS	South St. Paul, South St. Paul, Minnesota
SJC	Norman Y. Mineta San Jose International Airport, San Jose, California
SMO	Santa Monica Municipal, Santa Monica, California
SNA	John Wayne Airport-Orange County, Santa Ana, California
SQL	San Carlos, San Carlos, California
STP	St. Paul Downtown, St. Paul, Minnesota
SWF	Stewart International Airport, Newburgh, New York
TEB	Teterboro, Teterboro, New Jersey
TMB	Kendall-Tamiami Executive, Miami, Florida

UGN	Waukegan Regional, Chicago/Waukegan, Illinois
UZA	Rock Hill/York County/Bryant Field, Rock Hill, South Carolina
VGT	North Las Vegas, Las Vegas, Nevada
VNY	Van Nuys, Van Nuys, California
W66	Warrenton-Fauquier County, Warrenton, Virginia
WHP	Whiteman, Los Angeles, California
ZAU	Chicago ARTCC
ZBW	Boston ARTCC
ZDC	Washington ARTCC
ZFW	Fort Worth ARTCC
ZLA	Los Angeles ARTCC
ZMA	Miami ARTCC
ZNY	New York ARTCC
ZOA	Oakland ARTCC
ZTL	Atlanta ARTCC

CHARACTERIZATION OF AND CONCEPTS FOR METROPLEX OPERATIONS

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Ames Research Center

1.0 EXECUTIVE SUMMARY

Metropolitan areas with high demand are often served by a system of two or more airports whose arrival and departure operations are highly interdependent. Such an airport system is refferred to as a metroplex. The projected traffic growth will increase the coupling of operations in the metroplexes that already exist, and will potentially create new metroplexes. The coupling of operations requires that the solution for the airspace structure surrounding, and the traffic flows to and from airports within, a metroplex must be solved cooperatively as a system.

The parameters that determine the coupling of operations across a broad range of conditions and airspaces, and underlying issues and factors that drive metroplex operational complexity and practices, are not well understood. Understanding these parameters is critical to enabling the full runway infrastructure benefit of a metroplex in order to meet the demands anticipated by major metropolitan areas. An understanding of current metroplex operations and management—particularly the underlying issues and factors that drive metroplex operational complexity and practices—is essential to the development of approaches to coordinate operations effectively among increasingly coupled airports in the Next-Generation Air Transportation System (NextGen). The objectives of this project were:

- to identify the issues and constraints that dictate current practices (dependencies and interactions between metroplex airports) and are likely to extend to NextGen concepts
- to characterize the impact the introduction of NextGen concepts and capabilities will have on metroplex operations
- to investigate alternative concepts for significantly increasing capacity in high-demand metropolitan areas.

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This document is the final report of this research effort.

The research objective of this project was to develop a deeper understanding of the constraints on metroplex operations that reduce capacity and to use this understanding to develop and evaluate new metroplex design and operational techniques to increase capacity in high-demand metropolitan areas. This increase in capacity is essential to enable the National Airspace System (NAS) to accommodate the air traffic demand projected in the NextGen time frame. This accommodation will require research in not only airport operations and procedures but also high-density terminal airspace operations and procedures. The specific task objectives were as follows:

- Identify the dependencies and interactions among metroplex airports that affect metroplex operations.
- Develop a classification scheme for metroplex dependencies.
- Determine the impact that the introduction of NextGen concepts and capabilities will have on metroplex operations.
- Investigate new and innovative methods for significantly increasing the capacity of metropolitan airspace and airports.

To achieve the research objectives, a comprehensive research approach was developed and implemented. The research project started with the *literature review*, which focused on three areas:

- The state of the art for metroplex operations today
- The concepts and capabilities relevant to future metroplex operations
- The identification of candidate metroplex sites for site-survey study that would follow

With the identified candidate sites, a series of comprehensive *metroplex site surveys* were conducted. The goals of the site surveys were:

- To develop a thorough understanding of the metroplex issues and constraints through studying real-world examples
- To catalog the traffic flow dependencies and interactions at each site
- To document the best practices at each facility to handle metroplex issues, constraints, and dependencies
- To collect information about planned future developments relevant to the metroplex problem at each site

The next task process, *characterization of metroplex operations*, used information and data collected through the literature review and site surveys. Qualitative analyses and internal subject domain expert evaluations were employed to develop classifications of metroplex issues and airspace interdependencies. Quantitative metrics were developed to measure the intensity and types of interactions between metroplex airports and specific traffic flows.

The knowledge achieved through the previous three task processes led to *metroplex concept analysis* and the development of an *experiment plan*. Practices to handle traffic interdependencies and traffic coordination were abstracted into the temporal-spatial displacement concept on which an evaluation framework was based and developed. The existing NextGen concepts were carefully reviewed and compared against the temporal-spatial concept to identify the most relevant concepts. Based on this principle, new concepts were also proposed to close any gaps in forming innovative solutions for significantly increasing the capacity of, and improving the efficiency for, metroplex operations. The experiment plan was then developed to form control parameters that reflect the end effects of various concepts studied in lieu of modeling any specific concepts.

Two separate *metroplex experiments* were formed to first test the basic concepts with a ***Generic Metroplex*** model, and then develop solutions and verify the solution with a model of the New York TRACON (N90) and surrounding metropolitan area—the most complex metroplex in the NAS. The Generic Metroplex experiment was based mainly on a linked-node queueing-process model that can be reconfigured to test different metroplex airspace designs and traffic coordination techniques. The general strategy for the experiment was to first simulate current-day conditions, and then test increasingly higher levels of metroplex technologies defined by control parameters developed in the previous task process, the Metroplex Concept Analysis. The outcome of this task is the quantitative assessment of the impact of NextGen and newly proposed concepts.

The last task process, *analyses and documentation*, is the process of analyzing experiment results and reviewing all research outcomes achieved. The outcome is this metroplex final report and recommendations of metroplex technologies and further metroplex research that is needed to achieve the ultimate goal of mitigating metroplex interactions.

Through this research, the Georgia Institute of Technology, Atlanta, Georgia, (GaTech) Metroplex team systematically studied the parameters that determine the coupling and inefficiencies in metroplex operations; developed a framework to evaluate concepts and capabilities that manage the coupling of metroplex operations; and conducted the initial simulations to evaluate the impact of down-selected technological capabilities to identify the most promising concepts. These tasks highlight key findings of this research, and details of these research results are documented in this report. Additional information is also available in the individual reports and papers described in appendix B.

The GaTech team discovered from a thorough literature review that, although certain aspects of the metroplex problem have been touched on by various previous studies, there has been no systematic research in the interdependencies among arrival and departure operations. A close inspection of interdependencies and interactions among metroplex airports suggests that they can be divided into two fundamental types. The first can be categorized as preexisting conditions, while the second can be categorized as the air-traffic-control (ATC) response to those preexisting conditions. The difference between these two types is that different measures can be taken to counter the same set of preexisting conditions, or dependencies, as illustrated by the metroplex site-survey findings. Of course, there are some measures that may be taken at different sites to serve similar purposes. Through some of the measures, such as segregated routing, traffic flows within a metroplex may operate independently. However, the dependencies between airspace would still be there—there is a price to pay to segregate the flow. It is thus important to maintain the distinction between the intrinsic dependencies between arrival and departure operations at metroplex airports and the practices to counter those intrinsic interactions and dependencies. The former defines a metroplex, and the latter provides solutions to the metroplex problem.

1.1 Characterization of Metroplex and Metroplex Operations

Based on the site-survey studies, through subject domain expert evaluation and qualitative analyses, the team identified and rank listed major metroplex issues. The rank-orderd list of 12 major metroplex issues identifies the intrinsic dependencies in metroplex operations. Among them, “multi-airport departure merge over common departure fix” was identified as the most critical issue across the four metroplex sites surveyed. Other issues of primary importance include:

- Major volume-based traffic-flow-management (TFM) restrictions
- Proximate-airport configuration conflicts
- Slow inter-airport ground connectivity
- Inefficient/high-workload airport configuration changes
- Inefficient multi-airport departure sequencing
- Major secondary-airport flow constraints

Other issues that are also critical but affect only certain metroplexes include:

- Inefficient “flushing” of airport flows
- Effects of special-use airspace (SUA) and terrain, which caused additional flow dependencies
- Severe limitations on instrument procedures due to a proximate airport
- Insufficient regional-airport capacity

The team focused on airspace-related issues and conducted detailed analysis of practices in handling these issues. The result was a categorization of airspace interactions into these six types:

- Sharing of fixes through metering
- Sharing of path segments through metering
- Sharing of airspace volume through holding or stopping the flow
- Vertical flow segregation
- Lateral flow segregation
- Downstream flow restrictions for multiple airports

Through quantitative analyses, three sets of metrics were developed to categorize existing metroplexes in the NAS and to identify potential future metroplexes necessitated by regional traffic growth. By utilizing basic geographic information about metroplex airports, several metrics were developed to measure the intrinsic dependencies within each metroplex. Quantitative analyses using these metrics indicated that the four metroplex sites surveyed can be ranked in increasing order of intrinsic dependency as: Atlanta Large TRACON (A80) < Miami Tower/TRACON (MIA) < Southern California TRACON (SCT) < N90. Among the four metroplexes, N90 is the most complex—consistent with site-survey results and common understanding. The analyses also revealed that a metroplex could be normally identified with a core of a radius of 15 to 20 nautical miles (nm) within which the dependencies among airports are strongest.

An arrival-flow airspace volume-based metric was used as the "distance" measure for clustering airports into metroplexes and identifying potential future metroplexes in the NAS. The clustering algorithm was calibrated to capture the 15 metropolitan areas identified in the Federal Aviation Administration's (FAA's) Operational Evolution Partnership (OEP) initiative. Applied to the projected terminal-area-forecast (TAF) data for 2025, the clustering algorithm identified 18 metroplexes, three of which were identified as new metroplexes in 2025: Minneapolis, Boston, and Cincinnati.

1.2 Evaluation of Impact of NextGen and Team Proposed Concepts

To implement the framework for evaluating the impact of NextGen and team-proposed future concepts and capabilities, temporal control was represented by:

- Traffic-flow coordination or scheduling that provided target times (e.g., fix-crossing times and takeoff times)
- Traffic-flow metering or surface management to achieve the target times

Spatial control was represented by:

- Lateral and vertical separation standards
- Airspace design geometries and segregated three-dimensional (3-D) routes based on separation standards and aircraft (AC) performance limits

The temporal-control concepts were modeled as several prototype arrival scheduling algorithms and models of metering accuracy. The spatial-control concepts were modeled as different airspace geometries. For the Generic Metroplex study, four geometries were developed:

- Geometry 1 (baseline airspace) represented a standard four-corner post route structure.
- Geometry 2 represented a shared-route airspace.
- Geometry 3 (decoupled airspace) consisted of duplicate entry fixes at each corner to segregate traffic flows to the two airports.
- Geometry 4 consisted of 32 entry and exit fixes, each associated with a fully segregated, most-direct route to each airport.

For the N90 Metroplex, a NextGen fully decoupled route structure was developed.

A method using "intersect-flow" metrics was developed to measure the complexity of traffic-flow interactions within a metroplex terminal area. Applying this analysis to the Generic Metroplex revealed that geometry 3 (decoupled airspace) reduced the traffic-flow interaction over the baseline (geometry 1), while geometry 2 (representing extensive path sharing) and geometry 4 (a fully segregated most direct route) increased traffic-flow interaction over the baseline. A Generic Metroplex delay versus arrival-rate sensitivity analysis also revealed that when runways (as opposed to entry fixes) are the choke points, increasing the number of entry fixes to segregate traffic to different airports would not necessarily help in reducing delays. As such, the Generic Metroplex simulation focused on the baseline (geometry 1) and the dual-corner-fix (geometry 3) airspace only.

This report summarizes the aggregated effects of scheduling and decoupled airspace from the Generic Metroplex linked-node queueing simulation study and the N90 Metroplex Airport and Airspace Delay Simulation Model (SIMMOD) simulation study. The Generic Metroplex simulation revealed that, when scheduling was applied to coordination of arrival traffic flows, the systemwide arrival delays incurred at the metroplex terminal-area boundary and within the terminal area were reduced by 73% in the case of the baseline airspace. Without scheduling, the use of dual-corner fixes did not achieve delay reductions. With scheduling, the dual-corner fixes provided a 23% delay reduction from the baseline, achieving a combined 79% delay reduction from the case of baseline airspace without scheduling. The N90 simulation revealed that, applied separately, the NextGen fully decoupled airspace and the arrival scheduling reduced systemwide arrival air delay incurred within the N90 terminal area by 28% and 60%, respectively, from current-day operations. Combined together, the decoupled airspace and the arrival scheduling reduced the systemwide arrival air delay from the level in current-day operations by 79%, the same result as was observed in the Generic Metroplex study.

In both the Generic Metroplex study and the N90 simulation study, scheduling provided greater delay reductions than the segregated route airspace geometries. The Generic Metroplex simulation also revealed that, with lower metering accuracy, the effectiveness of scheduling was negatively impacted, but the majority of delay reductions from scheduling were retained even with the worst-case metering accuracy. This finding suggests that scheduling tools can be developed to achieve revolutionary delay reductions even with current-day metering accuracy. Future four-dimensional trajectory (4-DT) operations would then provide further enhancements to the traffic scheduling and coordination.

As presented in this executive summary and documented later in this report, a significant range of metroplex issues and inefficiencies have been identified, a range of potential metroplex concepts have been analyzed, and significant potential benefits of metroplex concepts have been quantified, in both a set of representative Generic Metroplex configurations and for N90. The definition of these potential metroplex concepts, and quantification of the potential benefits, is the beginning of a broader set of metroplex research and development tasks and benefits-assessment tasks that the National Aeronautics and Space Administration (NASA) plans to perform to fully validate the concepts and requirements of improved metroplex concepts before transitioning such concepts to the FAA. In general these broader future metroplex research tasks can be categorized as:

- The development of refined concept modeling and prototype metroplex decision support tools
- Further investigation into the analysis of metroplex concept impacts

The recommendations are described in detail in section 9.2.

The research results of the GaTech team and the NASA metroplex research recommendations are critical to improving current and future NAS metroplex operational efficiency. As traffic demand increases in the future, more regions in the NAS are expected to become metroplexes. Thus, as these metroplexes grow, so will the expected levels of metroplex-induced air traffic delays due to the multiple metroplex issues and inefficiencies that have been studied in the current research. It is therefore important for NASA to take additional metroplex research steps such as those suggested in the previous discussion to move metroplex concepts out from a low technology-readiness-level (TRL) concept exploration phase, which forms the basis of this work, and move these concepts further along the TRL scale towards future operational implementation and deployment. This process will help ensure that the NAS will be prepared to minimize the expected significant growth in future metroplex delays.

2.0 INTRODUCTION

The National Aeronautics and Space Administration (NASA) Contract NNX07AP63A, titled "Characterization of and Concepts for Metroplex Operations", was performed by a team led by the Georgia Institute of Technology, Atlanta, Georgia (GaTech). This work was a response to Subtopic 20: Metroplex Operations, NASA Research Announcement (NRA) NNH06ZNH001, i.e., Research Opportunities in Aeronautics – 2006 (ROA-2006) [NRA06]. The research team (referred to as GaTech team hereafter) consisted of researchers from GaTech, ATAC Corporation, Metron Aviation, and Sensis Corporation.

The Federal Aviation Administration (FAA), the Joint Planning and Development Office (JPDO), and others have projected a significantly increased demand within the National Airspace System (NAS) by the time the Next-Generation Air Transportation System (NextGen) begins to reach maturity [AF09, BC06]. It is expected that much of that demand growth will be in major metropolitan areas. Metropolitan areas with high demand are often served by a system of two or more airports whose arrival and departure operations are highly interdependent. Such an airport system is refferred to as a metroplex as defined by the JPDO [JPDO07]. The projected traffic growth will increase the coupling of operations in the metroplexes that already exist, and will potentially create new metroplexes.

The coupling of operations requires that the solution for the airspace structure around, and the traffic flows to and from airports within, a metroplex must be solved cooperatively as a system. Metroplex operations as of today are nominally loosely coordinated. The parameters that determine the coupling of operations across a broad range of conditions and airspaces, and underlying issues and factors that drive metroplex operational complexity and practices, are not well understood. Understanding these parameters is critical to enable the full runway infrastructure benefit of a metroplex in order to meet the demands anticipated by major metropolitan areas. An understanding of current metroplex operations and management—particularly the underlying issues and factors that drive metroplex operational complexity and practices—is essential to the development of approaches to coordinate operations effectively among increasingly coupled airports in the NextGen. The objectives of this project were:

- To identify the issues and constraints that dictate current practices (dependencies and interactions between metroplex airports) and are likely to remain issues and constraints to the development of NextGen concepts
- To characterize the impact the introduction of NextGen concepts and capabilities will have on metroplex operations
- To investigate alternative concepts for significantly increasing capacity in high-demand metropolitan areas

This document is the final report of this research effort. This section (section 2) describes the background, objectives, and basic research approach. The remainder of the report includes results from the literature review (section 3), followed by a description of the major facts and outcomes from the site surveys (section 4). The qualitative and quantitative metroplex characterization effort is described next (section 5), and then a temporal-spatial framework developed from these steps for analyzing metroplex operations is described in detail (section 6).

Results from two experiments conducted utilized the framework are presented (sections 7 and 8), followed by conclusions and recommendations for the next steps and beyond (section 9).

Appendix A presents some of the metroplex-related concepts proposed during the GaTech team brainstorm, and appendix B summarizes publications by the research team in support of this final report.

A list of acronyms is provided at the beginning of the report. For the sake of simplicity, air-traffic-control (ATC) facilities are referred to by their identification codes in this report. The name of a facility may or may not be provided when it is first referred to, depending on the context. For this reason, a list of facility identifications is also provided so the reader can easily look up facility names found in the text.

2.1 Definition of the Term Metroplex and the Metroplex Problem

Although the term metroplex was used as early as the 1950s [J65], the North Texas Commission (NTC) maintains that the term "metroplex" was coined and copyrighted by NTC in 1972 to establish the identity of the now 12-county U.S. Census Metropolitan Statistical Area, which contains the two primary cities of Dallas and Fort Worth [NTC08]. It is said [R08] that the term "metroplex" was created by NTC from combining the words "metropolitan" with "complex". To differentiate itself from a chamber of commerce, NTC states that it represents the entire 12-county Dallas-Fort Worth Metroplex rather than just one community, and that NTC chooses to work on issues, challenges, and opportunities that can best be addressed cooperatively as a region. This concept represents some core concepts of the term, i.e., a large metropolitan area containing several cities, and the coordination among them to address common issues. Since the early 1970s, some scholars have used the term "metroplex" to describe a large urbanized area, including and surrounding several central cities, along with the adjacent hinterland [M84].

Inevitably, within the aviation community the use of the term "metroplex" is most often associated with the Dallas-Fort Worth International Airport [DFW92, CSF01, and HW06]. However, researchers in the aviation community used the term "metroplex" as early as 1964 to refer to a system of several airports [C64 and DKMS73]. The term has also been used for other specific meanings such as a group of three or more radar sensors [PWS80], a mini-hub type operation [H02], and "super" terminal radar approach control facilities (TRACONs) that involve the consolidation of individual TRACONs and support multiple high-traffic airports such as the "Potomac Metroplex" and the "Atlanta Metroplex" [HR97].

In developing the NextGen, the JPDO has officially defined the term "metroplex" as "a group of two or more airports whose arrival and departure operations are highly interdependent" [JPDO07]. The task of understanding and developing a solution for the airspace structure around and the traffic flows to and from airports in a metroplex is referred to as the "metroplex problem."

2.2 Research Objectives

The research objective of this project was to develop a deeper understanding of the constraints on metroplex operations that reduce capacity and to use this understanding to develop and evaluate new metroplex design and operational techniques to increase capacity in high-demand metropolitan areas. This goal is essential to enable the NAS to accommodate the air traffic demand projected in the NextGen time frame. Reaching the goal will require research in not only airport operations and procedures but also high-density terminal airspace operations and procedures. The specific task objectives were as follows:

Identify the dependencies and interactions between metroplex airports that affect metroplex operations.

The specific parameters, processes, and procedures that define and characterize metroplexes will be identified by investigating examples of metroplex constraints in the current instantiation of the NAS. This investigation will leverage prior research, site visits, and telephone interviews with subject-matter experts (SMEs), and documents such as airport master plans and FAA facility standard operating procedures (SOPs). To confirm and clarify the findings from these sources, data from recent operations will also be analyzed.

Develop a classification scheme for metroplex dependencies.

The scheme will be developed by conducting factor analyses to determine those factors or combinations of factors that have the greatest correlation with performance. The resulting correlations will be used to identify those metropolitan areas that currently meet the definition of a metroplex and to project new metroplex operations in the NextGen time frame. It will also enable NASA to model metroplex operations in super-density operations concept evaluations.

Determine the impact that the introduction of NextGen concepts and capabilities will have on metroplex operations.

The impact of NextGen concepts such as four-dimensional (4-D) trajectory-based operations, performance-based services, and increased environmental awareness will be analyzed using the advanced airport and terminal airspace demand projection, modeling, and simulation capabilities of the team. The results of these studies will be evaluated in terms of the classification scheme described in the previous objective so as to simplify the comparison of various possible NextGen scenarios.

Investigate new and innovative methods for significantly increasing the capacity of metropolitan airspace and airports.

Combining the team's expertise in optimization of airport and airspace capacity and environmental impact, new concepts and capabilities will be proposed, extending beyond those currently envisioned by the JPDO and analyzed in the previous objective. Again, analyses and simulations will be conducted to evaluate the potential benefits, and the results interpreted based on our metroplex classification scheme.

2.3 Research Approach

To achieve project objectives, a comprehensive research approach was developed and implemented. An overview of the research approach is presented as a block diagram in Figure 1. Four categories of information are presented. From left to right, the first group is the high-level project schedule depicted by block arrows pointing downwards from July 2007 to December 2009. Each year is denoted by a different color with increasing intensity. The schedule includes a three-month non-cost documentation period after the conclusion of the funded period ending September 30, 2009. For this reason, the period from October to December 2009 is denoted by the background color. The second group depicts the research objectives that were presented in more detail in section 2.2. The third group includes the task processes. This piece is the central piece of the research approach. Task processes are grouped by the same colors denoting different calendar years to show the progress of each task. These task processes are described in more detail in the following paragraphs.

The fourth group lists major outcomes from each of the task processes. Three types of connectors are used in the block diagram. Thick arrows denote the direction of task process flow. Thin arrows denote the direction of information flow. Connectors starting with a dot denote an objective-task supporting relationship. Thin arrows denote an output.

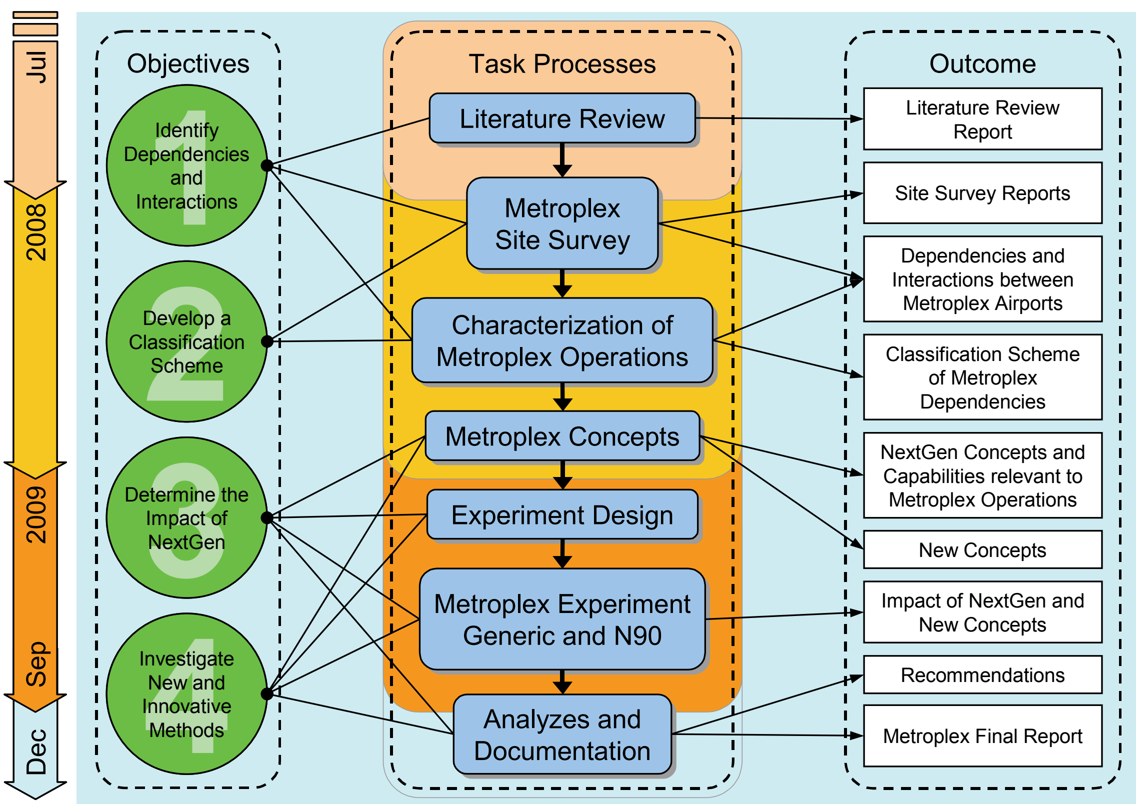

Figure 1. Research approach, supporting tools, output, objectives, and schedule.

The research project started with the ***literature review***, which focused on three areas:

- the state of the art for metroplex operations today
- the concepts and capabilities relevant to future metroplex operations
- the identification of candidate metroplex sites for site-survey study that would follow

The outcome of the literature review was a standalone report. The results from this task are also briefly summarized in section 3. The literature review supported the first objective: Identify dependencies and interactions.

With the identified candidate sites, a series of comprehensive ***metroplex site surveys*** were conducted. The goals of the site surveys were:

- To develop a thorough understanding of the metroplex issues and constraints by studying real-world examples
- To catalog the traffic-flow dependencies and interactions at each site
- To document the best practices at each facility to handle metroplex issues, constraints, and dependencies To collect information about planned future developments relevant to the metroplex problem at each site

The performance data analysis and reporting system (PDARS) [dBS03] was used to analyze traffic flows at each site. The site surveys provided a solid foundation for the remainder of the metroplex research tasks. Four metroplexes were studied: Atlanta (A80), Los Angeles Basin (SCT), New York (N90), and Miami (MIA). Outcomes of site surveys were documented in four standalone site-survey reports, one for each site studied. The results of the site survey are summarized through a comparative study presented in section 4. This task supported the following objectives:

- Identify dependencies and interactions.
- Develop a classification scheme for metroplex operations.

The next task process, ***characterization of metroplex operations***, was initiated not long after the metroplex site survey. Information and data collected through the literature review and site surveys were further processed. Qualitative analyses and internal subject domain expert evaluations were employed to develop classifications of metroplex issues and airspace interdependencies. Quantitative metrics were developed to measure the intensity and types of interactions between metroplex airports and specific traffic flows. The Tool for Analysis of Separation and Throughput (TASAT) [RC08] was employed to generate ideal arrival trajectories. These analyses served to synthesize the knowledge about and deepen the understanding of metroplex dependencies and interactions. Outcomes for this task were classification schemes, both qualitative and quantitative, of metroplex dependencies and documentation of these dependencies. Summaries of these analyses are presented in section 5. This task supported the following objectives:

- Identify dependencies and interactions.
- Develop a classification scheme for Metroplex operations.

The knowledge achieved through the previous three task processes led to *metroplex concept analysis* and the development of an *experiment plan*. Practices to handle traffic interdependencies and traffic coordination were abstracted into the temporal-spatial displacement concept on which an evaluation framework was based and developed. Traffic interdependencies and coordination can be addressed only through temporal displacement (delaying from ideal speed profile), or spatial displacement (moving away from the most direct route), or both, of one or more flows. The existing NextGen concepts were carefully reviewed and compared against the temporal-spatial concept to identify the most relevant concepts. Based on this principle, new concepts were also proposed to close any gaps in forming innovative solutions for significantly increasing the capacity of, and improving the efficiency for, metroplex operations. The experiment plan was then developed to form control parameters that reflect the end effects of various concepts studied in lieu of modeling any specific concepts. The automated future flight demand-generation tool, referred to as AvDemand [SHD07], was used to generate future traffic demand. The outcome of this task was documentation of metroplex concepts and experiment strategies; results are presented in section 6. This task is part of the effort to support the following objectives:

- Determine the impact of NextGen.
- Investigate new and innovative methods.

Two separate *metroplex experiments* were formed to first test the basic concepts with a *Generic Metroplex* model and then develop solutions and verify them with a model of *N90*—the most complex metroplex in the NAS. The Generic Metroplex experiment was based mainly on a linked-node queueing-process model that can be reconfigured to test different metroplex airspace designs and traffic-coordination techniques. Additional analyses were performed to evaluate the complexity of flow-interaction dependencies and the impact of different traffic scheduling algorithms. The N90 experiment was conducted using SIMMOD (see section 8.1.1). The general strategy for the experiment was to first simulate current-day conditions, and then test increasingly higher levels of metroplex technologies defined by control parameters developed in the previous task process. The outcome of this task is the quantitative assessment of the impact of NextGen and newly proposed concepts. The results are presented in sections 7 and 8 for the Generic Metroplex and the N90 experiments, respectively. This task is part of the effort to support the following objectives:

- Determine the impact of NextGen.
- Investigate new and innovative methods.

The last task process, *analyses and documentation*, is the process of analyzing experiment results and reviewing all research outcomes achieved. The outcome is this metroplex final report and recommendations of metroplex technologies and further metroplex research that is needed to achieve the ultimate goal of mitigating metroplex interactions. This task supported all four research objectives specified in section 2.2.

3.0 LITERATURE REVIEW

The objective of the literature review [RS09] was to determine the state of the art for managing interdependent airport operations under current and anticipated future operational situations, and assess the commonalities and significant differences across the range of “metroplex definitions” within the air-traffic-management (ATM) and research communities. This section also identifies and provides justification for candidate metroplex sites that warrant further investigation.

3.1 Selection of Literature for Review

The literature was selected and reviewed for its value to metroplex operations research. Sources for the literature included websites of related agencies, past research publications, simulation programs, and other items. Several team members collectively reviewed the literature and identified the objectives of each report, challenges, methods used to achieve the goals, and the results, or effects of implementation. Reviewers also provided critiques and stated the relevance of the literature to the metroplex research.

3.2 State of the Art for Metroplex Operations Today

This section is an integrated high-level summary of existing literature relevant to today’s metroplex operations. Subjects covered include dependencies and interactions, the state of the art for managing interdependent airport operations under current operational situations, and the commonalities and significant differences across the range of “metroplex definitions” within the ATM and research communities.

3.2.1 Location-Specific Studies

One of the main goals of this research was to identify factors affecting dependencies among airports within a metroplex. Previous studies have explored the problem at numerous sites and documented the measures being employed to handle the problem, although in very limited scope. For example, Newark International Airport in New Jersey (EWR) is particularly prone to adverse weather and is also affected by delays at John F. Kennedy International Airport (JFK) and LaGuardia (LGA), both in New York City. Consequently, different measures are put into place—such as fix restrictions; reroutes; decision support tools, e.g., the Departure Spacing Program (DSP); and communication among facilities—to tackle the delay problem, and these measures are well examined in [EC00]. In response to noise concerns regarding the New York/New Jersey/Philadelphia airspace redesign, MITRE Corporation presented numerous examples of traffic flow interactions between New York Metroplex airports and the existing measures to handle them [M07]. These measures are mostly procedural measures to restrict certain areas in the airspace to arrivals or departures to and from certain runways at certain airports, or to force arrivals and departures to fly certain flightpaths or vertical profiles. However, under certain conditions, departure traffic flows have to merge over a departure fix where coordination between airports becomes necessary. In some of these cases, longitudinal spacing between traffic from different airports is enforced, even though traffic may have already been vertically separated. For the measures discussed, environmental concerns are often raised.

Another airspace system design project focused on a case study of the Chicago area [V00]. As an initial assessment, the study focused on traffic to and from the hub airport Chicago O'Hare International Airport (ORD) rather than interdependencies among metroplex airports. One of the major issues in this analysis was the inability to gain access to quality data, so the outcome of the model simulation lacked validation. The aircraft trajectory model and safety model employed in the Chicago case study, however, may be of interest to the metroplex research.

The supplemental environmental assessment for the Las Vegas Four Corner Post Plan [LV07] provided some details of the existing and planned alternatives of operations at Las Vegas McCarran International Airport (LAS), along with the impacts of increased utilization of other airports in the vicinity of LAS. The criteria for screening alternative designs developed in this study may also be useful in judging alternative metroplex designs. The Los Angeles International Airport (LAX) Master Plan [LA07] is a public-access web site containing documents and facts about the LAX Master Plan. However, the Master Plan is focused on LAX infrastructure capacity and ground-movement operations. Therefore, it does not offer any substantive analysis of airspace interactions or relationships with/to other airports within the region of influence. It should thus act as a stepping-stone to a larger, more inclusive regional view that would be needed for a Los Angeles Metroplex study.

Each of these previous studies had specific local focus; however, some had resource limitations, and were thus very limited in terms of completely defining and explaining the metroplex problem. None of the location-specific studies had thoroughly explored the interdependencies between metroplex airports, whether in terms of runway configuration or airspace interactions. The intent of the metroplex site surveys conducted as part of this research effort was to fill gaps in knowledge pertaining to interdependencies between metroplex airports in relationship to runway configurations and/or airspace interactions.

3.2.2 Nation-Wide Analyses and General Reference

Two previous studies looking at the nation-wide airspace system are of interest to the metroplex research. A study on the emergence of secondary airports [BH05] examined 26 regional airport systems (see Figure 2(a)) within the United States. The regional airport systems were classified into several categories. The study analyzed the effects of utilizing secondary airports on National Airspace System (NAS) capacity and reliability, airline network efficiency, interdependencies between core and secondary airports, and environmental implications. However, the study lacked quantification of the features or characteristics of the airport systems. The regional airport system classification used in this study could, on the other hand, form a basis for identifying a classification scheme for metroplex interactions. Another study by the same authors explored the potential impacts of the entry of very light jets (VLJs) in the NAS [BH06]. VLJs are three- to eight-passenger turbofan aircraft that have a maximum takeoff weight below 10,000 lb. These aircraft have lower costs than conventional light jets, offer better performance (e.g., higher cruise speeds) than comparably priced turboprops, and are predicted to enter the NAS in large numbers. This study identified the fact that, in existing operations, light jet traffic tended to concentrate over key metropolitan areas, implying a potential impact of VLJs on future metroplex operations. Another implication was a strong interaction between VLJs and larger jet aircraft because they fly similar altitude profiles, and consequently new air-traffic-control (ATC) procedures and tools will be required to handle this situation in the terminal areas.

Of general interest to the improvement of metroplex operations is legislative and funding support. As early as 1997 [HR97], it was identified in a Federal Aviation Administration (FAA) benefit-cost analysis that a single consolidated metroplex control facility is the most cost-effective option for the Washington, D.C. metropolitan area, with a benefit-to-cost ratio of 17 to 1. The 105th Congress thus authorized the consolidation of terminal radar approach control facilities (TRACONs) in the Washington, D.C. area. The same benefit-cost study showed a huge benefit from accelerating the construction of the Atlanta Large TRACON, so the capital plan level of funding that had been previously reduced was restored. This restoration implies the importance of benefit-cost analyses for future metroplex operational concepts.

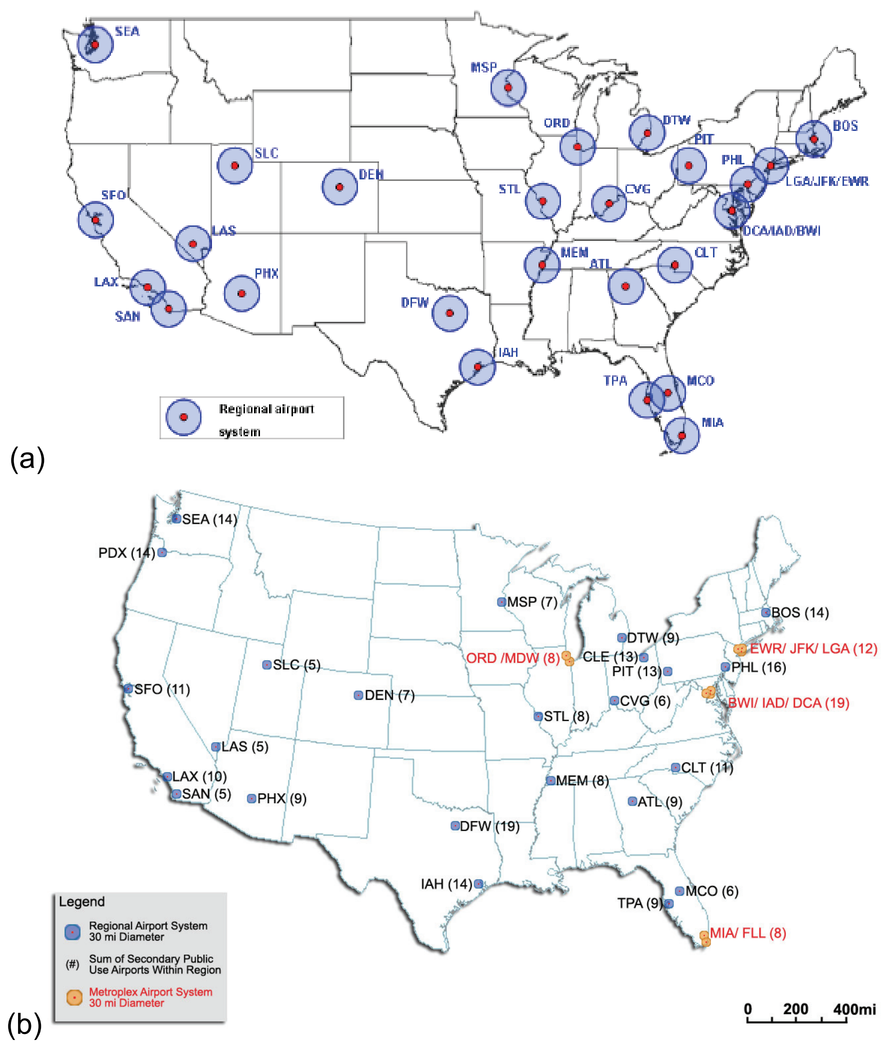

Figure 2. Location of candidate metroplex sites and metroplexes in the NAS.

3.2.3 State-of-the-Art Technologies Relevant to Metroplex Research

Numerous technologies have been developed and studied for application in metroplex operations, and some of them have been implemented, including technologies that enhance both ground operations and operations in terminal airspace. Strategic conflict probe tools such as the User Request Evaluation Tool (URET) have been successfully applied to en-route airspace, providing benefits to both the controller and the airspace user. The application of URET in the terminal airspace, particularly for the large "metroplex" TRACONs, was also evaluated [K03]. The study indicated that the functional accuracy of the conflict probe and trajectory modeling functions could be improved with intent information, and this improvement would allow the use of URET in metroplex terminal areas.

The transition from one airport configuration to another reduces capacity at the airport for a certain time period. While the transition is necessary when meteorological conditions around the airport change, runway usage can be optimized with respect to factors such as runway conditions and airport acceptance rate. The concept of an airport configuration planner and optimizer has been explored [S06 and S07]. An inventory of information relevant to runway usage at the 20 U.S. airports with the largest number of runway operations in 2005 was developed. A modeling framework was also developed that would enable runway usage optimization within a metroplex, accounting for uncertainty in the data and identifying a solution technique that would be sufficiently fast. Some of these analyses could be used as a reference for developing more sophisticated airport configuration planning and optimization concepts in highly interdependent metroplexes.

In quantifying delay-reduction benefits for aviation convective weather decision support systems such as the integrated terminal weather system (ITWS) and the corridor integrated weather system (CIWS), Evans et. al. [EA04] presented a comprehensive enumeration of different methods used. The discussion uncovered the complexity involved in such an analysis. Individual characteristics of metroplexes such as Atlanta and New York must be considered when assessing benefits of convective weather delay reducing systems rather than extrapolating the benefits from less busy airports or from other metroplexes. Benefit assessment by the direct comparison of delay statistics from time periods before and after a system is introduced is complicated by the need to equalize many factors affecting the delay. For such comparisons associated with metroplex assessments, specific "similar" situations before and after system introduction need to be examined, or the delay values need to be equalized by weather-impact indices.

NASA's Virtual Airspace Modeling and Simulation (VAMS) project [FS06] was a multiyear effort aimed at developing revolutionary operational concepts enabling dramatic increases in the capacity of the NAS by the year 2020. One of the studies [CSS04] evaluated the Automated Airport Surface Traffic Control concept using NASA's Airspace Concept Evaluation System (ACES). Limitations of ACES Build 2.0.3 terminal and airport models led to the failure or inconclusive results in most of the experiments conducted in the reported research work. Modifications to ACES made by subsequent builds and ongoing terminal modeling enhancements efforts may support metroplex environment modeling in ACES. Flight demand-set classification strategy (high vs. low demand, good vs. severe weather day) used in the study may be a good guideline for future studies involving system-wide ACES simulations.

3.3 Concepts and Capabilities for Future Metroplex Operations

This section presents an integrated high-level summary of the concepts and capabilities currently under development or evaluation that could be applied to metroplex operations under future operational situations.

3.3.1 Future Airspace Management

The Next-Generation Air Transportation System (NextGen) Concept of Operations (ConOps) [JPDO07] identified eight key enabling capabilities:

- Network-enabled information access
- Performance-based operations and services (PBS)
- Weather assimilated into decision making
- Layered, adaptive security
- Positioning, navigation, and timing (PNT) services aircraft trajectory-based operations (TBO)
- Equivalent visual operations (EVO)
- Super-density arrival/departure operations (SDO)

Most of these capabilities are relevant to future metroplex operations. Some of the capabilities have been explored in previous studies.

One of the PBS concepts is the extended use of flight-management-system (FMS) and area-navigation-system (RNAV) arrival procedures. A preliminary study [M01] indicated that by flying a set of four FMS/RNAV procedures from each of the four corner posts designed for Seattle-Tacoma International Airport in Seattle, Washington (SEA) runway 16R, three minutes average delay reduction per aircraft and 14% increase in runway throughput could be achieved.

The current split between en-route and terminal ATC services is a legacy of compromises among automation/surveillance, traffic demand, and the more tactical procedures needed to manage arrivals and departures to and from airport runways. While these compromises do not restrict the flow at smaller airports, in the nation's larger metropolitan areas—especially the eight largest—these restrictions limit the efficiency of flow and the full utilization of capacity at the associated airports. To address the issues, the Integrated Arrival/Departure Control Service (Big Airspace) Concept of Operations was developed [FAA05b]. A complementary suite of validation activities has been performed to evaluate the feasibility of the concept and to assess benefits and assumptions [FAA07d]. Big Airspace promises two main deliverables that, if achieved, will dramatically impact NAS operations:

- Integrated arrival/departure airspace
- Improved air traffic services to serve as the model for the future

The concept validation research found that an integrated arrival and departure concept would be applicable and beneficial for any major metropolitan area with very large airports, particularly those with multiple airports whose arrival and departure flows interact. The validation report emphasizes that there must be improvement in technology for communications, surveillance equipment, situational analysis (traffic management), and information processing (i.e., controller information tools) for the concept to work effectively.

Another future concept of operations that has been studied was to enhance the NAS payload capacity by moving away from hub-and-spoke operations to point-to-point (PTP) direct services for travelers and shippers [SKKJ04]. The core idea of PTP was to:

- Provide smaller towered and nontowered airports with enhanced low-visibility operations and ATM automation
- Utilize terminal-area time-based ATM
- Integrate strategic en-route ATM and flight management
- Expand traffic-flow management
- Expand fleet ground operations capability
- Leverage advanced aircraft avionics and aircraft types to increase capacity

A benefit-cost analysis [SH04] indicated that for a predicted year 2022 demand level (twice the level of year 2002), PTP provides an average of 9.8 minutes of delay time savings per flight, despite an increase of 30% more total number of flights than the predicted non-PTP case. For the Chicago area, PTP is estimated to provide a capacity increase on the order of 70% relative to the non-PTP case. Results from a terminal simulation [PSB05] indicated that, for the non-PTP case using the conventional routing, the percentage of aircraft in conflict remained roughly constant at 50% as traffic density increased to the 2022 demand level. With the introduction of the PTP concept, the percentage of aircraft in conflict dropped to a 25% level. Also, in the PTP case, conflicts were evenly distributed as opposed to the non-PTP case, where conflicts increased dramatically as aircraft approached major airports (within 15 nm). For metroplex operations, this increase appears to suggest that future demand growth may be best accommodated by secondary airports.

In another study, knowledge of weather effects on noise impact was applied to a case study of developing noise-abatement procedures [CH04]. The authors postulated a revised noise-abatement procedure for departures on runway 4R at Boston Logan that adapts to different weather conditions to minimize the number of residents within the sound exposure level (SEL) above 70 dBA noise contour. Similar strategies could be employed in metroplex design to either mitigate noise or improve traffic throughput.

3.3.2 Future Traffic Demand

The development of operational concepts in the NextGen depends on the accurate prediction of future traffic demand. Sensis Corporation has developed an automated future flight demand-generation tool, referred to as AvDemand [SHD07]. This tool provides the user with extensive options in defining future demand datasets tailored to their evaluation needs, a capability that does not exist in other demand-generation methods. The tool generates future demand as a large number of flights with well-defined schedules that are accurately defined in time and space throughout the flight by a flight plan. A demand-loading analysis for a future 3X demand set (relative to the year 2002 level) was conducted in order to evaluate the impact of future NextGen system requirements [SHW07]. Future unconstrained demand loading for both airports and the NAS were analyzed using airport and airspace demand-to-capacity metrics resulting from the output of the AvDemand tool. The potential impact of both capacity-increasing concepts and potential demand changes were evaluated. The results suggest that 3X demand sets represent very demanding scenarios for future ATM concepts, and that expected heterogeneous demand growth will result in required improvements to NextGen local airport and airspace capacities that are significantly greater than three times current levels. This tool and the methodology can be used in the metroplex project to design experiments for proposed NextGen metroplex operation concepts.

3.4 Justification for Candidate Metroplex Sites That Warrant Further Investigation

While there exists much literature related to metroplex operations, the metroplex problem has not been systematically studied before. As discussed earlier, the predicted future traffic growth will increase the coupling of operations in exiting metroplex airspace, and will potentially create new metroplex areas. The natural first step in exploring the metroplex problem is to investigate existing metroplex sites in the NAS to obtain a deeper understanding of the metroplex problem in real-world operations. Given the limited resources and time available, only a small number of metroplex sites could be studied. Candidate metroplex sites were selected by reviewing the list of metroplexes identified in the literature and comparing their basic characteristics. The FAAs couldOperational Evolution Partnership (OEP) initiative [FAA07b] has identified that over the next 20 years, U.S. population and economic growth are expected to be concentrated in 15 metropolitan areas. These metropolitan areas are listed in Table 1 [FAA08b].

To identify the issues and constraints that dictate current practices (dependencies and interactions between metroplex airports) and to determine the state of the art for managing interdependent airport operations, a list of candidate metroplex sites needed to be determined for further investigation. The FAA's list of OEP 15 metropolitan areas was used as the starting point. Figure 2 shows the location of candidate metroplex sites identified in previous studies. Figure 2(a), borrowed from Bonnefoy and Hansman [BH05], lists metroplexes identified in a study of the emergence of secondary airports. Figure 2(b) is quoted from Sensis' work for the NASA NextGen Airspace Project [FS06]). Note the existence of two 3-OEP-airport metroplexes (New York: EWR/JFK/LGA, and Washington, D.C.: BWI/IAD/DCA), and two 2-OEP-airport metroplexes (Chicago: ORD/MDW, and Miami: MIA/FLL), all of which were included as candidate metroplexes for further study. A list of major airports was also developed according to their projected demand/capacity ratio based on 3X demand and the 2015 OEP baseline capacity [SHW07] for identifying candidate metroplexes. This list is shown in Table 2 along with identified capacity needs from the FAA document "Capacity Needs in the National Airspace System (FACT-2)" [FAA07a].

TABLE 1. OEP 15 METROPOLITAN AREAS WITH PROJECTED FAST GROWTH

Metro Area (TRACON)	Associated Airports			
OEP Airport ID, Name	**ID**	**Airport Name**	**State**	**City**
Atlanta (A80)	PDK	Dekalb-Peachtree	GA	Atlanta
ATL, Atlanta Hartsfield Intl.	RYY	Cobb County-McCollum Field	GA	Atlanta
	FTY	Fulton County Airport-Brown Field	GA	Atlanta
Charlotte (CLT)	JQF	Concord Regional	NC	Concord
CLT, Charlotte/Douglas Intl.	UZA	Rock Hill/York County/Bryant Field	SC	Rock Hill
Chicago (C90)	ARR	Aurora Municipal	IL	Chicago
MDW, Chicago Midway **ORD**, Chicago O'Hare Intl.	UGN	Waukegan Regional Airport	IL	Chicago/Waukegan
	LOT	Lewis University Airport	IL	Chicago/Romeoville
	IGQ	Lansing Municipal Airport	IL	Chicago/Lansing
	DPA	Dupage	IL	Chicago/West Chicago
	PWK	Chicago Executive	IL	Chicago/Wheeling
	RFD	Chicago/Rockford Intl.	IL	Rockford
	MKE	General Mitchell Intl.	WI	Milwaukee
	ENW	Kenosha Regional	WI	Kenosha
	GYY	Gary/Chicago Intl.	IN	Gary
Houston (I90)	HOU	Houston Hobby	TX	Houston
IAH, George Bush Intl.	EFD	Ellington Field	TX	Houston
	CXO	Lone Star Executive	TX	Houston
	DWH	David Wayne Hooks	TX	Houston
	IWS	West Houston	TX	Houston
	SGR	Sugar Land	TX	Houston
	LVJ	Pearland Regional	TX	Houston
	AXH	Houston Southwest	TX	Houston
Las Vegas (L30)	VGT	North Las Vegas	NV	Las Vegas
LAS, Las Vegas McCarran Intl.	HND	Henderson Executive	NV	Las Vegas
Los Angeles (SCT)	VNY	Van Nuys	CA	Van Nuys
LAX, Los Angeles Intl.	WHP	Whiteman	CA	Los Angeles
	POC	Brackett Field	CA	La Verne
	CNO	Chino	CA	Chino
	BUR	Bob Hope	CA	Burbank
	SNA	John Wayne Airport-Orange County	CA	Santa Ana
	ONT	Ontario Intl.	CA	Ontario
	LGB	Long Beach /Daugherty Field	CA	Long Beach
Minneapolis (M98)	ANE	Anoka County	MN	Minneapolis

TABLE 1. OEP 15 Metropolitan Areas with Projected Fast Growth (CONT.)

Metro Area (TRACON)	Associated Airports			
OEP Airport ID, Name	ID	Airport Name	State	City
MSP, Minneapolis-St Paul Intl.	21D	Lake Elmo	MN	St. Paul
	STP	St. Paul Downtown	MN	St. Paul
	SGS	South St. Paul	MN	South St. Paul
	MIC	Crystal	MN	Minneapolis
	FCM	Flying Cloud	MN	Minneapolis
	LVN	Airlake	MN	Minneapolis
New York (N90)	CDW	Essex County	NJ	Caldwell
JFK, New York John F. Kennedy Intl. **LGA**, New York LaGuardia **EWR**, Newark Intl.	TEB	Teterboro	NJ	Teterboro
	MMU	Morristown Municipal	NJ	Morristown
	FRG	Republic	NY	Farmingdale
	SWF	Stewart Intl.	NY	Newburgh
	ISP	Long Island-MacArthur	NY	Islip
	ABE	Lehigh Valley Intl.	PA	Allentown
	HPN	Westchester County	NY	White Plains
Philadelphia (PHL)	PNE	Northeast Philadelphia	PA	Philadelphia
PHL, Philadelphia Intl.	ACY	Atlantic City Intl.	NJ	Atlantic City
	LOM	Wings Field	PA	Philadelphia
	ILG	New Castle	DE	Wilmington
Phoenix (P50)	FFZ	Falcon Field	AZ	Mesa
PHX, Phoenix Sky Harbor Intl.	DVT	Phoenix Deer Valley	AZ	Phoenix
	SDL	Scottsdale	AZ	Scottsdale
	CHD	Chandler Municipal	AZ	Chandler
	GEU	Glendale Municipal	AZ	Glendale
	IWA	Williams Gateway	AZ	Phoenix
San Diego (SCT)	SEE	Gillespie Field	CA	San Diego/El Cajon
SAN, San Diego Intl. Lindbergh	CRQ	McClellan-Palomar	CA	Carlsbad
	SDM	Brown Field Municipal	CA	San Diego
	MYF	Montgomery Field	CA	San Diego
San Francisco (NCT) **SFO**, San Francisco Intl.	RHV	Reid-Hillview of Santa Clara County	CA	San Jose
	LVK	Livermore Municipal	CA	Livermore
	CCR	Buchanan Field	CA	Concord
	PAO	Palo Alto Airport	CA	Palo Alto
	SQL	San Carlos	CA	San Carlos
	HWD	Hayward Executive	CA	Hayward
	OAK	Metropolitan Oakland Intl.	CA	Oakland
	SJC	Norman Y. Mineta San Jose	CA	San Jose
Seattle (S46)	BFI	Boeing Field	WA	Seattle
SEA, Seattle-Tacoma Intl.	RNT	Renton Municipal	WA	Renton
	S50	Auburn Municipal	WA	Auburn
	PAE	Snohomish Co (Paine Fld)	WA	Everett
	S43	Harvey Field	WA	Snohomish

TABLE 1. OEP 15 Metropolitan Areas with Projected Fast Growth (CONT.)

Metro Area (TRACON)	Associated Airports			
OEP Airport ID, Name	**ID**	**Airport Name**	**State**	**City**
South Florida (MIA, PBI)	FXE	Fort Lauderdale Executive	FL	Fort Lauderdale
MIA, Miami Intl. **FLL**, Fort Lauderdale-Hollywood Intl.	TMB	Kendall-Tamiami Executive	FL	Miami
	LNA	Palm Beach County Park	FL	West Palm Beach
	OPF	Opa Locka	FL	Miami
	PBI	Palm Beach Intl.	FL	West Palm Beach
Washinton Baltimore (PCT)	JYO	Leesburg Executive	VA	Leesburg
IAD, Washington Dulles Intl. **DCA**, Ronald Reagan National **BWI**, Baltimore-Washington Intl.	HEF	Manassas Regional/Harry P. Davis Field	VA	Manassas
	DMW	Carroll County Regional	VA	Westminster
	W66	Warrenton-Fauquier County	VA	Warrenton
	MTN	Martin State	MD	Baltimore
	FDK	Frederick Municipal	MD	Frederick

The number of candidate sites to be surveyed was limited to a subset of existing metroplexes, and sites were selected to represent the breadth of metroplex definitions and operational concepts across the ATC community today. The metroplexes described in the following sections are but a representative sample of the wide range of operations that can be observed in the NAS today. The descriptions of interactions and dependencies are not intended to be complete. Rather, the descriptions are intended to illustrate the breadth of issues that can be encountered. In-depth analyses of the surveyed sites are presented in site-survey reports [RC09b, SL09, TL09, and SR09] and the contrast and comparison report [RC09a].

The New York Metroplex

The airspace around the ***New York metropolitan area*** is arguably the most complicated in the United States. The New York Metroplex contains three OEP airports—EWR, JFK, and LGA—as well as another major general aviation airport—TEB—within a circle of radius 10 nm. These four airports averaged almost 4000 operations per day in 2006 [OP08]. There are also 15 secondary airports in the vicinity, four of which are among the 100 busiest U.S. airports. Although the New York airspace has been carefully designed to minimize the need for coordination between airports under typical operating conditions, the configuration and operations of the airspace does in part depend on the runway configurations at the various airports within the metroplex. In severe weather, many ATC facilities in the New York area use the DSP developed by the FAA to schedule departure releases at adapted airports so that the resulting demand at departure flow fixes does not surpass prevailing flow rates at the fixes. Operations in the New York Metroplex are supported by the New York TRACON (N90) and the New York Air Route Traffic Control Center (New York ARTCC, New York Center, or ZNY).

TABLE 2. AIRPORTS SORTED BY DEMAND/CAPACITY RATIO AT 3X DEMAND

Airport	**3X Demand Analysis Problem Airport? (Demand/Capacity Ratio [5])**	**FACT-2 Report Problem Airport? (Needs Additional Capacity by Year)**			**FACT-2 Report Problem Metropolitan Area? (Needs Additional Capacity by Year)**			**Airport Falls in a Metroplex Studied by the Metroplex Project?**	**OEP Airport**	**FAA AC 150/5060-5 Airport Class**	**TACEC Airport[6]**	**Existing or Planned ASDE-X Airport[7]?**	**Existing or Planned Aerobahn Airport[8]?**
		2007	**2015**	**2025**	**2007**	**2015**	**2025**						
LAS	3.94	-	√	√	-	√	√	-	√	18	√	2010	-
JFK	3.03	-	√	√	√	√	√	√ (N90)	√	4	√	2008	-
FLL	2.9	√	√	√	-	-	√	√ (MIA)	√	12	√	2008	-
EWR	2.58	√	√	√	√	√	√	√ (N90)	√	10	√	2009	-
SAN	2.36	-	-	√	-	-	√	√ (SCT)	√	1	-	2010	-
ORD	2.27	√	√	√	-	√	√	√ (C90)	√	?	√	E	-
LAX	2.02	-	-	√	-	√	√	√ (SCT)	√	8	√	2008	-
CLT	1.75	-	√	√	-	√	√	-	√	11	-	E	-
ATL	1.71	-	-	√	-	√	√	√ (A80)	√	8	√	E	-
BOS	1.58	-	-	√	-	-	-	-	√	10	√	2009	-
SFO	1.57	-	-	√	-	√	√	√ (NCT)	√	13	√	-	-
SNA	1.51	-	√	√	-	√	√	√ (SCT)	-	1	-	2009	-
SJC	1.51	-	-	-	-	√	√	√ (NCT)	-	2	-	-	-
DTW	1.37	-	-	-	-	-	-	-	√	6	√	2008	E
LGA	1.27	√	√	√	√	√	√	√ (N90)	√	9	-	2011	-
DFW	1.07	-	-	-	-	-	-	√ (D10)	√	16	√	2010	-
JAX	0.89	-	-	-	-	-	-	-	-	14	-	-	-
SDF	0.79	-	-	-	-	-	-	-	-	12	-	E	-

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[5] Demand/Capacity ratio based on 3X demand and the 2015 OEP baseline capacity [SHW07].

[6] Based on VAMS report Terminal Area Capacity-Enhancing Concept (TACEC) Operations Analysis [FS06].

[7] Year: Government Fiscal Year (GFY) in which ASDE-X will be commissioned at the airport; E: Existing ASDE-X Installation airport.

[8] E: Existing Aerobahn Installation airport.

The Los Angeles Basin Metroplex

LAX is the fourth busiest airport in the United States, averaging 1800 operations per day in 2006. Within 30 nm of LAX in the ***Los Angeles metropolitan area*** are seven other airports, all among the 150 busiest U.S. airports. Furthermore, three of these airports—VNY, LGB, and SNA—rank in the top 25, with an average total of 3100 operations per day, and are within 20 nm of LAX; but the vast majority of their flights are general aviation (GA). The close proximity of these airports causes their arrival and departure paths to cross over and under each other, and some of the airports also compete for arrival and departure fixes. Because LAX has the majority of the commercial traffic, it generally is given the priority, and the other airports alter their operations as required. To minimize the coordination required for runway configuration changes and to maximize the use of the preferred runway configurations and terminal-area paths, the threshold for calm-wind runways tends to be 10 knots rather than the usual 5 knots. Operations in the Los Angeles Basin Metroplex are supported by the Southern California TRACON (SCT) and the Los Angeles ARTCC (ZLA).

The San Francisco Bay Metroplex

The ***San Francisco Bay metropolitan area*** includes only one OEP airport—SFO—but it also includes two other major airports—OAK and SJC. These three airports are within a circle of radius 15 nm. SFO and OAK are about 10 nm apart, but SJC is about 25 nm away from both of them. The average daily total number of operations for these three airports in 2006 was 2500. In comparing this figure to other metroplexes, however, one must keep in mind that much of the traffic at OAK is air cargo, which tends to occur in the late evening or early morning. There are also four other airports in the area that are among the 150 busiest U.S. airports. The runway configurations at the major airports in this metroplex are closely coordinated. Typically, SFO chooses its configuration, and the other two major airports use their configurations that are most aligned with SFO. If doing so would be unsafe, then they contact SFO, which changes its configuration if possible. Even when the runway configurations are properly aligned, east operations are complex because the arrival path to SFO runway 19 crosses over the arrival path to OAK runway 11 twice, a situation that generally causes a restriction on the OAK arrival flow rate. Operations in the San Francisco Bay Metroplex are supported by the North California TRACON (NCT) and the Oakland ARTCC (ZOA).

The Washington, D.C. Metroplex

The ***Washington, D.C. metropolitan area*** contains three OEP airports—BWI, DCA, and IAD—within a circle of 30-mile radius. IAD and DCA are about 20 nm apart, and BWI is less than 30 nm from DCA. IAD averaged 1200 operations per day in 2006, but BWI and DCA each had only 800, giving a total of 2800 daily operations. The runway configurations of these three airports are independent. They do share departure fixes, however, and there are altitude restrictions on some arrival and departure paths to avoid conflicts. Operations in the Washington, D.C. Metroplex are supported by the Potomac TRACON (PCT) and the Washington ARTCC (ZDC).

The Chicago Metroplex

The ***Chicago metropolitan area*** includes two OEP airports—ORD and MDW—less than 15 nm from each other. There are no other airports in the TRACON that are among the 150 busiest in the United States. For the most part, ORD, which is the second busiest airport in the United States with 2600 daily operations in 2006, operates independently; and MDW, with 800 daily operations, changes its arrival and departure procedures to avoid conflicts. Typically, this adjustment requires changing only the flightpaths; but, when ORD is departing off runway 22L, MDW departures off runway 31C must be cleared by the departure controller to avoid conflicts. The most extreme interdependence in this metroplex is the interference of MDW arrivals on runway 13C with both departures from runway 22L and arrivals to runway 14L at ORD. In fact, departures off runway 22L must be stopped because aircraft turning onto the 13C final approach are only 7 nm south of ORD. Operations in the Chicago Metroplex are supported by the Chicago TRACON (C90) and the Chicago ARTCC (ZAU).

Dallas-Fort Worth Metroplex

DFW, the third busiest airport in the United States with 1900 daily operations in 2006, is about 10 nm west-northwest of DAL, which averaged 700 daily operations. The ***Dallas-Fort Worth metropolitan area*** is similar to the Chicago metroplex in terms of the number of major airports and the distance between them, but DFW and DAL have significantly fewer operations than ORD and MDW. Additionally, the DFW metroplex has approximately twice as many secondary airports in the top 500, with over twice as many operations as the secondary airports in the Chicago Metroplex. The runway configurations at DFW and DAL are typically aligned. Simultaneous visual departures from DAL are not allowed in north flow because their departure paths head toward the DFW departure paths. When using instrument-landing-system (ILS) approaches in south flow, only a single stream of arrivals to DAL is allowed in order to avoid dependency with DFW arrivals because the extended final approach courses of the two airports converge. Operations in the Dallas-Fort Worth Metroplex are supported by the Dallas-Fort Worth TRACON (D10) and the Fort Worth ARTCC (ZFW).

The Miami Metroplex

The ***Miami*** Metroplex is the only other metroplex with two OEP airports (i.e., MIA and FLL) within 20 nm of each other. Dependencies within this metroplex are expected because of the proximity of the airports. However, traffic volume at airports in this metroplex is relatively moderate as compared with many other metroplexes; the dependencies are likely less severe. A unique characteristic of the Miami Metroplex is that MIA, FLL, and major secondary airports in this metroplex have similar runway orientation and runway configurations. Thus, this metroplex seems to provide an example of unqiue practices for handling dependencies among airports with similar runway configurations. Operations in the Miami Metroplex are supported by the Miami TRACON (MIA), the Palm Beach TRACON (PBI), and the Miami ARTCC (ZMA).

The Atlanta Metroplex

The ***Atlanta*** Metroplex contains the busiest airport in the United States with 2700 daily operations in 2006. Operations in this metroplex are dominated by the traffic to and from Atlanta Hartsfield International Airport (ATL). Traffic to and from other, smaller airports is normally routed around the ATL traffic pattern. A corridor over ATL exists to allow departure traffic from smaller airports to fly direct to their destinations. Atlanta thus represents another type of metroplex operation. Operations in the Atlanta Metroplex are supported by the Atlanta Large TRACON (A80) and the Atlanta ARTCC (ZTL).

Some characteristics of these metroplexes are summarized in Table 3. This table, in conjunction with the descriptions of dependencies in this section, also indicates that these examples provide a good breadth of metroplex operations.

TABLE 3. SOME CHARACTERISTICS OF METROPLEX EXAMPLES

Number of Airports	NY	LA	SF Bay	DC	Chicago	DFW	Miami	Atlanta
OEP Airports	3	1	1	3	2	1	2	1
Top 50 Airports	3	4	2	3	2	2	2	1
Top 100 Airports	8	5	6	3	2	2	4	2
Top 200 Airports	13	10	12	4	3	5	5	3
Ops/Day at Top 50	3400	4900	1900	3000	3400	2600	1900	2700
Length Scale (nm)[a]	10	20	15-25	20-30	15	10	20	N/A

[a] The length scale indicates distance between primary airports.

4.0 METROPLEX SITE-SURVEY STUDY

The objective of the metroplex site-survey study is to develop a deeper understanding of these parameters and issues through examining the current operations at representative metroplexes in the National Airspace System (NAS). Within the resource and time-frame limitations of this project, the research team visited Atlanta, Los Angeles, New York, and Miami.

Among the sites visited, Atlanta represents a metroplex with a single dominant large hub [FAA09a] airport and much smaller satellite airports [RC09b]. The Los Angeles (LA) Basin represents a metroplex with multiple medium-to-large hub airports that are heavily affected by terrain and special-use airspace (SUA) [SL09]. The New York Metroplex represents a metroplex with multiple, tightly spaced large hub airports. Thus, operations are confined in limited airspace [TL09]. Miami represents a metroplex with two large hub airports and relatively small satellite airports such that interactions between two airports with similar configuration can be investigated [SR09].

The locations of the sites visited are shown in Figure 3 along with other major metroplexes in the NAS. The results of this effort are summarized in the following sections.

4.1 Site-Survey Procedure

The steps employed to collect, review, analyze, and disseminate information on operations at the specific metroplex sites studied are discussed in the following sections.

4.1.1 Site Visit

Prior to each site visit a detailed questionnaire was prepared and sent to the air-traffic-control (ATC) facility, and later used as a guideline during the visit. The questionnaire, developed with the assistance of experienced controllers, covers both generic aspects of metroplex operations and unique operational and environmental conditions specific to the site. Questions were normally related to hub airport configurations, arrival/departure routes, traffic-flow management (TFM), terrain, SUA, weather, noise restrictions, and most importantly, interaction and coordination with adjacent facilities. These facilities may include an air route traffic control center (ARTCC), terminal radar approach control facilities (TRACON), air traffic control tower (ATCT, or Tower), airport ramp tower, and military ATC.

Figure 3. FAA's 15 OEP metropolitan areas with visited sites highlighted.

The site visit typically consisted of a briefing on facility operations and traffic-management procedures, followed by a roundtable interview with a facility manager, a representative from the Traffic Management Unit (TMU), and sometimes controllers. Major discussion focus was given to specific traffic-flow interactions and coordination procedures, as well as to system automation and TFM tools that might have been used to assist the coordination procedures. Each facility provided an overview on how dependent or independent adjacent airport flows either conflicted or operated as single airports. Within the metroplex facilities, primary airports were identified and examined as to their interaction and control of adjacent facility configurations and/or traffic flows. Traffic flow and departure spacing were also discussed and determined if selective airports received priority flows or releases. Often, a tour of the control room or tower cab provided opportunities for reviewing procedures and tools working with live traffic. Training materials were also collected during these visits.

Facilities visited included, in chronological order: Atlanta Large TRACON (A80), Southern California TRACON (SCT), New York TRACON (N90) and Center (ZNY), and Miami Tower/TRACON (MIA). The New York site visit also included visits to the Towers at John F. Kennedy (JFK), LaGuardia (LGA), Newark (EWR), and to the Continental Airlines ramp tower at EWR and Delta ramp tower at JFK.

4.1.2 Data Analysis

Airport statistics, traffic flows, standard-terminal-arrival-route (STAR) and standard-instrument-departure (SID) procedures, facility standard operating procedures (SOP), letters of agreement (LOAs), navigation charts, and relevant literature were reviewed prior to the site visits. Also reviewed were SOPs of adjacent facilities not visited to determine interactive flows. After the visit, detailed analyses were conducted. These analyses fell into four categories, described in the following sections.

Airport Data and Traffic Statistics

For each metroplex, a list of airports was generated based on the distance from the “core” hub (the largest airport, or the airport that is given highest operational priority), runway length, traffic statistics, Federal Aviation Administration’s (FAA’s) airport categorization [FAA09a], and supporting architecture [FAA09b]. The airport list provided a basis for data-analysis efforts. Detailed traffic demand versus capacity analysis was performed for large hub airports in the metroplex. Capacity and operational constraints, and issues that have implications on metroplex operations, were identified through analyzing data collected during the site visit, from the airport owner and operator, and from government databases.

Traffic-Flow Analysis

Traffic-flow analysis was performed utilizing the performance data analysis and reporting system (PDARS), which processes both en-route and terminal flight data and radar data (including every radar hit). Sample data were filtered by aircraft category (jet, or tuboprop, and props), airport, and operation (arrival, departure, or over flight) to reveal traffic patterns and flow interactions. Shared arrival and departure fixes were identified and viewed using PDARS in order to identify possible choke points or congestive flows. Different meteorological conditions, such as visual meteorological conditions (VMC), instrument meteorological conditions (IMC), and storm events, as well as runway configuration changes, were analyzed. Results were represented both in static and replay format indicating proximity of airports, airspace boundaries, crossing points and altitude assignments, arrival and departure transition areas (arrival and departure area (ATA and DTA, respectively), special-use airspace (SUA) and terrain, etc.). Sample data were also provided to the team for quantitative analysis (see section 7.2.3).

Air-Traffic-Control Procedures

ATC procedures are defined by published STARs and SIDs, facility SOP, and LOAs with interacting ATC facilities or military regarding the use of SUA. These procedures also cover the use of special ATC automation tools and programs across facilities such as the Severe Weather Avoidance Plan (SWAP) [FAA09c]. In-depth analysis focused on detailed traffic-flow interactions and coordination procedures. An interaction is defined as an extra spatial or temporal restriction imposed on one ATC facility because of the proximity of another. Interactions include airspace delegation, arrival and departure routes and altitudes, coordination of departure release, restrictions on runway use, interdependencies between runway configurations at different airports, and initiation and use of special programs. A scheme was developed to use a tree structure to present individual interactions as leaves. Analysis results are presented with details as an appendix to each of the site-survey reports, and as sections in the main body of those reports highlighting key points.

Analysis of Environmental Constraints

For each metroplex site, available noise studies and Environmental Protection Agency (EPA) regional air-quality classification standards [EPA08a] were reviewed to determine noise and air-quality impacts and constraints affecting future metroplex design. Water-quality impacts at airports originate primarily from the use of deicing and anti-icing chemicals and specific operational practices. Greenhouse gases were not addressed. It is important to note that increased aviation activity will contribute to greenhouse gases [FAA05a] and that inventory and control of these contributions [S09] is likely to be a factor in some aspects of metroplex design.

4.2 Facility Comparison

The metroplexes were contrasted and compared based on the data documented in metroplex site-survey reports [RC09b, SL09, TL09, and SR09]. The TRACON, as the primary ATC facility managing terminal-area operations, is the primary focus in the following discussion. Because a TRACON may serve more than one metroplex (e.g., Southern California TRACON (SCT) serves the Los Angeles (LA) Basin and San Diego), when focus is given to specific metroplexes, metroplex names may be used. It should be noted that TRACON identifications (IDs) are sometimes used loosely to reference both the TRACONs and the relevant metroplexes in context (e.g., SCT may also be used when referencing the LA Basin). Because of its complexity and its importance in this research, the comparison of metroplex operations is discussed in a separate subsection.

4.2.1 Facility Overview

The geographic location, the airspace boundary, and major operational areas for each of the four TRACONs are shown in Figure 4. While the size of the airspace boundary reflects the geographic scope of responsibility, the number of operational areas in a TRACON may be an indication of operational complexity, without regard to traffic volume. Among the four, MIA is the smallest and it has only a single operating area, so it could be expected to be the least complex. SCT has six areas, but it should be noted that Palm Springs International Airport (PSP)and Miramar Marine Corps Air Station (NKX, which serves San Diego) are some distance away from the other four areas. N90 has five areas and they all have overlaps, so it could be expected to be the most complex. A80 has the largest coverage and operational areas. The complexity of A80 could be expected to be somewhere between the complexities of MIA and SCT. A comparison of other facility characteristics is shown in Table 4.

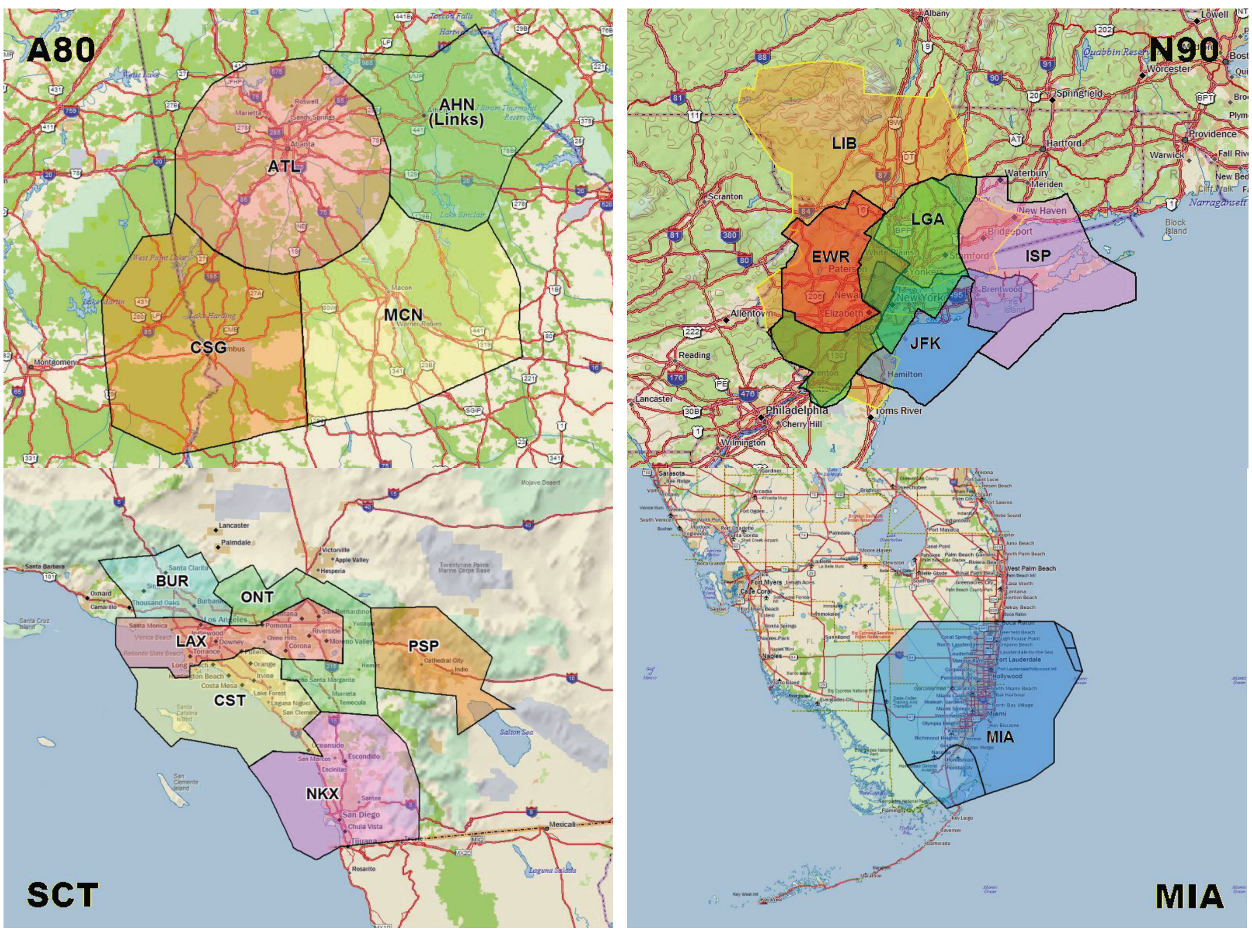


Figure 4. A80, N90, SCT, and MIA TRACON boundary and operational areas with same scale.

TABLE 4. METROPLEX FACILITY COMPARISON

Item	A80	SCT	N90	MIA
Overview	Serves worlds busiest airport – ATL	Worlds busiest TRACON	Four busy airports (3 OEP + TEB) within 10-nm radius	All major airports aligned north-south along coast
Coverage (nm^2/ft)	25,110/up to 14,000	14,920/up to 17,000	17,246/up to 17,000	5,817/16,000
Usable Airspace	76%	45%	82%	99%
Airports	25	49	~50	10a
OEP Large Hub Airports	1: ATL	2: LAX, SAN	3: JFK, LGA, EWR	2: MIA, FLL
FAA Towers	3	17	11	4
Federal Contract Towers	4	7	5	2
Military Towers	3	6	1	1
Class B Airspace	1: ATL	2: LAX, SAN	1: JFK, LGA, EWR	1: MIA
Class C Airspace	1: CSG	4: BUR, ONT, SNA, RIV (SAN)	1: ISP	1: FLL
Terminal Radar Service Area	1: MCN	1: PSP	None	None
Military Restricted Area	1 cluster inside; 2 clusters surrounding	1 cluster inside; 5 clusters surrounding	1 cluster inside; 2 clusters surrounding	None inside; 1 cluster surrounding
Air Defense Identification Zone (ADIZ) & Warning Areas	1 cluster inside 4 clusters surrounding	None inside; 6 clusters surrounding	None inside; 2 clusters surrounding	None inside; 4 clusters surrounding
Interacting ARTCC	ZTL	ZLA	ZNY, ZBW, ZDC	ZMA
Geographic Location	Southeast Inland	Southwest Coast	Northeast Coast	Florida Peninsula
International Border	None	Mexico	None	None

Note: Potomac TRACON (PCT), an airport at the MIA/Palm Beach International Airport (PBI) TRACON boundary, is officially supported by PBI, so it is not counted in the number of airports.

In Table 4 the usable airspace is defined as the percentage of the volume of TRACON airspace above minimum vectoring altitude with respect to the total airspace above mean sea level (MSL), so it should be an indication of terrain constraints. Other items should be self-explanatory. From the table, one can conclude that A80 hosts a metroplex with a single dominant large hub airport. SCT hosts two metroplex operations with LA Basin representing a metroplex with multiple medium-to-large hub airports (six air carrier airports) that is significantly affected by terrain and SUA. N90 hosts a metroplex with multiple, tightly spaced, large hub airports (three major airports within a 10-nm radius), so operations near the airport are severely confined by airspace. MIA hosts a metroplex with two large hub airports and relatively small satellite airports such that interactions between two airports may be studied relatively easily.

4.2.2 Traffic Statistics

The numbers of annual instrument operations for 2007 for the four TRACONs are listed in Table 5. Also listed are the FAA rank of each TRACON and a loading derived by dividing the annual operations by the coverage area from Table 4. Of interest is MIA, with the smallest number of annual instrument operations yet the highest traffic loading per unit of surface area covered. Given the much lower percentage of usable airspace, SCT still qualifies as the busiest TRACON in the world.

Table 6 lists the annual 2007 itinerant (traveling from one airport to another) air carrier operations, and total operations at metroplex airports whose annual total itinerant operations are 100,000 or more. Total itinerant operations include air taxi, general aviation, and military operations that are not listed in the table. The Metroplex Total is the sum total for listed airports in the metroplex. Weight is the percentage of metroplex traffic to/from a given airport indicating traffic distributions among metroplex airports. The data show that the Atlanta metroplex has the busiest hub airport and fewest heavily trafficked airports. The New York Metroplex has the highest number of heavily trafficked airports.

4.2.3 Core Hub Airports

A core hub airport is the airport with the highest traffic volume or highest overall operational priority within the metroplex; often these two aspects are aligned. A comparison of core hub airports would thus reveal the most critical issues related to hub airports that may be of significance at the metroplex level. The comparison of metroplex core hubs, namely ATL, LAX, JFK, and MIA, are summarized in Table 7.

All sites have ground transportation congestion issues, with Los Angeles and New York facing the most serious problem. Atlanta currently has only one commercial airport, but that may change as demand grows. Ground connection between JFK and LGA is relatively short, but connections with other airports are almost unacceptable for connecting a flight. The situation is similar for Los Angeles Metroplex airports. The connection between MIA and FLL, however, is improving with a new multimodal transit center under construction.

TABLE 5. ANNUAL TRACON INSTRUMENT OPERATIONS (2007 DATA)

Item	A80	SCT	N90	MIA
FAA Rank [a]	5	1	2	9
Operations [a] (1,000)	1,433,000	2,243,000	2,066,000	943,000
Loading (1,000/nm^2)	57.07	150.34	119.80	162.11

a. Data source: “Administrator’s Factor Book,” November 2008 [FAA08a]

TABLE 6. ANNUAL ITINERANT OPERATIONS AT METROPLEX AIRPORTS WITH ANNUAL ITINERANT OPERATIONS OF 100,000 OR MORE

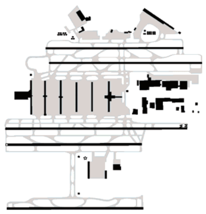
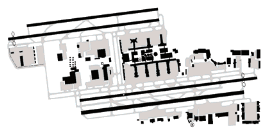
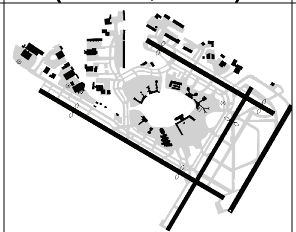
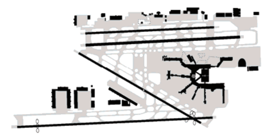
Metroplex	Airport Annual Statistics[a]					Metroplex Total
	ID	*Air Carrier*	*Total*	*Growth*	*Weight*	
Atlanta	ATL	713,815	989,295	2.45%	86%	1,152,467
	PDK	24	163,172	0.40%	14%	
Los Angeles Basin	LAX	467,071	672,095	1.58%	39%	1,714,664
	SNA	92,450	252,624	0.46%	15%	
	ONT	89,970	142,666	-1.72%	8%	
	BUR	58,970	183,930	-1.85%	11%	
	LGB	26,668	195,303	0.73%	11%	
	VNY	0	268,046	0.68%	16%	
New York Metro	JFK	350,421	453,258	0.41%	23%	2,011,295
	EWR	273,752	444,881	0.38%	22%	
	LGA	201,374	401,410	-0.15%	20%	
	ISP	27,558	111,934	0.41%	6%	
	HPN	11,116	184,975	0.82%	9%	
	FRG	201	106,961	0.26%	5%	
	TEB	6	202,128	0.41%	10%	
	MMU	0	105,748	-0.18%	5%	
Miami	MIA	294,068	386,645	1.52%	39%	979,445
	FLL	189,310	304,595	1.99%	31%	
	TMB	32	122,165	2.72%	12%	
	FXE	0	166,040	0.54%	17%	

a. Data source: "2008 Terminal Area Forecast (TAF)," January 2009 [TAF08]

Airport demand and capacity are represented by a typical VMC weekday in 2007. The demand was divided into quarter-hour slots and then compared with VMC and IMC capacities from the FAA 2004 capacity benchmark [FAA04]. A total daily demand/capacity ratio [WL01] was calculated by dividing the total daily operations with 16 hours worth of VMC capacity. It is seen that, with the exception of MIA, the core hub airports are very congested, with the worst situation at JFK. However, the capacity constraints at ATL and LAX are currently surface limitations (LAX has one-tenth of the acres of Dallas) while at JFK it is more an airspace problem, although limited arrival gates and construction causes gridlock during peak periods.

Three of the core airports have east or west operations with one direction used more often. JFK has many different configurations because of the crossing runway layout. At N90 the JFK/LGA and EWR/TEB airports require close coordination procedures to maximize traffic flows, primarily because of airspace congestion and the little airspace available to vector aircraft for additional spacing.

TABLE 7. METROPLEX CORE HUB AIRPORTS

Item	A80: ATL	SCT: LAX	N90: JFK (+ LGA, EWR)	MIA: MIA (+ FLL)
Airport Layout				
Location	• 11 statute miles south of Atlanta downtown	• 15 statute miles southwest of Los Angeles downtown	• 12 statute miles east of Lower Manhattan	• 5 statute miles west of Miami downtown
Inter-Airport Ground Connection	• No secondary commercial airport	• Flyaway bus to VNY 60 min • Congestion a problem • No rail connection	• Van/express bus to LGA 30 min, to EWR ~90 min • No direct rail connection	• Car/shuttle to FLL ~45 min • Tri-Rail connects MIA and FLL (<1 hour), and PBI
Demand and Capacity	• > IMC capacity for 21 slots • > VMC capacity for 8 slots • Total daily ratio: 0.77; very congested	• > IMC capacity for 7 slots • > VMC capacity for 1 slot • Total daily ratio: 0.72, very congested	• > IMC capacity for 33 slots • > VMC capacity for 21 slots • Total daily ratio: 0.88, very congested	• < VMC/IMC capacity • Total daily ratio: 0.44, not congested
Surface Limitation (Arrival throughput must be limited to avoid gridlock)	• Limited gates for the volume • Lack of a "penalty box" or overflow areas • Surface limitation may become a factor for arrival rates during busy periods when tri-runway landings in effect	• Limited airport real estate: limited taxi areas and gates • Limited holding space between closely spaced runway pairs • Endangered species limit feasibility of western end-around taxiways • Runway incursion problems	• Limited airport real estate at hub airports: limited taxi areas layout • Surface limitations less an issue • Runway capacity mostly driven by airspace	• At both MIA and FLL, surface traffic congestion is generally not considered a major problem • Dade County Aviation Department controls certain loading ramps; coordination with Tower necessary
Airport Configura-tion	• East, west • West used more often	• East, west • West is dominant	• Many, Runways 31L/R used more often	• East, west • East used most of time

4.2.4 Environmental Constraints

Metroplex design and operation is influenced by environmental sustainability. As more aircraft are squeezed into densely populated regions and as smaller airports are more frequently utilized, noise, air quality, and water are concerns for metroplexes. Thus, one must consider a range of environmental factors. Table 8 summarizes and compares the environmental constraints and issues of each metroplex.

There are substantial regional differences related to weather patterns and population distributions, and there are similarities related to urban locations where air quality is an issue. Three of the four metroplexes are classified as nonattainment (not meeting air-quality standards) for 8-hour ozone [EPA08a, EPA08b] and 24-hour particulate matter 2.5 (PM2.5) [EPA08a, EPA06]. Air quality is a very important issue in Southern California, as evidenced by its current nonattainment classification, which is expected to remain through 2020. Increases in metroplex traffic may further impact SCT air quality, making it more difficult to meet EPA standards.

Noise constraints are at the forefront for each metroplex. Airports located in densely populated areas receive very little support to expand surface area or adjust traffic flows to improve operations. All N90 airports are noise sensitive. The New York/New Jersey/Philadelphia Final Environmental Impact Statement (FEIS) [FAA07c] addressed noise constraints for five major airports. The FEIS found that each of the alternatives would result in changes where noise exposure is increased to within one of the FAA criterion thresholds, indicating the challenges facing metroplex operations in meeting increased demand.

Water quality appears to be of least concern to the impacted regions. All of the metroplexes have acceptable procedures in place that control the amount of runoff from airport surfaces.

TABLE 8. ENVIRONMENTAL COMPARISON

Item	A80	SCT	N90	MIA
Air Quality EPA Standards: 8-hour ozone: 0.075 ppm 24-hour; PM2.5: 35 μg/m^3	• 8-hour ozone: – Non-attainment around A80 ATL area – Attainment by 2020 [a] • 24-hour PM2.5: – Non-attainment around A80 ATL area – Reduced non-attainment around ATL by 2020 [a]	• 8-hour ozone: – SCT non-attainment – To remain non-attainment in 2020 [a] • 24-hour PM2.5: – SCT non-attainment – To remain non-attainment in 2020 [a] • Air quality high visibility issue	• 8-hour ozone: – Non-attainment – Some distant areas to remain non-attainment in 2020 [a] • 24-hour PM2.5: – Non-attainment – Metro area to remain non-attainment in 2020 [a]	• 8-hour ozone: – Attainment – To remain attainment in 2020 [a] • 24-hour PM2.5: – Attainment – To remain attainment in 2020 [a]
Noise	• ATL mitigation programs: noise abatement, land use • 65 DNL contours slowly increase • Major issue is night operations	• Very sensitive issue • Major growth constraint • Most strict noise program at SNA, other airports as well • Curfews, noise abatement procedures in place	• Noise sensitive 24 hours a day for New York Metroplex airports • Land use, runway use, over flights, increased operations, and nighttime operations (due to delay) major contributors • Procedures a major measure	• Very sensitive issue • Major growth constraint east, north, and south of MIA • Curfews, noise abatement procedures in place
Water Quality	• Impact increase due to 5th runway • Sewer system is sufficient • Mitigation plan in place	• Process in place to ensure the proper disposal of non-storm water discharge at some airports (e.g., LAX, LGB) • Protect the quality of storm water, e.g., at VNY	• HPN, ~750 ft from source of 90% of New York City's drinking water, thus protected • HPN surrounding water continuously monitored • No adverse effect from New York Metroplex airports	• Additional runway development at FLL will negligibly increase annual surface water pollution • Sewer system is sufficient • Mitigation plan in place

a. EPA projection. Data source: 8-hour ozone [EPA08b], 24-hour PM2.5 [EPA06]

4.3 Operation Comparison

4.3.1 Nominal Traffic Flows

VMC nominal traffic flows are presented in Figure 5. These traffic flows reflect the ATC response to the metroplex problem in today's environment. There are dramatic differences among the four metroplexes.

ATL's four-corner post-arrival operation is clearly seen. Because of high traffic volume at the northeast corner, two independent entry flows may be used. Traffic flows from the other feeds may be adjusted based on the demand from the northeast corner. Where departure flows cross arrival flows, altitude restrictions are enforced. Satellite flows are normally routed around and below ATL traffic (not shown). Turboprop and jet departures of secondary airports can be stacked (11,000 and 13,000 ft) with the ATL traffic in the feed to ZTL.

In Miami, although MIA and FLL do not have traditional standard four-corner post operations, the arrival corridors do serve the same purposes. Because of their distance (18 nm), traffic flows from these two airports—especially the high-volume traffic to and from the north—may cross with proper vertical separation and use different arrival and departure gates. Less-congested airspace also allows for mixing of air traffic from satellite airports (smaller airports surrounding MIA and FLL) with no problem. ZMA uses transition areas and often reroutes arrival and departure traffic during weather events. Since ZMA and MIA regularly operate with

Figure 5. Comparison of metroplex nominal traffic flows.

thunderstorm activity, the facilities utilize efficient SWAP procedures and maintain traffic flows. FLL and MIA can operate independently in different configurations without a decrease in capacity.

A four-corner post operation is not observed in the LA Basin because of airspace constraints, terrain, and adjacent airport flows (six air carrier airports). Sharing arrival and departure gates/fixes is common, although other airport flows (arrival and departures) from the east are pushed below the primary LAX flow. Traffic flows from different airports do merge and cross, but that normally occurs some distance away from the airport. Flows seem to be confined, but gaps do exist (see north of ONT and south of CNO). Those gaps are actually terrain to be avoided—ONT airport sits in a valley east of LAX. SCT and N90 both have high business jet and turboprop traffic to an adjacent airport (SNA, LGB, VNY, SMO).

Traffic flows in the New York Metroplex are dense and very complex. If multiple colors were not used, the traffic pattern would not be discernable. Sharing arrival and departure gates is very common, although JFK traffic flows are less dependent because of the ocean arrivals. The crossing and merging of traffic flows occur much closer to the hub airports. Because the three large hub airports are so close to each other, there is not much airspace available for vectoring within the terminal area. Using an extended final approach to manage arrival traffic is not possible because airspace is shared with other arrival and departure areas. LGA and JFK have highly dependent operations; EWR and TEB operations are also highly dependant, especially when operations are set to EWR runway 4 and TEB runway 6. Business jet/turboprop airports HPN and TEB share arrival fixes and departure fixes. Holding is also a frequent problem at multiple entry fixes.

4.3.2 Airspace Delegation and Operating Procedures

The comparison of airspace delegation and operating procedures is summarized in Table 9. Airport configuration coupling is a problem for the LA Basin and New York, but the problem is most severe for the latter, mostly because of the proximity of airports and local winds. Configuration change is difficult for all metroplexes investigated, except for Miami; the two major airports (MIA and FLL) have similar east-west configurations and are laid along the north-south coast line, resulting in fewer restrictions. Weather is a common issue, although situations are not all the same. The west coast airports deal with low stratus clouds and winds, while the east coast airports have more severe weather problems. Terrain and SUA are significant constraint factors for the LA Basin, but less a problem for others. The eastern seaboard SUA located off the east coast and extending up to the New York area can now be used by civilian traffic under a LOA with the military to relieve congestion during severe weather or during holidays (normally released under Presidential Directive).

The term *interaction* represents either the direct results of airport dependencies or the ATC response to those dependencies. For the LA Basin, the impact of BUR's configuration on VNY during Santa Ana winds is an example of the former type. Routing satellite traffic around ATL traffic is an example of the latter, meaning that a different measure could be taken given proper technology. Atlanta, by sacrificing the performance of satellite traffic, has achieved high throughput at a single large commercial hub to serve a metropolitan area. Miami, by spatially

TABLE 9. AIRSPACE AND OPERATION COMPARISON

Item	A80	SCT	N90/ZNY	MIA
Airport Configura-tion Change	• Independent of each other • ATL change during busy hours avoided if possible for throughput; may even change in advance to avoid delay	• Coupled with each other to certain degree • Change must also be coordinated with ZLA • Only when absolutely needed	• Strongly coupled • Determined by TRACON; JFK given higher priority • Difficult to change; flushing and stop may be needed	• No coupling, unconstrained airspace • Change frequently as needed • TRACON positions remain the same, altitude flips
Airspace Structure Issues	• Class B lack northeast corner extension; plan in place	• Uneven TRACON top ranging from 6,000 to 17,000 ft	• Lack airspace in N90/ZNY; little room for maneuver	• Need to expand Class B to include FLL (Class C)
Weather	• Convective weather (CW)	• Santa Ana winds/May–August coastal fog/CW	• Summer CW/winter snow storm (de-icing)	• Extensive summer thunderstorms
Terrain	• No major terrain	• Large mountains confine traffic	• No major terrain	• No major terrain
SUA	• Not a major problem	• Complex, confines traffic flow	• Eastern seaboard SUA can now be used during weather	• Not a major problem
Interaction among Traffic at Different Airports	• World's busiest airport • Satellite traffic routed around and below ATL traffic • Satellite departures handled by "release and hope" • PDK jet often released with altitude-restricted climbs	• VNY may be shut down if BUR unable to change to certain configuration • Share arrival and departure fix; northbound departure extremely congested • Sharing departure queue information desired by SCT	• Little room for EWR 29 landing/11 missed approach because of proximity of LGA • Competing airspace with traffic common • Sharing arrival/departure routes requires vertical or temporal separation	• MIA and FLL arrivals from southwest and northeast tend to share the same STAR • Other hub traffic is often spatially separated • Satellite arrivals mixed in and may call TRACON for departure release
Interaction with Center Airspace	• CSG, MCN, and AHN areas may be released back to ZTL	• Configuration changes require ZLA sector changes	• Arrival flows pushed back into en-route; lacks airspace	• Configuration changes require altitude changes only

separating traffic at two hub airports, achieves similar success. When demand increases dramatically, and when multiple airports are involved (see Table 6) complicated issues emerge, and simple solutions may no longer keep up with demand. This situation can be exasperated by flow constraints to other Operational Evolution Partnership (OEP) airports, especially for metroplexes with constrained airspace or when large hubs are closely located, as illustrated by the interactions in the LA Basin and New York Metroplex as shown in Table 9.

4.3.3 Automation Tools

This section identifies tools that assist in the coordination of traffic at different airports but are beyond those commonly used for normal tasks. Some of these tools are developed specifically for, and tailored to, each facility. The Airport Resource Management Tool (ARMT) assists with balancing runways and reducing ground delays (at ATL and MIA). The Daparture Spacing Program (DSP) allows departure traffic from multiple airports (eight in the N90 airspace) to share spacing over specific fixes and reduces delay by allowing the Towers to manage ground movement and stage aircraft according to a priority list. TFM tools include a suite of tools that allow the sharing of traffic flows with adjacent ATCTs and the Center. TFM tools also address Ground Delay Programs (GDPs), Airspace Flow Programs (AFPs), SWAP, mile-in-trail (MIT) compliance, and other local flow-management systems. Airport Surface Detection Equipment, Model X (ASDE-X) is a runway safety tool that enables controllers to detect potential conflicts. It is primarily a tower tool, but it can be shared with TRACONs to share ground movement and congestion information. Ramp towers at JFK and EWR use traffic flow-management tools that provide smoother ground staging of aircraft and collaborative coordination. The Continental Airline ramp tower at EWR has an excellent rapport with the EWR tower. Center TRACON Automation System/Traffic Management Advisor (CTAS/TMA) allows for the spacing and sequencing of arrivals into primary metroplex airports through automated flow assigned delays at higher altitudes. This tool provides individual flow and multicenter capabilities that are progressing into metroplex areas.

Current application of these tools at the metroplex sites is shown in Table 10. Note that all four metroplexes have CTAS/TMA installed (LAX uses TMA most of the time, MIA part time; ATL is developing TMA; and N90 is testing TMA during selective periods to EWR) and they all have some TFM tools. DSP directly supports metroplex operations, but is installed only in New York. Currently the application of most of the tools is experimental in nature. Experience gained during the process should be valuable for supporting future development.

TABLE 10. COMPARISON OF THE USE OF AUTOMATION TOOLS

Tool	Atlanta	LA Basin	New York		Miami
	A80/ATCT	*SCT/LAX*	*N90/ATCT*	*ZNY*	*MIA/ATCT*
ARMT	Yes	No	No	No	Yes
DSP	No	No	Yes 8 ATCTs	Yes	No
TFM Tools	Yes	Yes	Yes	Yes	Yes
ASDE-X	Yes	No	Yes	No	No
CTAS/TMA	ATL	LAX	EWR		FLL

4.4 Lessons Learned and Implications for Metroplex Performance and Design

4.4.1 Summary of Metroplex Site Visits

The team's review of four representative metroplex sites in the United States—Atlanta, Los Angeles, New York, and Miami—was conducted based on a detailed study of interdependencies among airports in proximity within the resident TRACON. These four metroplexes provided an interesting study since they present different metroplex characteristics based on traffic flows, airport geographic proximity, terrain, crossing routes, weather patterns, and airport demand. SCT and N90 have similar metroplex operational complexities due to traffic density and flows, although the N90 operation presents two closely coupled operations (EWR/TEB and JFK/LGA) within a major metroplex. MIA and ATL metroplex operations present independent operations with fewer constraints or flows to adjacent airports.

SCT is constrained by terrain and airport location, placing a constraint on individual flows. Although LAX determines the Southern California airport flows, the other five major air carrier airports create complexity along with business jet and turboprop traffic into other adjacent airports. SCT airports and flows are primarily east-west. Much of the arrival/departure traffic flows from/to the east and north and airport flows are highly structured and constrained because of traffic density. Most of the LA Basin traffic is restricted based on the primary LAX flow, and is dependent on the operation of LAX. SAN works within a separate but smaller metroplex, although SAN traffic flows to and from the LA Basin are based on the configuration of the LAX traffic flow. SUA is another constraint factor for the LA Basin. Because of terrain and SUA constraints, departures are more constrained than arrivals in SCT.

N90 presents the most complex metroplex operations and restrictive airport flows. A New York–New Jersey airspace redesign is underway; workgroups and facilities are studying 77 identified problems [ARC07]. The dependencies between EWR and TEB operations and airport configurations often restrict arrival and departure flows. A proposed area-navigation-system (RNAV)/required-navigation-performance (RNP) approach for runway 6 at TEB should assist with operations when EWR is on a runway 4 operation. JFK and LGA are highly dependent on each other's operations as well as the demand and configuration of EWR. N90 primarily decides the optimal configuration of the airports, and firmly controls the arrival and departure demand into these airports. The Air Traffic Control System Command Center (ATCSCC) removed the three primary New York airports from OEP departure flow restrictions in order to alleviate departure delays at LGA/EWR/JFK. N90 is fed by three adjacent En-Route Centers and adjacent TRACONs that create traffic-flow restrictions to manage the number of routes. Similar to SCT, departures from major airports within N90 share certain departure fixes. DSP and TMA are currently being used and tested in N90. However, the potential capabilities of these tools have not been utilized to their full extent because of a lack of adequate information sharing between different systems and implementation-related issues.

A80 operates independent flows to ATL and adjacent airports. The ATL metroplex does not have the number of air carrier airports or the complexity that the other metroplexes experience. ATL can operate east or west without an impact on the configuration of adjacent airports. Secondary airport flows are routed around and below ATL flows. ATL does experience airspace constraints while landing to the west, and it experiences difficulty with aircraft exiting Class B airspace to the east. ATL maximizes use of the runways and delivers traffic at minimal spacing. Compared to SCT and N90, ATL does not have a terrain problem, airspace constraints, or competing flows from other commercial airports.

MIA Metroplex operations are not as constrained, and the primary airports (MIA/FLL) can continue independent operations in east or west configurations. All of the MIA area airports have east-west runways, and flows at secondary airports can operate independently in either the east-flow or west-flow configurations. Flows to and from MIA and FLL are routed via separate gates and fixes. ZMA/MIA does not have airspace, SUA, or terrain constraints. Traffic flow from the adjacent business aircraft airport does not create issues with the flow from the two primary airports. During the winter PBI flows are segregated from flows to MIA/FLL because of high business jet demand ("snowbird flights") during this period. Although MIA is the primary airport, FLL operates independently except during severe weather conditions, in which SWAP procedures are efficiently implemented to continue operations.

4.4.2 Implications on Metroplex Performance and Design

The different ways that interdependencies and traffic coordination are managed imply that current practices were evolved over years of operations and thus are most often location-specific. An initial review of these practices identifies some patterns. For example, in A80, flights to and from secondary airports are routed to fly longer routes so that flights to and from ATL can use routes that are more direct. In MIA, flights to and from MIA use different routes and gates from those for FLL flights. By employing this system, routes for flights at both airports are more or less displaced from routes that are more direct to their corresponding airports. In both cases, the effect appears to be spatially displacing traffic so that safe separation can be achieved without heavy temporal coordination between the airports. When lateral airspace is limited, traffic for different airports may be vertically stacked over a common fix, but often some traffic coordination or spacing is still needed. On the other hand, when certain departure gates are shared (frequently in SCT and N90), departures from certain airports may need to get approval before release, or in extreme cases, departures at certain airports may be temporarily stopped or held to make airspace available for operations at nearby bigger airports. In this case, temporal displacement is used as the sole means to separate traffic. These observations motivated additional rigorous analysis in order to characterize and classify metroplex operations from which a unified framework may be developed to systematically study the metroplex problem. The site survey also highlighted the need to study more sites, to more fully capture all the aspects of the metroplex problem, and to identify best practices across metroplexes in the NAS.

Through some of the measures, such as segregated routing, traffic flows within a metroplex may operate independently. However, airspace dependencies would still exist. One has to pay a price to getthe flow segregated. It is thus important to maintain the distinction between the intrinsic dependencies between arrival and departure operations at metroplex airports and the practices to counter those intrinsic interactions and dependencies. The former defines a metroplex and the latter provides solutions to the metroplex problem.

5.0 CHARACTERIZATION OF METROPLEX OPERATIONS

The ultimate goal of this task was to develop an abstract of metroplex operations to guide their evaluation and future study. This work was based on the literature review and site surveys described in sections 3 and 4. In the process, both qualitative and quantitative steps have been taken. This work focused on four areas. The first was a qualitative evaluation of the impact of major metroplex issues on metroplex operations. The second was a categorization of metroplex airspace dependencies, based on examples of measures being taken by the air traffic control (ATC) to handle traffic flows in response to the intrinsic dependencies among metroplex airports. The third area was a quantitative measurement of the intrinsic interactions and dependencies among airports within a metroplex, accounting for geographic locations, traffic volume, and infrastructure at metroplex airports. The measurement can be applied to characterize different metroplex sites. The last area was a metroplex clustering analysis that used an arrival flow airspace volume-based metric as the "distance" measure. This analysis was developed to clustering airports into metroplexes and identifying potential future metroplexes in the National Airspace System (NAS). The following sections describe these steps.

5.1 Metroplex Issues

This section presents a set of metroplex issues that were identified as a result of the metroplex literature review [RS09] and the metroplex site-survey studies at A80 [RC09b], SCT [SL09], N90 and ZNY [TL09], and MIA [SR09]. A subjective evaluation process was employed to prioritize the issues identified in order to rank their (adverse) impact on the metroplex operations. Figure 6 provides an overview of this process. Note the GMN acronym in the figure is the Gorman VORTAC ATC facility.

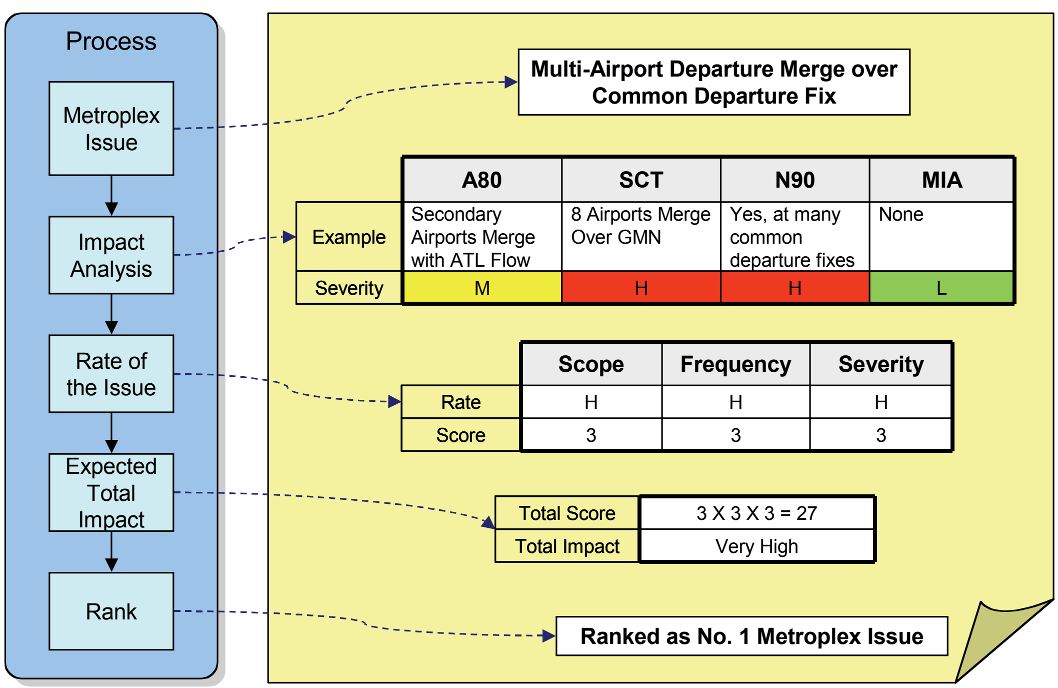


Figure 6. Metroplex issues prioritization process.

For each identified issue, the team collected documentation and verbal information from operational experts for each of the four site-visit locations and from the metroplex literature survey. Subject-matter experts (SMEs) on the research team used this information and their judgment to give each metroplex issue a "total score" that was intended as a qualitative way to rank its importance. The score is based on ratings in the categories of "scope", "frequency", and "severity". The "scope" rating was determined based on the relative geographical extent of the issue in and across the different sites. Both a metroplex site-specific Scope rating as well as an overall scope rating was determined; the overall scope rating was applied. A rating of high (numerical value of 3), medium (numerical value of 2), or low (numerical value of 1) was provided, with high given to an issue found at most or all of the sites and low given to an issue found at only one of the sites. "Frequency" rating was similarly scored, based on how frequently (i.e., in terms of times per day) the metroplex issue would be expected to be encountered. "Severity" rating was also similarly scored, based on how severe the relative traffic disruption is expected to be when the metroplex issue is encountered. For each metroplex issue, the expected total impact was computed as:

$$\textit{Expected Total Impact} = \textit{Scope Rating} \times \textit{Frequency Rating} \times \textit{Severity Rating}$$

Each of the identified metroplex issues underwent the scope, frequency, and severity analyses and was assigned a total score with a maximum value of 9 and a minimum value of 1 based on the formula shown. The metroplex issues were then prioritized and ordered based on the total scores in a decreasing manner, as shown in Table 11.

TABLE 11. METROPLEX ISSUES PRIORITIZATION SUMMARY

#	Metroplex Issue	Scope					Frequency	Severity	Expected Total Impact
		A80	SCT	N90	MIA	Over-all			
1	Multi-Airport Departure Merge over Common Departure Fix	M	H	H	L	H	H	H	Very High
2	Major Volume-based TFM Restrictions	M	M	H	L	H	H	H	Very High
3	Proximate-Airport Configuration Conflicts	M	H	H	L	H	H	Var	High
4	Slow Inter-Airport Surface Connectivity	M	H	H	M	H	H	Var	High
5	Inefficient/High Workload Airport Configuration Changes	M	H	H	L	H	Var	H	High
6	Inefficient Inter-Airport Departure Sequencing	M	H	H	L	H	H	M	High
7	Flow Constraints	H	H	H	M	H	H	M	High
8	Inefficient "Flushing" of Airport Flows	M	H	H	L	H	M	M	Medium
9	External SUA Causes Flow Dependencies	L	H	M	L	M	H	Var	Medium
10	Terrain Causes Flow Dependencies	L	H	L	L	L	H	H	Medium
11	Severe Limitations on Instrument Procedures due to Proximate Airport	L	L	M	L	L	L	H	Low
12	Insufficient Regional Airport Capacity	L	L	M	L	L	L	H	Low

The definitions of the issues shown in Table 11 are listed in Table 12 for quick reference. Detailed examples of these metroplex issues have been cataloged in a separate document [SS09b]. The abstract of that document is also given in appendix B.3.1. Readers are referred to the document for a complete description.

Issues in Table 11 are arranged in the decreasing order of their expected total impact. Per the aforementioned rating process, 2 of the 12 issues have “very high” expected total impacts. One of these, Multiple Airport Departure Merges over a Common Departure Fix, in the case of SCT included up to 8 airports feeding traffic over a common fix. The other issue that was rated “very high” was Major Volume-based TFM Restrictions, which relates to either standing departure MIT restrictions or flow-rate restrictions on peak arrival flows.

Five issues have “high” expected total impacts. Proximate-airport configuration conflicts in the table concern dependencies where the otherwise unconstrained departure or arrival flows were significantly constrained by other proximate airport flows. Slow inter-airport ground connectivity limits the flexibility of passengers and air carriers serving them to maximize use of proximate airports. Inefficient/high workload airport configuration changes concern the high air traffic disruption due to significant multifacility coordination; for SCT, this coordination requires multi-airport, multi-TRACON sector, and ARTCC sector coordination. Inefficient multi-airport departure sequencing concerns the difficulty of coordinating departure sequencing and timing to maximize flow across departure fixes, and the simultaneous sequencing of departures to support existing Traffic Management Initiatives, noise restrictions, and individual airport throughput. Major secondary airport flow constraints typically involve additional coordination of, and flight delays for, secondary airport traffic to safely merge with primary airport flows.

Three issues have “medium” expected total impacts. Inefficient “flushing” of airport flows concerns dynamic tactical preference of the departure or arrival flow of one airport to “flush” congestion while delaying the opposing flow of traffic of the “flushing” airport (e.g., departures, if arrivals are being flushed, and vice versa) as well as proximate airport traffic. The final two issues of “medium” impact were tied to the impacts of special-use airspace (SUA) and terrain, reducing the usable airspace for traffic flows and causing additional airport flow dependencies.

Two additional issues were identified that were rated “low” impact: severe limitations on instrument procedures due to proximate airport primarily involved the severe limitations on arrival traffic to EWR runway 29, when the issue of insufficient regional airport capacity concerns the region’s available runway capacity relative to existing demand.

TABLE 12. IDENTIFIED MAJOR METROPLEX ISSUES

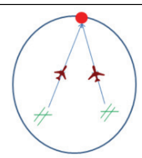
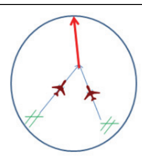
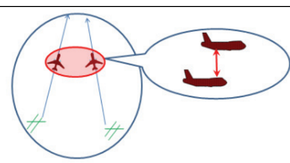
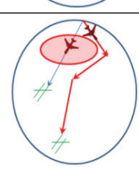
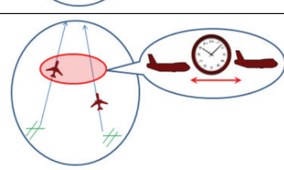
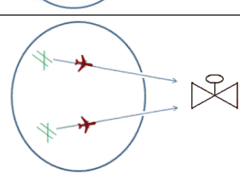
#	Metroplex Issue	Definition
1	Multi-Airport Departure Merge over Common Departure Fix	Occurs when flights from at least two separate airports are procedurally merged over at least one common departure fix.
2	Major Volume-based TFM Restrictions	Occurs when a significant level of TFM restrictions due to demand-to-capacity overloads exist at airspace fixes or at airports.
3	Proximate-Airport Configuration Conflicts	Occurs when an airport configuration change of one of at least two proximate airports puts restrictions on flights flying to/from other proximate airport(s). This change involves flows from one impacting another airport's flows, causing significant rerouting or delays.
4	Slow Inter-Airport Ground Connectivity	Occurs when inadequate surface transportation of passengers between airports causes significant delays and consequently limits the efficient use of airports by passengers.
5	Inefficient/High Workload Airport Configuration Changes	Occurs when any major airport configuration change requires significant workload because of reasons such as: coordination of a large number of personnel, FAA facilities, and airports; and sector reconfigurations.
6	Inefficient Multi-Airport Departure Sequencing	Occurs when departure sequencing of flights from multiple airports requires conservative flight restrictions.
7	Major Secondary Airport Flow Constraints	Occurs when conflicts between a primary airport and a secondary airport lead to constraints on secondary airport flows. Typically, secondary airport traffic will be held below primary airport traffic flows or will be routed around the primary airport traffic patterns, resulting in longer flightpaths.
8	Inefficient "Flushing" of Airport Flows	Occurs when ATC uses a "flushing" technique that constrains other airport traffic flows in order to expedite one airport's arrival or departure flights as a way to solve a particular congestion problem (e.g., airport arrival gridlock).
9	External SUA Causes Flow Dependencies	Occurs when SUA external to the TRACON constricts TRACON flows into narrow corridors and forces inter-airport traffic-flow dependencies.
10	Terrain Causes Flow Dependencies	Occurs when terrain internal to the TRACON constricts TRACON flows into narrow corridors and forces inter-airport traffic-flow dependencies.
11	Severe Limitations on Instrument Procedures due to Proximate Airport	Occurs when the use of instrument procedures is severely constrained because of the existence of a proximate airport.
12	Insufficient Regional Airport Capacity	Occurs when there is generally not enough TRACON runway capacity to efficiently serve the air traffic demand.

5.2 Categorization of Metroplex Airspace Interactions

Metroplex airspace dependencies were categorized based on observations from metroplex site visits and performance-data-analysis-and-reporting-system (PDARS) traffic-flow data analysis. The ultimate goal of these dependency categorizations was to determine the most severe "types" of metroplex interdependencies and the best solution to handle them.

The following methodology was followed: Metroplex site-visit notes from the Georgia Institute of Technology (GaTech) team (A80 [RC09b], SCT [SL09], N90 and ZNY [TL09], and MIA [SR09]) and Mosaic-ATM team (NCT [A07] and N90 [A08]) were studied and information was extracted on the observed interdependencies for each of the visited sites. This information was analyzed and the interdependencies were categorized according to the way the airspace is shared among traffic flows. Through this process, six metroplex airspace interdependency categories were identified. They are illustrated in Table 13.

TABLE 13. MAJOR METROPLEX AIRSPACE INTERDEPENDENCIES

#	Diagram	Definition
1		Arrivals/departures to/from two or more proximate airports use the *same points in the airspace* – Arrival/Departure fixes
2		Arrivals/departures to/from two or more proximate airports use *common path segments* – STARs and SIDs
3		Arrivals/departures to/from two or more proximate airports intend to use the *same volume of airspace* but they are *vertically separated*
4		Arrivals/departures to/from two or more proximate airports intend to use the *same volume of airspace* but they are *laterally separated*
5		Arrivals/departures to/from two or more proximate airports intend to use the *same volume of airspace* but they are *temporally separated*
6		*Downstream restrictions*, applied across multiple airports in the metroplex

Next, analysis was made to assess the possible ATC techniques or airspace/procedure design to mitigate each category of airspace interdependency. During the analysis, it was recognized that the local solutions generated for each category of interdependency could be different at different facilities. Mitigation approaches for the identified interdependencies are summarized as follows along with one or two real-world examples for each category. For each category, the mitigation approaches that could be used are listed in a perceived order of efficiency.

Category 1: Sharing Common Points in Airspace

Examples:

- SCT: Departures from eight airports in the LA Basin towards northern California are merged over the GORMAN (GMN) departure fix.
- N90: TEB south departures have to be merged with EWR south departures and then pass over shared departure fixes.

Mitigation Approaches:

- Keep departure flights from each airport on physically separated routes until just before they reach the terminal-radar-approach-control-facilities (TRACON) boundary and then merge them at the departure fix, without coordination of takeoff times.
    - Handle flights as/when they show up on the TRACON radar.
    - Ask for excess mile-in-trail (MIT) separation from each airport.
- Keep departure flights from each airport on physically separated routes until they are past the TRACON boundary and let the center merge them.
- Disallow the use of certain boundary fixes to a particular airport.
- Arrival/departure from one airport shuts down arrivals/departures from the other airport.
- One airport needs to call the TRACON for departure release.
    - Departure from this airport has to be fit into a gap in the arrival/departure stream going to the other airport.
- Both airports need to call the TRACON for departure release.
- Coordinate four-dimensional (4-D) trajectories of arrival and departure flights from both airports.

Category 2: Sharing Common Path Segments

Example:

- NCT: During the night (10 p.m. to 7 a.m.), quiet/silent departure procedures are used at SFO and OAK—both airport departures have to follow the same route within the immediate departure sector and hence departure times have to be coordinated across the two airports.

Mitigation Approaches:

- Keep flights from each airport on physically separated routes until just before they reach the standard-terminal-arrival-route/standard-instrument-departure (STAR/SID) start point and then merge them at the start point, without coordination of takeoff/landing times.
  - Handle flights as and when they show up on the TRACON radar.
  - Ask for excess MIT separation from each airport and center.
- Disallow the use of certain STARs/SIDs to a particular airport.
- Arrival/departure from one airport shuts down arrivals/departures from the other airport.
- One airport needs to call the TRACON for departure release.
- Both airports need to call the TRACON for departure release.
- Reduce complexity by coordinating airport runway configuration changes across both the airports.
- Coordinate 4-D trajectories of arrival and departure flights from both airports.

Category 3: Intending to Share Airspace Volume but Profile Altered for Vertical Separation

Examples:

- NCT: Under VMC, HWD arrivals keep below OAK arrivals, and these two arrival streams are independent.

Mitigation Approaches:

- Departures/arrivals to one airport have altitude restrictions—e.g., departures/arrivals to one airport have to keep out of the way of traffic of the other airport.
- Departures/arrivals to both airports have altitude restrictions to keep out of each other's way.
- Increase in-trail spacing between an arrival/departure stream to one airport to avoid wakes generated by an arrival/departure stream to the other airport.
- Reduce complexity by coordinating airport runway configuration changes across both airports in the metroplex.
- Disallow usage of a certain route by one airport when the other airport experiences heavy traffic over a proximate route.
- Deliver aircraft to the adjacent center/accept aircraft from the adjacent center in stacks—different altitudes for traffic going to/coming from different metroplex airports.
- Coordinate 4-D trajectories of arrival and departure flights from both airports.

Category 4: Intending to Share Airspace Volume but Path Altered for Lateral Separation

Examples:

- A80: PDK arrivals from south of ATL are routed around ATL patterns.
- N90: SWF airport traffic flows are routed around the New York metropolitan area, through ZBW, before going south.

Mitigation Approaches:

- Departures/arrivals to one airport are assigned indirect routes between the airport and the metroplex boundary to keep out of the way of traffic of the other airport.
- Departures/arrivals to both airports are assigned indirect routes between the airport and the metroplex boundary to keep out of each other's way.
- Reduce complexity by coordinating airport runway configuration changes across all airports in the metroplex.
- Disallow usage of a certain route by one airport when the other airport experiences heavy traffic over a proximate route.
- In bad weather, congestion effects are amplified because there is already a large volume of unusable TRACON airspace.
    - Respond by applying ground holds and en-route airborne holding.
- Coordinate 4-D trajectories of arrival and departure flights from both airports.

Category 5: Intending to Share Airspace Volume but Temporally Separated

Examples:

- N90: Morristown Municipal Airport (MMU) always calls for release—calls departure handoff position at N90 (in the EWR area). Cannot rely on MMU hitting departure release time, so vectoring has to be used to merge stream (with EWR) before handing off to EWR.

Mitigation Approaches:

- One airport calls the TRACON for departure release.
    - Departure from this airport has to be fit into a gap in the arrival/departure stream going to the other airport.
- Both airports call the TRACON for departure release.
- Merges/crossings in the TRACON airspace are handled tactically.
    - Handle flights as and when they show up on the TRACON radar.
    - Ask for excess MIT separation from each airport and the center.
- Arrival/departure to one airport shuts down arrivals/departures to the other airport.

- Reduce complexity by having a tight coordination of runway configurations across both airports.
- Have one airport tower act as the "tower for own airport plus the other airport" using surface surveillance capabilities.
- Use Traffic Management Advisor (TMA)/the Departure Spacing Program (DSP) or other similar temporal coordination tools.
- Coordinate 4-D trajectories of arrival and departure flights from both airports.

Category 6: Downstream Restrictions

Examples:

- ZNY typically applies one Air Traffic Control System Command Center (ATCSCC)-generated restriction per plane in departure queue (except in rare cases): approval request (APREQ), DSP, MIT, expected departure clearance time (EDCT), or other.

Mitigation Approaches:

- Use DSP or another similar temporal coordination tool to handle the imposition of multiple downstream constraints like MIT requirements APREQs, departure release times, ground-delay programs, etc.
- Departure trajectories are tactically modified to provide enough spacing at the TRACON boundary.
    - Handle flights as and when they show up on the TRACON radar.
    - Ask for excess MIT separation from each airport.
- Coordinate 4-D trajectories of arrival and departure flights from both airports.

Conclusions

All observed interdependencies across the visited metroplex sites can be divided into a few categories. Mitigation techniques to these interdependencies are site-specific and they differ widely. Local procedures tend to be evolved rather than freshly designed. The most prevalent kind of metroplex interdependency is flights to/from multiple airports that use a common volume of airspace. Separating flows in horizontal space or coordinating departure or landing time are the most common responses to these interdependencies. A single Next-Generation Air Transportation System (NextGen) concept with the potential to most efficiently solve the observed metroplex problems is: coordinated planning of 4-D trajectories for all arrivals and departures to and from all metroplex airports.

5.3 Geographic Metroplex Dependency Metrics

A close inspection of dependencies and the interactions between arrival and departure operations at metroplex airports suggests that they can be divided into two fundamental types. The first can be categorized as preexisting conditions, while the second can be categorized as the ATC response to those preexisting conditions. The difference between these two types is that different measures can be taken to counter the same set of preexisting conditions, or dependencies, as illustrated by the metroplex site-survey findings. Searching for the best solution to counter the intrinsic dependencies between arrival and departure operations at metroplex airports is the ultimate goal of this research. However, it is important to understand those dependencies first. A set of geographic metroplex dependency metrics has been developed to measure those dependencies. With these metrics, the metroplexes in the NAS can be characterized, and ideally, measures demonstrated to be effective in one metroplex can be evaluated to identify their potential effectiveness in another.

This set of metroplex dependency metrics was developed to measure dependencies contributed by factors that are a subset of preexisting conditions such as airport geographic locations, runway length, and traffic volume. They are not developed to measure ATC response solutions such as airspace design, traffic patterns, and operational procedures.

5.3.1 Pairwise Airport Dependency

As shown in Figure 7, the most important geographical factor for a pairwise airport dependency is the distance between the two airports. The dependency reduces as distance increases. The length of the runways is another factor. Dependency increases as runway length increases because of the ability of the airport to accommodate larger aircraft. Traffic volume is also an important factor. Other factors include the airport configuration and runway orientation, surrounding terrain, and nearby special-use airspace. Because of time and resource limits, these other factors are not considered in the current study.

As an initial attempt to model the effect of the distance between a pair of airports, a Gaussian base function was selected (Figure 8), which has been commonly used in many fields to model spatial correlation. The Gaussian base function is used to represent the dependency between a pair of airports at any given distance apart. The selected function is normalized to 1 (fully dependent) at 0 nm, and 2% (somewhat arbitrary) at 70 nm. This distance was selected because Class B airspace is normally limited to 35 nm from the hub airport, and thus dependencies between airports more than 70 nm apart are normally no longer a terminal-area problem.

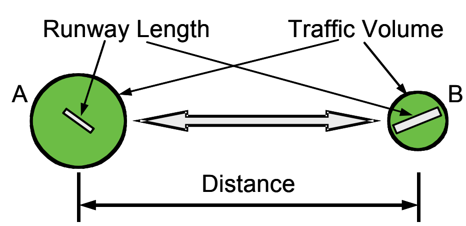


Figure 7. Considered contributors to pairwise airport dependencies.

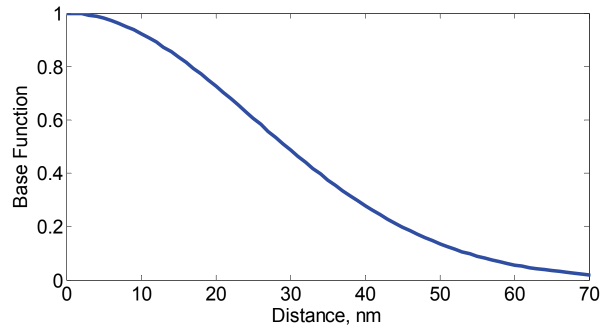


Figure 8. The Gaussian base function used to model the distance effect on pairwise dependency.

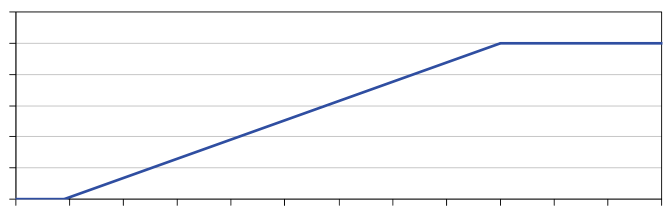


Figure 9. The runway factor.

The effects of runway length and traffic volume are modeled as a weight function for each airport, also normalized to have a maximum value of 1. To measure the contribution of runway length, the Federal Aviation Administration (FAA)-recommended runway length for a 10+ seat small airplane is used as a reference. This runway length is a function of airport elevation and the mean daily maximum temperature in the hottest month [AC150-5325-4B]. A runway length less than 0.18 times the reference length is rated at 0 and the runway length greater than 1.8 times the reference length is rated at 1 because the former can accommodate only ultralights and the latter can accommodate large jets. A linear relationship is assumed for the runway factor, as shown in the following equation and graphically in Figure 9. The runway ratio in the equation and Figure 9 is defined as the ratio of the longest runway at the airport over the recommended runway length for a 10+ seat small airplane operating at the airport.

$$RunwayFactor = \begin{cases} 1, & RunwayRatio > 1.8 \\ (RunwayRatio - 0.18)/(1.8 - 0.18), & 0.18 \le RunwayRatio \le 1.8 \\ 0, & RunwayRatio < 0.18 \end{cases}$$

To measure the contribution of traffic volume, an annual level of itinerant operations of 365,000 (equivalent to an average of 1,000 operations per day) or more was selected to represent an impact factor of 1. This level represents a typical level of operations for the busiest airports in the NAS; 21 such airports in 2007 [TAF08] had this level of annual operations. Unlike runway length, the minimum value for the traffic-volume factor is set to 0.1 even if the number of itinerant operations is zero. This value is set to avoid excluding under-utilized airports from the analysis. There may be potential traffic growth in the future if sufficient runway infrastructure is in place. A linear relationship is assumed for the traffic-volume factor, as shown in the following equation and graphically in Figure 10.

$$TrafficFactor = \begin{cases} 1, & ItinerantOperations > 365{,}000 \\ 0.9 \times ItinerantOperations / 365000, & 0 \le ItinerantOperations \le 365{,}000 \\ 0.1, & ItinerantOperations = 0 \end{cases}$$

The airport weight is given by the product of these two factors:

$$AirportWeight = RunwayFactor \times TrafficFactor$$

The pairwise dependency is defined as the product of the weights of the two airports and the value of the Gaussian base function corresponding to the distance between the two airports. By this definition, the pairwise dependency could have a maximum value of 1 (fully dependent) and a minimum value of 0 (independent). Example pairwise dependencies between the major hub airports and other airports at the four metroplex sites studied during the site survey are listed in Table 14. These dependencies were the highest pairwise dependencies at each site.

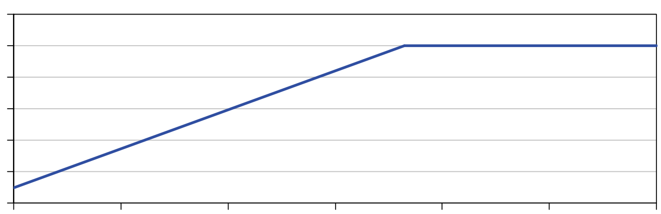


Figure 10. The traffic-volume factor.

TABLE 14. MAJOR PAIRWISE AIRPORT DEPENDENCIES FOR FOUR METROPLEXES

Location	**Central Hub**		**Other Airports**		**Distance, nm**	**Dependency**	**Qualitative Rating**
	Code	***Weight***	***Code***	***Weight***			
A80	ATL	1.00	PDK	0.31	15.6	0.25	Medium
SCT	LAX	1.00	VNY	0.91	16.5	0.73	High
			LGB	0.54	14.8	0.46	Medium
N90	JFK	1.00	EWR	1.00	18.1	0.77	High
			LGA	0.90	9.3	0.84	High
MIA	MIA	0.99	FLL	0.83	18.3	0.63	High
			OPF	0.27	6.8	0.26	Medium

As can be seen, the pairwise dependencies were highest for JFK because the other two interacting airports are also Operational Evolution Partnership (OEP) large hub airports. In A80, although ATL was (still is) the busiest airport in the world, the second busiest airport in the metroplex, PDK, had a much lower traffic volume. As such, the pairwise dependency for ATL was lowest among all airport pairs listed in the table. The pairwise dependencies for LAX were less than that for JFK, but greater than that for MIA.

5.3.2 Metroplex-Wide Airport Dependencies

With the pairwise airport dependency, new metrics can be defined to measure the metroplex-wide airport dependencies. For this purpose, a metroplex was defined to have an outer range (radius) limit from the central hub airport. Airports outside this limit were ignored. A metroplex is also assumed to have an inner core with a given radius from the central hub airport. Airports inside the core are referred to as “core airports” and airports outside the core ring, but within the metroplex range limit they are referred to as “outlying airports,” as shown in Figure 11. To calculate metroplex-wide dependencies, dependencies between core airports and all airports within the range limit are accounted for. For outlying airports, only dependencies with core airports are accounted for. Dependencies between outlying airports are assumed to be local issues at remote areas, and are ignored. Special cases of the core radius include:

- 0 nm, the core consists of the central hub airport only
- 35 nm, the core consists of all airports within the central hub Mode C area
- Radius limit, all airports within the range limit

An intermediate metric is the one-to-all dependency—the sum of dependencies between one airport and all other airports within the metroplex range limit. This metric is most suitable for characterizing dependencies among a major hub and other airports within a metroplex. A 75-nm metroplex range limit was selected for use in this analysis. One-to-all dependencies for major hub airports within the four metroplexes studied are listed in Table 15. Again, the table shows that dependencies are highest for N90 large hub airports and least for the A80 large hub airport.

Three hub airports in SCT, i.e., SNA, BUR, and ONT, are medium hub [FAA09a] airports; thus they have lower one-to-all dependencies than those of any of the large hub airports.

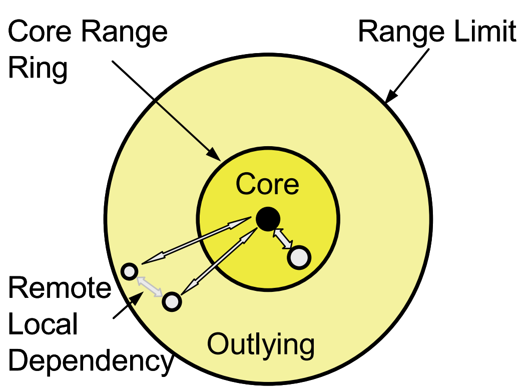


Figure 11. The metroplex geographic dependency model.

TABLE 15. DEPENDENCIES BETWEEN HUB AIRPORTS AND ALL OTHERS WITHIN 75 NM OF THE CENTRAL HUBS

Location	Hub	# Other Airports	Hub-to-All Dependency	Location	Hub	# Other Airports	Hub-to-All Dependency
A80	ATL	47	1.22	N90	JFK	61	3.08
SCT	LAX	49	2.80		EWR	61	3.22
	SNA	49	1.18		LGA	61	3.12
	BUR	49	0.90	MIA	MIA	20	1.63
	ONT	49	0.85		FLL	20	1.64

The metroplex-wide metric is defined by the core-to-all dependency—the sum of dependencies between each airport inside the core range ring and all other airports within the metroplex range limit. The metric is most suitable for measuring the total level of dependencies within a metroplex. The metric was calculated for the four sites studied, with a core radius varying from 0 to 75 nm. The results are shown in Figure 12.

For any given metroplex, the higher the core-to-all dependency, the higher the overall dependency is within the metroplex. When the metroplex core radius is set to 0, the core-to-all dependency reduces to the one-to-all dependency for the central hub airport. When the metroplex core radius is set to the range limit (75 nm in this case), the core-to-all dependency becomes the sum of all pairwise dependencies. Thus, the radius of the core is an important parameter for the core-to-all metric to be comparable between different metroplexes. As seen from Figure 12, there appears to be some value for the core size in all four metroplexes below which the core-to-all dependency grows rapidly with increasing core size. Above this value, the core-to-all dependency may still grow, but at a much slower pace. This value appears to be a natural selection of the core size of 16–18 nm, as shown in Figure 12 by the shaded vertical band. Another important observation is the clustering of the core-to-all dependencies for N90 and SCT on the higher side, and the clustering of MIA and A80 on the lower side. This observation is consistent with the findings from the site-survey study that the coupling of metroplex traffic flows is strongest in N90 and SCT, and relatively moderate in MIA and A80.

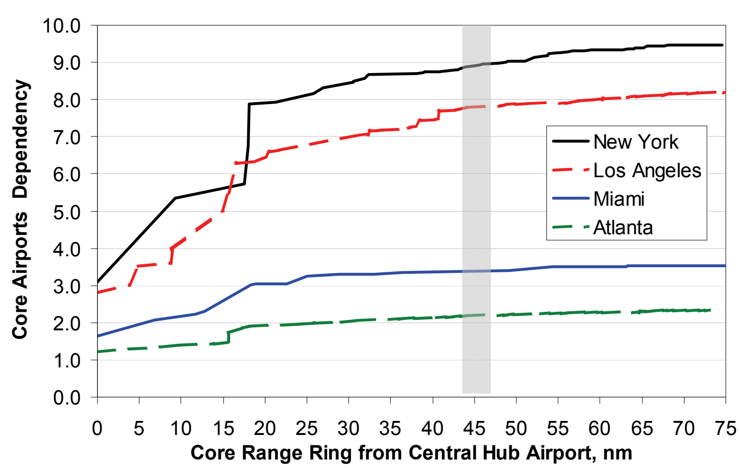


Figure 12. Metroplex core-to-all dependency versus core size.

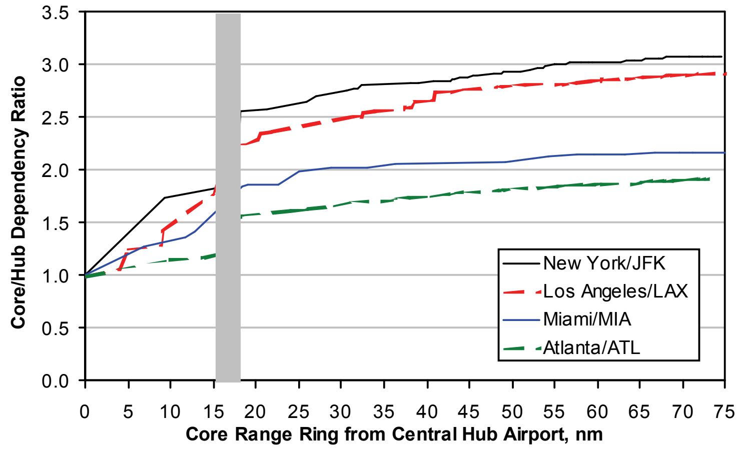


Figure 13. Metroplex dependency ratio versus core size.

A derived metric can be defined as the ratio of metroplex core-to-all dependency and the central hub one-to-all dependency. This metric is most suitable for measuring the concentration of dependencies within a metroplex. The minimum value of this metric is 1, indicating that the metroplex is dominated by the central hub airports. The higher the value is, the less the dominance of the central hub. The high value would likely represent the existence of multiple major hub airport operations in the metroplex. The results of calculation of this metric for the four metroplex sites studied are shown in Figure 13.

As seen from Figure 13, while there exist a clustering of N90 and SCT, and one of MIA and A80, there are differences within the clusters. For example, as shown in Table 15, MIA has a higher one-to-all dependency than ATL; if the one-to-all dependencies were the same, the difference between MIA and A80 could have been higher than indicated by the figure because MIA has two major hub airports, while ATL is the only hub airport in Atlanta.

5.3.3 Summary

By utilizing basic geographic information about metroplex airports, several metrics were developed to measure the intrinsic dependencies within each metroplex. The pairwise airport dependency metric is the basis on which other metrics were built. The one-to-all dependency is most suitable for measuring dependencies between a major hub and other airports within a metroplex. The core-to-all dependency is most suitable for measuring the total level of dependencies within a metroplex. The metroplex dependency ratio metric is most suitable for measuring the concentration of dependencies within a metroplex. An interesting observation is that, for these four metrics, the consistent order of increasing metrics indicates A80 < MIA < SCT < N90. Among the four metroplexes, N90 is the most complex.

5.4 Metroplex Clustering Analysis

Two valid questions for any study of metroplexes and their inherent dependencies is which airports, given their traffic levels, form a metroplex and where are the locations of the metroplexes in the NAS. To attempt to answer these two questions, a new numerical metric of metroplex dependency was defined based on studying unrestricted arrival trajectories. This metric was then used as the distance measurement for a clustering analysis to identify metroplexes in the NAS with current and future traffic levels at each airport.

5.4.1 Dependency Metric for Clustering Analysis

A numerical metric is desirable for understanding the growth of each metroplex, determining when future traffic levels dictate that an airport rises to join a nearby metroplex, and studying the creation of new metroplexes as traffic increases.

The notion of this metric is that each airport has an unrestricted arrival airspace (volume) surrounding it, and if the arrival airspace of two neighboring airports overlaps, aircraft flying through this shared space would cause interaction. This interaction is a measure of the added complexity required to properly separate traffic from the interacting neighboring airport. This pairwise complexity could typically be mitigated through procedure design, airspace design, scheduling and coordination, or any other method used to reduce airspace complexity. The metric presented here (a more detailed description can be found in [MC09]) attempts to capture such interaction.

Before considering how much one airport will affect its neighbor, one must first understand the unrestricted operations of an airport. Ideally, arrivals would follow a most direct route to the runway and fly most economical vertical and speed profiles—on which the engine power would remain idle until the aircraft is established on the final approach. To provide a more precise approximation to the arrival space, the aircraft trajectory simulation functionality of the Tool for Analysis of Separation and Throughput (TASAT) [RC08] was used to generate 4-D trajectories for several aircraft types, arriving from each degree of direction at the top of decent to the runway threshold. The trajectories were generated using 360 unrestricted continuous-descent arrivals (CDAs), one for each degree of arrival direction. Each lateral track was defined by three waypoints:

- Entry point at top of descent
- Turn onto final (10 nm from runway threshold)
- Runway threshold

These flightpaths were used to define the required airspace of “optimal” arrival into an independent airport. An example of these flightpaths for several aircraft types, including a B737-800, B747-400, and B757-200, is given in Figure 14. This figure depicts an arrival airspace that approximates a cone. This cone was used to represent the area of arrivals for a truly independent airport with unrestricted operations.

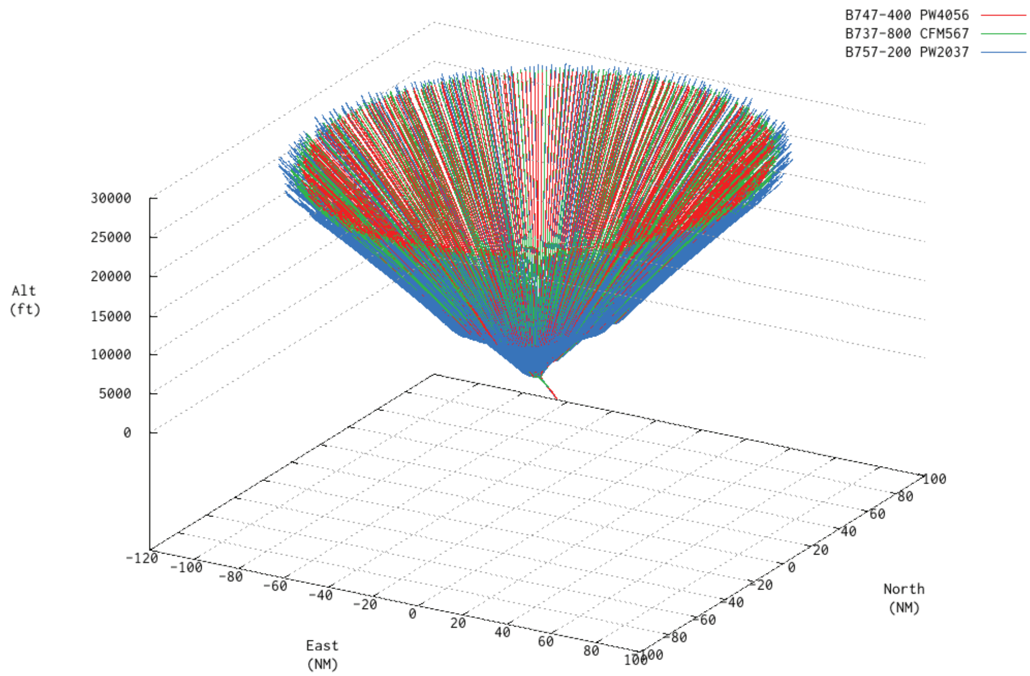


Figure 14. Flightpaths defining arrival cone.

Finding the interaction between optimal arrivals at different airports is a slightly more complicated matter. Here the maximum altitude and minimum altitude CDA flightpaths were used to define a cone with thickness. Two of these cones were overlaid on two separate airports respectively. For the sake of discussion, these airports are referred to as $airport_i$ and $airport_j$. The volume of $cone_i$ that lies in $cone_j$ is used as the measure of the interaction. To calculate the volume of intersection for $airport_i$, the volume of the $cone_i$ shell that lies within the convex hull of the truncated $cone_j$ was integrated. This volume represents the space that, if an aircraft was descending through this space into $airport_i$, would require some effort to keep it deconflicted from any aircraft arriving into $airport_j$. This effort is not necessarily the effort required by an air traffic controller, but could also be the work required to develop spatially deconflicted STARs, or even the cost in implementing an advanced time-based metering system.

To account for the amount of traffic that actually has to deconflicted, the annual traffic volume from the 2008 TAF [TAF08] database as provided by the FAA was used. The pairwise interdependency metric can then be defined as:

$$metric_{i,j} = \frac{volume_i \cdot volume_j \cdot traffic_i \cdot traffic_j}{fullvolume^2}$$

Where:

- $volume_i$ is the volume of integration of $cone_i$ in $cone_j$.

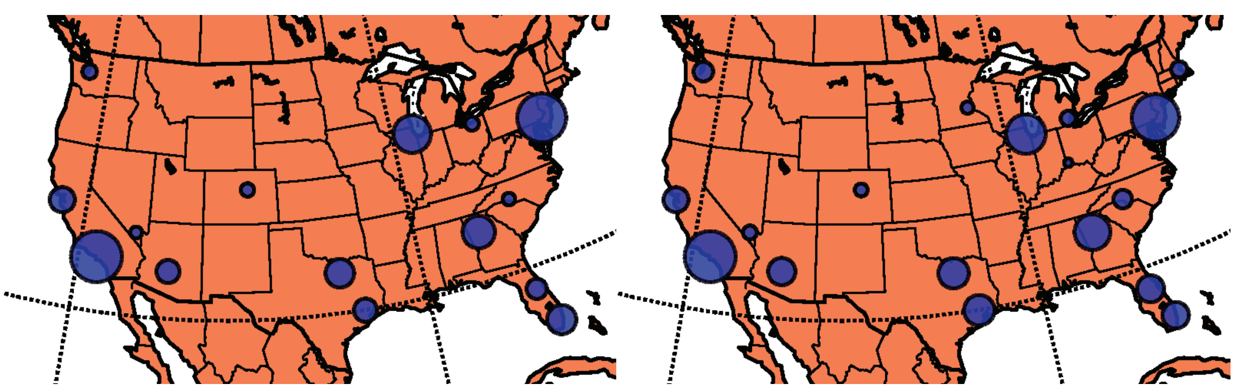
- $volume_j$ is the volume of integration of $cone_j$ in $cone_i$.
- $traffic_i$ is the annual number of operations at $airport_i$ from the TAF database.
- $traffic_j$ is the annual number of operations at $airport_j$ from the TAF database.
- *Fullvolume* is the full volume of the cone used for normalization.

5.4.2 Identifying Metroplexes in the NAS

Once the metric was defined, values of it were calculated for all airports included in the TAF database. These values were then used in a clustering analysis to determine which airports should be clustered into metroplexes. For this clustering analysis, a Quality Threshold clustering algorithm [HKY99] was used. To tune the threshold value, the number of metroplexes was selected to be 15, to match as best as possible the 15 metropolitan areas listed in Table 1.

Example results for the calibration with 2008 data are shown in Figure 15(a). This figure depicts the 15 "metroplexes" as defined by our clustering algorithm. The relative sizes of the points relate to the relative strengths of the total interaction for each metroplex. Notably, the Los Angeles Metroplex and the San Diego Metroplex were identified as a single metroplex by this algorithm; and the New York City Metroplex, the Philadelphia Metroplex, and the Washington, D.C. Metroplex were also identified as a single metroplex. The Minneapolis Metroplex was not identified as a metroplex. Denver, Dallas-Fort Worth, Orlando, and Cleveland were identified as additional metroplexes. The discrepancies came from the fact that the FAA 15 OEP metroplexes were identified based on future capacity needs.

Figure 15(b) shows the metroplexes identified using the projected TAF data for 2025. Using the same threshold, as was determined from tuning with the 15 metroplexes for 2008, resulted in a total of 18 metroplexes with this dataset. The differences between Figure 15 (a) and (b) include growth in most metroplexes identified for current traffic level, and three newly identified metroplexes: Minneapolis, Boston, and Cincinnati. For further results and analysis, please see the separate report [MC09] (abstract cited in B.3.2).



(a) (b)

Figure 15. Location of metroplex clusters—current and future.

6.0 FRAMEWORK FOR EVALUATING METROPLEX OPERATIONAL CONCEPTS

With the knowledge achieved so far, this section sets up a framework for evaluating metroplex operational concepts. The observed practices to handle traffic interdependencies and traffic coordination were abstracted into a temporal-spatial displacement concept. Existing Next-Generation Air Transportation System (NextGen) concepts were carefully reviewed and compared against the temporal-spatial concept to identify the most relevant concepts, along with new concepts proposed to close any gaps in metroplex operations. The experiment strategy was developed to test the end effects of various concepts studied in lieu of modeling any specific concepts. Spatial and control parameters were then discussed. It was determined that a Generic Metroplex experiment was to be employed to test various combinations of control parameters to identify the most promising concepts and capabilities for metroplex operations. Selected concepts were to be tested using an Airport and Airspace Delay Simulation Model (SIMMOD) N90 model to verify the effectiveness of those concepts in a specific metroplex environment. Traffic coordination techniques, used in both the Generic Metroplex and N90 Metroplex experiments, are also discussed in this section.

6.1 Temporal-Spatial Displacement Concept

From studying four metroplexes that span the range of airspace design geometries and traffic-flow interactions seen in the National Airspace System (NAS), it was observed that there is no one specific metroplex solution strategy that is employed exactly the same at all of the metroplexes. There are significant differences in the way the traffic flows are handled to deal with metroplex traffic dependencies. For example, when the proximity of airports causes interactions between traffic flows to and from different airports, traffic flows may be laterally segregated at one location, e.g., the segregation of FLL and MIA flows in the MIA Terminal Radar Approach Control Facilities (TRACON), while traffic flows at another location may involve traffic at one airport being stopped or requiring prior approval before being released for departure, e.g., departures from LGA and EWR merging over the ELIOT fix in N90. However, there are also some similarities in the way air traffic controllers handle traffic. For example, flights from major or dominant hub airports are frequently given priority, allowing them to operate unrestricted arrivals and departures while traffic at nearby airports is either routed around the traffic to/from the priority airports or is restricted at departure time such that it fits in the gaps within the flow to/from the priority airports.

In section 5.2, the observed airspace interactions are abstracted into six distinct categories. The goal of air traffic control (ATC) in these categories, and in the case of restrictions at departure times, is to spatially separate aircraft at any given time so that limited resources can be shared by different traffic flows. Metroplex airspace interdependencies and control actions are based on traffic flows, so they are limited to four dimensions: three space dimensions and one time dimension. At the most abstract level, the strategies and tactics employed at the different metroplexes in response to dependencies involve either spatial or temporal displacement from ideal four-dimensional trajectories (4DTs): routing, vertical profiles, desired departure time, or desired speed profiles. Traffic is separated by one or both of the two methods. The traffic can be deconflicted by stretching paths of some or all flights so that different traffic flows will traverse different volumes of airspace separated *spatially* per the minimum separation requirement, as shown in Figure 16. Alternatively, traffic can be deconflicted by regulating the time of some or all flights so that different flights will traverse the same volume of airspace, or a given point, at different *times* separated by a certain minima. Three examples of temporal control methods are shown in Figure 17, including holding, acceleration, and deceleration. The spatial separation in the former option and the temporal separation in the latter can be employed to achieve similar effects because an equivalent separation exists in terms of either distance or time.

The properties of the spatial displacement strategy and the temporal displacement strategy are summarized as:

- Spatial displacements
    - Deviations (horizontal and/or vertical) from the ideal three-dimensional (3-D) arrival and departure paths that serve to de-conflict traffic flows; flows are spatially separated
    - ***Pros***: Easy to handle temporal uncertainty
    - ***Cons***: May be subject to airspace limitations and spatial uncertainty
- Temporal displacements
    - Deviations (air/ground holding or speed adjustment) from the preferred time profile that serve to de-conflict traffic flows that traverse a common volume of airspace for a finite period; flows are temporally separated
    - ***Pros***: Simpler airspace structure and use of less airspace
    - ***Cons***: May be subject to time limitations and temporal uncertainty

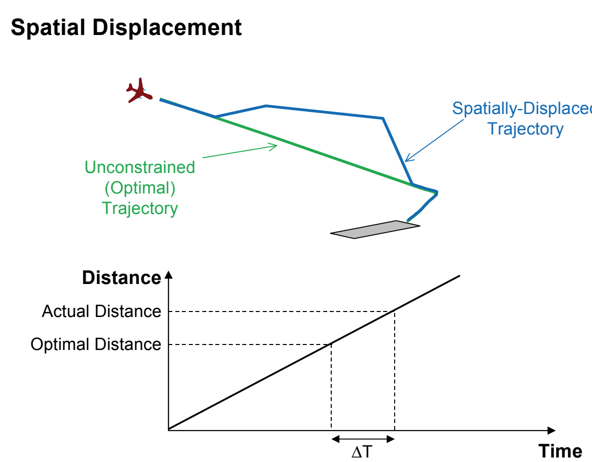


Figure 16. Total displacement due to spatial de-confliction.

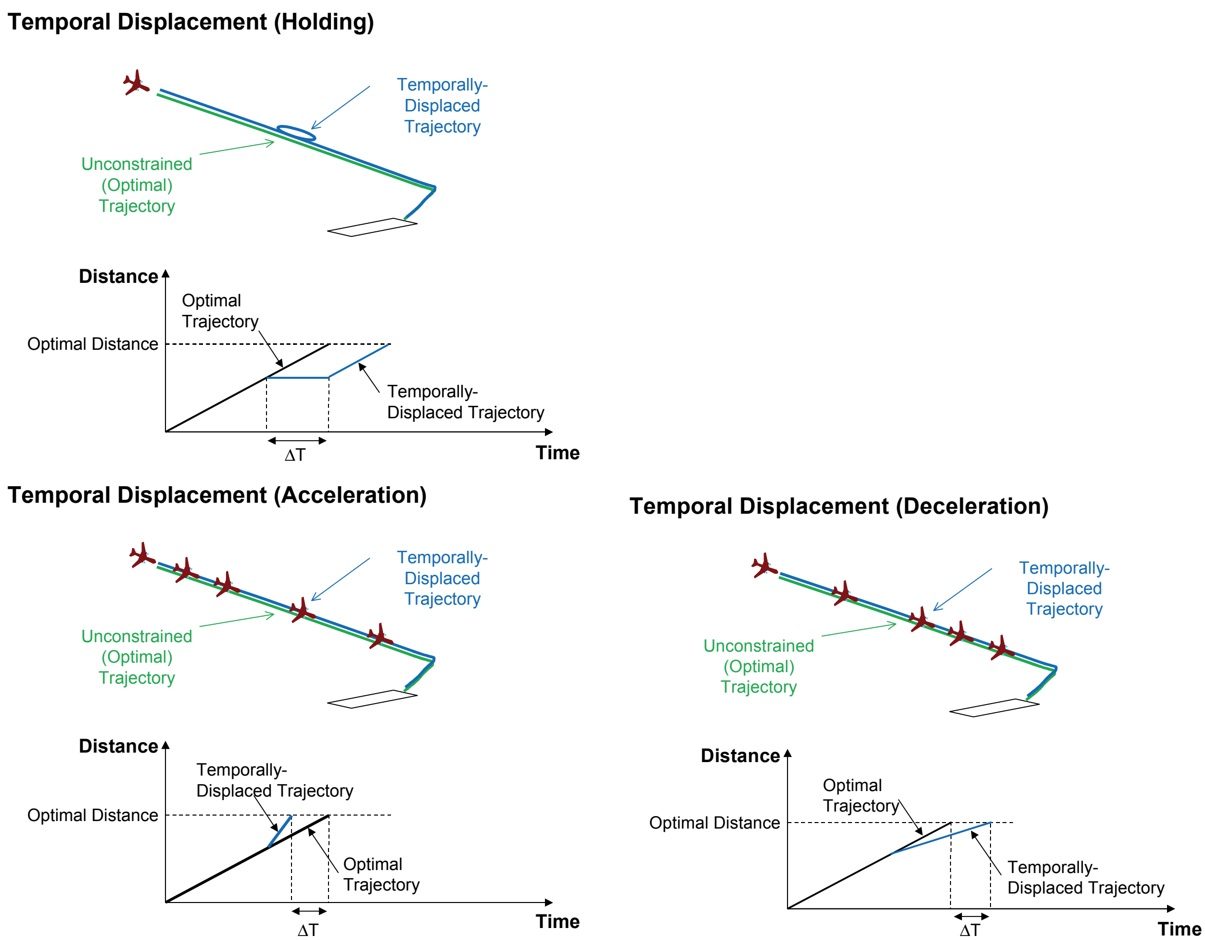


Figure 17. Total displacement due to temporal de-confliction.

Control actions for a given flight or traffic flow may include one or both types of displacements to achieve a total displacement that can be expressed in terms of time:

$$\Delta T_{total} = \Delta T_{spatial} + \Delta T_{temporal} = (\Delta T_{lateral} + \Delta T_{vertical}) + (\Delta T_{holding} + \Delta T_{speed})$$

or in terms of a generic energy metric:

$$\Delta E_{total} = \Delta E_{spatial} + \Delta E_{temporal} = (\Delta E_{lateral} + \Delta E_{vertical}) + (\Delta E_{holding} + \Delta E_{speed})$$

The two abstracted displacement strategies and the six interaction categories from section 5.2 provide bases for a framework for analyzing the impact of new NextGen technologies on metroplex operations. In current-day operations, significant spatial and temporal inefficiency exists because of a lack of coordination between facilities, a lack of well-defined flightpaths, and the significant amount of temporal uncertainties. The optimal solution to the metroplex problem would be one that satisfies the required total time displacement while minimizing the energy metric. The required time displacement itself is influenced by many factors, such as: *runway geometry*, *airspace geometry*, *separation standards*, *traffic demand* as a function of time, and *operating condition* and *constraints* (weather, airspace, environmental, and uncertainties). Given these factors, the energy metric is influenced by the *trade-off* between spatial displacement and temporal displacement, and the specific design and performance of each of the two control strategies. Searching for the optimal solution would require employing concepts that would, first, minimally satisfy the required displacements, and then minimize the energy metric for the required displacement.

6.2 NextGen and Team-Proposed Concepts and Their Implications

As described in the previous section, the nature of the metroplex problem results in significant spatial and temporal inefficiencies for flights into and out of proximate airports with coupled air traffic flows. What is the best way to alleviate these spatial and temporal inefficiencies, given a particular set of feasible technologies and procedures? The answer remains to be discovered, but a common way to express one or more solutions is in the form of new "metroplex concepts". These concepts can be specifically focused on alleviating metroplex inefficiencies, or can have an indirect impact on metroplex inefficiencies. The research investigated both types of concepts. "True" metroplex concepts specifically focus on directly alleviating multi-airport inefficiencies, and are discussed in the following section. Specific quantitative metroplex assessments are discussed in sections 7 and 8. "Incidental" metroplex concepts are NextGen concepts that affect metroplex inefficiencies, but are not specifically targeted to alleviate the multi-airport traffic-flow dependencies. A qualitative analysis of their impacts was performed.

6.2.1 "True" Metroplex Concepts

Over the course of this project, the evolution of the Joint Planning and Development Office's (JPDO's) NextGen Concept of Operations (ConOps) [JPDO07] was followed, in pursuit of any new NextGen "true" metroplex concepts proposed by the JPDO community. The JPDO NextGen ConOps defines the term metroplex, but it does not identify future concepts to mitigate metroplex dependencies. The only explicit reference to a metroplex is for flow contingency management (FCM) to address "multiple types of constraints, including airspace, airport, and metroplex constraints". Investigation into the JPDO's Integrated Work Plan [JPDO08a, JPDO08b] revealed that the JPDO has added metroplex-related NextGen concepts as two major Operational Improvements: "Efficient Metroplex Merging and Spacing", to be operational in 2018, and "Integrated Arrival/Departure and Surface Traffic Management for Metroplex," to be operational in 2022.

The *Efficient Metroplex Merging and Spacing* concept focuses on using airborne merging and spacing and improved Air Navigation Service Provider (ANSP) capability and procedures to allow greater traffic throughput and reduced ANSP workload in terminal areas by reducing spacing buffers between traffic streams approaching and departing multiple metroplex runways. These capabilities are similar to the airborne merging and spacing capability described in [BAK04].

The *Integrated Arrival/Departure and Surface Traffic Management for Metroplex* (IADSTMM) concept supports efficient metroplex traffic-flow planning and execution through new procedures, metroplex airspace planning, and traffic-flow-management (TFM) automation, as well as trajectory management automation for real-time management of all aircraft 4-D trajectories for the ANSP. This concept also supports "better-equipped, better-served" air-traffic-management (ATM) preferences and is a step towards gate-to-gate 4-D trajectory management. These capabilities are similar to the Integrated Metroplex Planning and Control concept described in [V06], and the Integrated Metroplex Departure Planner described in [SS08] and [SS09a].

As a result of successful operational introduction, these two JPDO metroplex concepts could serve to mitigate metroplex issues identified in Table 11, including:

- Multi-airport departure merge over common departure fix
- Major volume-based TFM restrictions
- Inefficient/high workload airport configuration changes
- Inefficient inter-airport departure sequencing
- Major secondary airport flow constraints
- Inefficient "flushing" of airport flows
- Insufficient regional capacity

The Georgia Institute of Technology (GaTech) team took some time to further flesh out the details of the IADSTMM concept. A similar concept was independently formulated in team discussions and it was concluded that the automated, multipoint scheduling and 4-D trajectory-based traffic-management approach had significant merit in terms of potential reduction in current-day metroplex inefficiencies. The core scheduling element of such a concept is shown in Figure 18. This concept provides automated generation of optimal schedules for arrivals, departures, and surface movements throughout the metroplex airspace and multiple airport surfaces. The next section describes the IADSTMM concept, followed by brief mention of other concepts that the GaTech team brainstormed.

Integrated Arrival/Departure and Surface Traffic Management for Metroplex (IADSTMM) Concept

In a metroplex environment, multiple proximate airports compete for the concurrent usage of shared airspace resources like common points (e.g., arrival fixes, departure fixes, other merge points), common routes (e.g., standard terminal arrival routes (STARs), standard instrument departures (SIDs)), or common volumes (e.g., arrival corridors). ANSP responses to such cross-airport interactions encompass the entire spectrum from pure temporal separation to pure spatial separation. With pure temporal separation, the ANSP controls the times at which aircraft enter the terminal-radar-approach-control (TRACON) airspace or times at which aircraft cross certain points in the airspace; with pure spatial separation, the ANSP keeps traffic flows to multiple interacting airports from conflicting by separating them in altitude or in the lateral dimension. The IADSTMM concept is on the pure temporal separation end of this spectrum of responses.

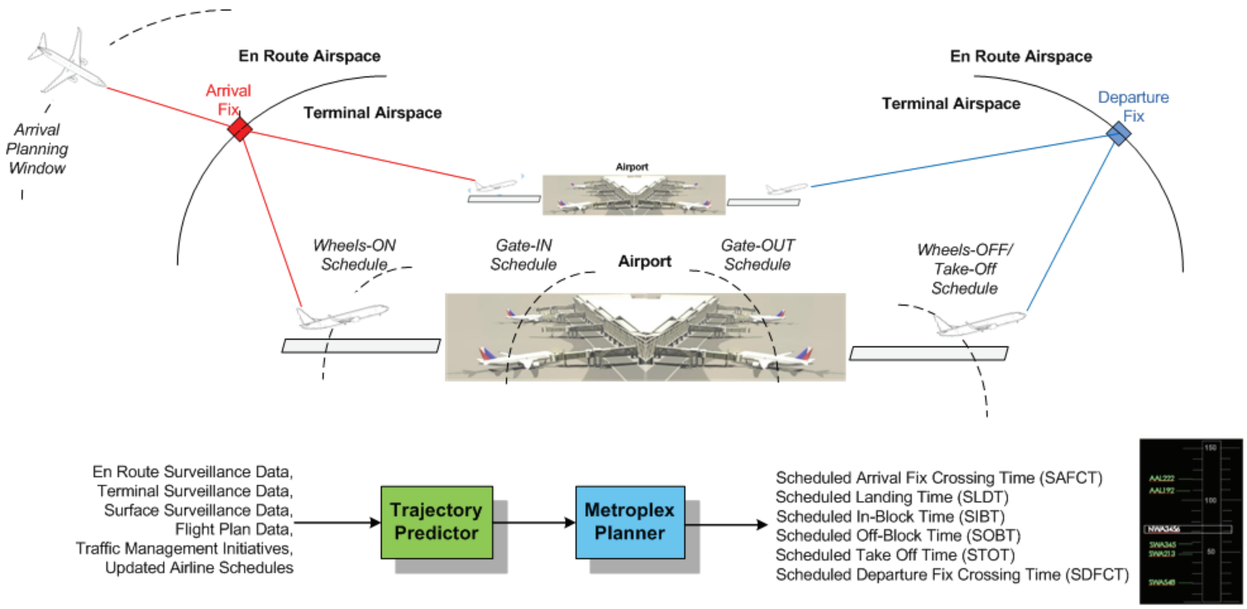


Figure 18. The Integrated Arrival/Departure and Surface Traffic Management for Metroplex (IADSTMM).

A decision support tool that will enable the ANSP to temporally separate interacting traffic flows originating from/going to multiple metroplex airports is needed to enable safe and efficient traffic flows in the NextGen metroplex environment. With such a tool available to the ANSP, flights from individual airports will be able to fly their most efficient arrival/departure routes, with the ANSP providing temporal controls to keep flights safely separated.

The GaTech team proposes a similar temporal separation tool for allocation of shared airspace resources, and airport resources like runways and gates. Each user (a metroplex airport in this case) would be allowed to share the resource by allocating a time slot to it. Each resource will have a dynamically computed schedule of usage, which shall be computed by optimizing over traffic coming from all metroplex airports. For example, in the case of New York Metroplex, the busiest departure fix—ELIOT—is commonly shared among LGA, EWR, and TEB departures. The proposed temporal scheduler would compute an optimized departure fix-crossing schedule for all flights expected to take off from all three airports within some look-ahead time (LAT) window.

TRACON controllers use the IADSTMM decision support tool to meter traffic crossing the boundary fixes to balance the arrival/departure demand across multiple boundary fixes, multiple TRACON sectors, and multiple metroplex airport runways, and to handle merging and crossing traffic by utilizing the tool-provided target fix-crossing times. Airport ground controllers also use the tool as guidance for building the sequence of departures so that the departure traffic load is balanced across all TRACON departure sectors and departure fixes. The tool can simplify the job of airport local controllers by delivering a sufficiently spaced and order-optimized sequence of aircraft on final approach.

The IADSTMM tool is a decision support tool for TRACON and air-traffic-control-tower (ATCT) controllers. The tool re-plans periodically with a certain LAT window. For example, it can be configured to re-plan every 5 minutes with a LAT window of 30 minutes. At the beginning of each re-plan cycle the tool takes in the following data as input:

- Estimated pushback, spot-out, takeoff times, and departure fix-crossing times for all departure flights expected to take off from airports in the metroplex within the LAT window
- Estimated arrival–fix-crossing times, landing times, and spot-in and gate-in times for all arrival flights expected to cross any arrival fix on the metroplex boundary within the LAT window
- Estimated merge-point/crossing-point crossing times for all merging or crossing traffic expected to be in the metroplex airspace within the LAT window

The IADSTMM tool then computes the time-access schedule for each shared metroplex resource—arrival/departure fix, merge point/crossing point, runway, shared airspace corridor—by using an optimization-based scheduling algorithm. The optimized deconflicted crossing times/landing times/takeoff times are sent back to the controllers. The controllers use these times as guidance for metering and routing the traffic within their spheres of control.

The IADSTMM temporal separation tool maximizes metroplex throughput and decreases controller workload by assisting:

- Ramp controllers at individual metroplex airports in figuring out the correct departure sequence by providing target pushback times for flights
- Ground controllers at individual metroplex airports in figuring out the correct departure sequence by providing target takeoff times for flights and spot release times
- Local controllers at individual metroplex airports by delivering aircraft with just enough separation (i.e., separation as close as possible to the minimum required spacing) on the final approach
- TRACON arrival and departure controllers by providing target meter-fix-crossing times for arrival and departure flights
- TRACON arrival and departure controllers in properly handling merging and crossing traffic within the metroplex by providing target intermediate-fix-crossing times, target landing/takeoff times, etc., and by de-conflicting traffic at the merge/cross points
- The air-route-traffic-control-center (ARTCC) controllers in providing arrival–fix-crossing time sequences and crossing times that support maximum metroplex throughput but are sensitive to dynamic metroplex constraints

A nominal IADSTMM architecture is shown in Figure 19. As a result of the successful implementation of this concept:

- Improved flow management in the metroplex can reduce delays for aircraft that arrive into major hub airports during heavy rush periods as well as reduce the standard deviation of TRACON transit times, thereby increasing the predictability of aircraft operations. Improved fuel efficiency also results from the reduced delays.

- The IADSTMM tool can reduce controller workload by providing the controllers with deconflicted target fix-crossing times and target landing or takeoff times. Also, improved flow management will enable more efficient utilization of metroplex resources (boundary fixes, runways, terminal routes) during rush periods, resulting in increased throughput, as well as increased Traffic Management Initiative compliance.

The implementation of an IADSTMM in its full four-dimensional trajectory (4-DT) multipoint scheduling capability provides an opportunity for future NextGen metroplex automation to alleviate both spatial and temporal metroplex inefficiencies. The beneficial impact of the IADSTMM concept depends the temporal and spatial accuracy and uncertainties inherent in the underlying traffic flows, as well as the fundamental metroplex geographical and air traffic demand constraints. Therefore, a parametric analysis of the potential benefits of the IADSTMM concept for a "generic airspace" was conducted, and is detailed in section 7 of this report.

In addition, some other potential metroplex decision support tool features could be added to IADSTMM, as suggested in Figure 20. These features include Metroplex Airspace Capacity Management, Metroplex Airport Capacity Management, and Metroplex Trajectory Management in addition to the nominal, multipoint scheduling inherent in the Metroplex Flow Contingency Management.

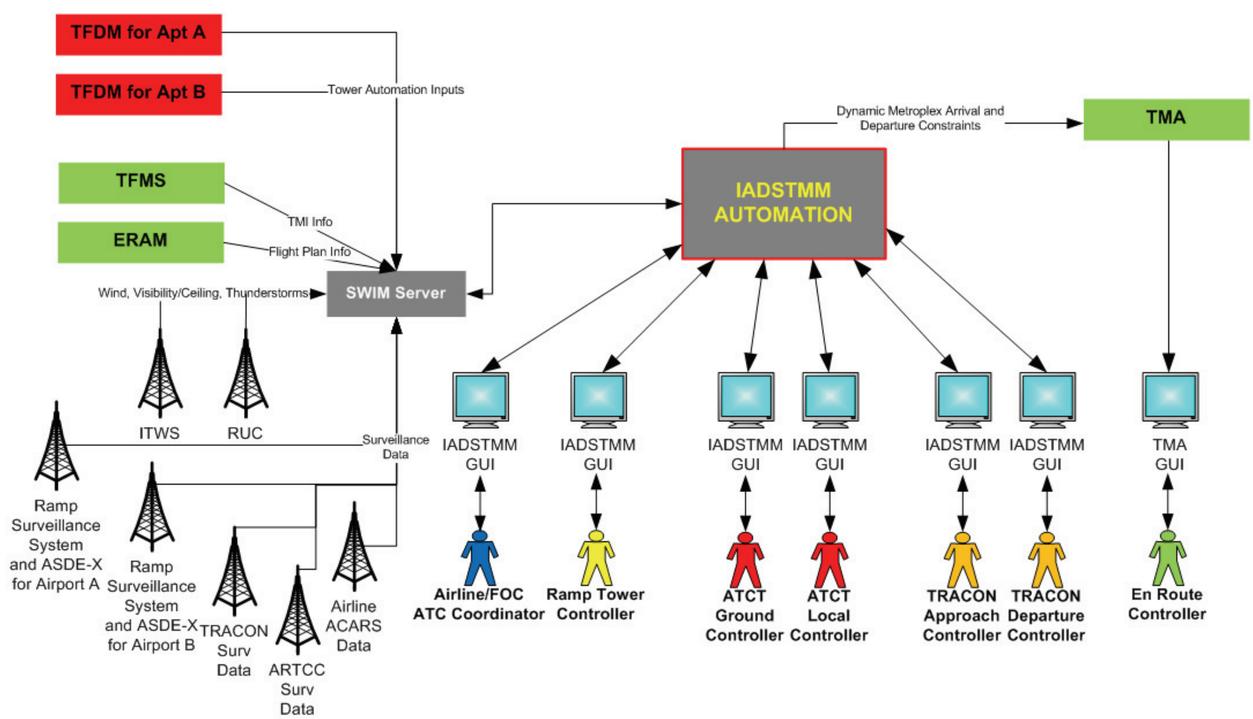


Figure 19. Nominal IADSTMM architecture.

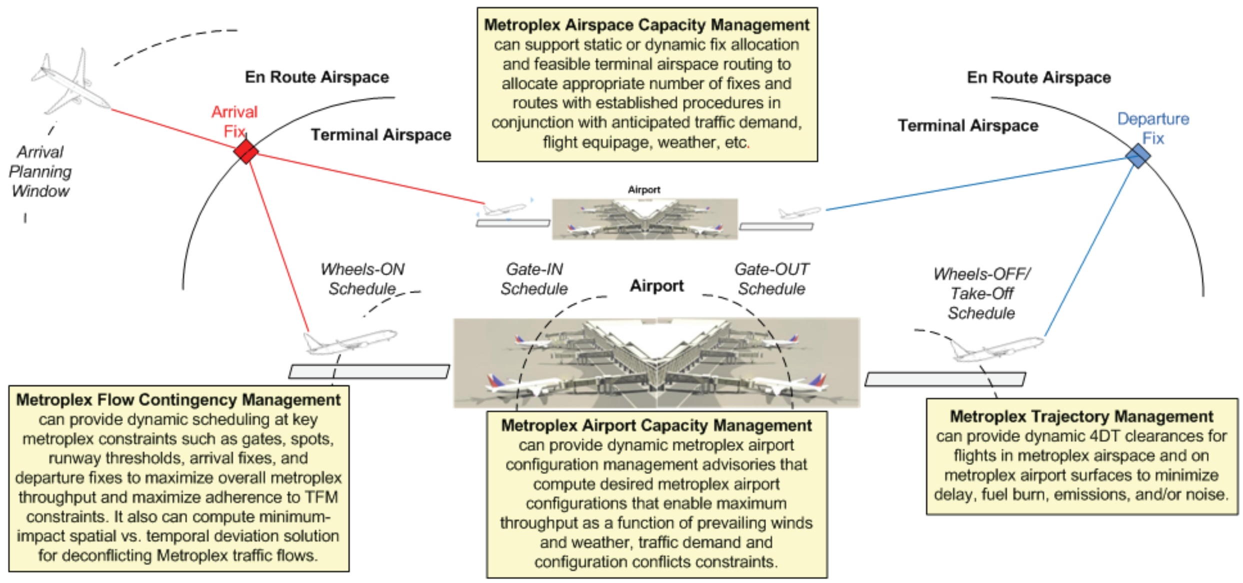


Figure 20. Additional integrated metroplex features for the IADSTMM.

Expected Impact of JPDO "True" Metroplex Concepts

It is believed that both of the JPDO-derived "true" metroplex concepts would reduce metroplex temporal and spatial inefficiencies. Temporal inefficiency involves queueing delays due to metroplex interdependencies and associated uncertainties. Spatial inefficiency involves aircraft separation via routing and altitude restrictions. The expected impacts of the two JPDO metroplex concepts are shown in Table 16.

Efficient metroplex merging and spacing are enabled by using more flexible aircraft trajectories along with tighter inter-aircraft spacing, and thus are expected to have both temporal and spatial impacts. The Integrated Arrival/Departure and Surface Traffic Management for Metroplex concept builds on metroplex-wide scheduling and 4-DT trajectory-based airborne and surface operations, so it also has both temporal and spatial impact.

TABLE 16. IMPACT OF JPDO NEXTGEN "TRUE" METROPLEX CONCEPTS ON METROPLEX INEFFICIENCIES

#	NextGen Concept	Spatial Impact	Temporal Impact
M1	Efficient metroplex merging and spacing	Improved routing and airspace footprint	Reduced variation in inter-arrival time
M2	Integrated arrival/departure surface traffic management for metroplex	Integration of trajectory, separation, and capacity functions enables full situation awareness and efficient collaboration to balance demand and maximize runway and airspace use, allowing for both spatial and temporal impacts.	

Other Metroplex Concepts

During the project, based on specific knowledge gained during the site visits (especially the New York Metroplex visits), the GaTech team brainstormed other concepts to alleviate the metroplex inefficiences. These concepts are listed in appendix A.

Expected Impact of Team-Proposed "True" Metroplex Concepts

In addition to the "true" metroplex concepts defined in the JPDO NextGen ConOps, the research team examined other new concepts leveraging future capabilities to mitigate identified metroplex issues. An analysis was conducted on the impact of each of the new concepts on metroplex temporal and spatial inefficiencies. These results are listed in Table 17. These capabilities would support increased, more efficient, and more environmentally sensitive utilization of existing metroplex runways and airspace for current and future aircraft.

6.2.2 "Incidental" Metroplex Concepts

"Incidental" metroplex concepts are NextGen concepts (or basic metroplex infrastructure improvements) that affect metroplex inefficiencies, but are not specifically targeted to alleviate multi-airport traffic-flow dependencies. A set of these candidate "incidental" metroplex concepts was identified, and a qualitative analysis of their impacts was conducted.

First, the JPDO Integrated Work Plan (IWP) [JPDO08a, JPDO08b] was analyzed to identify a broad set of representative NextGen concepts, and to postulate their reductions on metroplex temporal and spatial inefficiencies. The identified candidate concepts are shown in Table 18. All of the concepts are expected to mitigate temporal and/or spatial metroplex trajectory inefficiencies.

6.3 Experiment Strategies

As seen in section 6.2, there are many new concepts that could contribute to improving metroplex operations. From a temporal-spatial displacement point of view, a given type of displacement (as defined in section 6.1) can be achieved by one or more metroplex concepts, although potentially through different mechanisms. Assessments to evaluate each metroplex concept would be very time-consuming, and would generate redundant results, yet key driving factors influencing system performance could be buried in repeated information. As such, the experiments were developed around the abstracted impact of concepts, not around the details of implementations of individual concepts. The impact of baseline operations and future metroplex concepts was represented as a set of variables, each spanning a range of values reflecting the advancement of technology from the current state to that in a future NextGen time frame.

TABLE 17. IMPACT OF TEAM-PROPOSED "TRUE" METROPLEX CONCEPTS ON METROPLEX INEFFICIENCIES

#	New Concept	Spatial Impact	Temporal Impact
N1	Optimized profile 4-D RNP arrival	RNP lateral path and vertical profile reduces airspace occupied	More predictable flight time
N2	Optimized profile 4-D RNP departure	RNP lateral path and vertical profile reduces airspace occupied	More predictable flight time
N3	Closely spaced arrival and departure gates	Enables lateral spacing of traffic when traversing through airspace previously permitting only one stream	Lateral path may be shortened
N4	Vertically stacked arrival departure gates	Enables vertical spacing of traffic when passing through the same geographic location	Lateral path may be shortened
N5	Optimized multi-airport departure sequencing and scheduling	No impact	Reduced time uncertainty and delay
N6	Dynamic transition routing and dynamic anchor points (multiple fixes per anchor point)	Different routes may be selected to spatially separate traffic based on real-time traffic conditions	Different routes may be selected for different flights to achieve metering within the terminal area
N7	Integrated TRACON/Center airspace redesign	Improves transition of traffic between TRACON and Center airspace. Aircraft trajectory least constrained by airspace delegation (impacts both)	
N8	Integrated metroplex network (air/ground connection between airports and traffic allocation among metroplex airports)	Traffic allocation at different metroplex airports significantly affects metroplex operations. It influences the actual separation minima used at each airport, and narrows the fleet mix for flights to and from a given airport or runway (impacts both).	
N9	Environmental management for operations	Environmental Management System (EMS) impacts the tactical and strategic operation of the metroplex. It will interface with other decision-support and planning tools supporting metroplex operations. It significantly affects routings and arrival/departure profiles (impacts both).	
N10	Metroplex runway configuration planner	Optimized configuration selection among airports; enables effective change of traffic flows during runway configuration change	Enables runway configuration change at optimal time to reduce delay

TABLE 18. IMPACT OF JPDO NEXTGEN "INCIDENTAL" METROPLEX CONCEPTS ON METROPLEX INEFFICIENCIES

#	NextGen Concept	Spatial Impact	Temporal Impact
C1	Cockpit-based all weather merging and spacing (CAVS)	Routing and final approach fix changes	Reduced aircraft spacing
C2	Continuous-descent arrival (CDA)	Continuous vertical profile	Higher average speed
C3	Independent parallel (2500–4300 ft) or converging approach	No impact	Reduced aircraft spacing
C4	Time-based metering	More efficient routing based on precise crossings	Reduced longitudinal spacing
C5	En-route traffic optimization	More efficient conflict resolution and closer to optimal altitudes	Reduced time because of optimized arrival sequencing
C6	Stochastic traffic-flow management	Alternative routing strategies	Reduced variation in arrival time
C7	Surface traffic optimization	Changed fix-to-runway assignments and rerouting	Reduced taxi time and departure time variation; improved airport reconfigurations
C8	Wake vortex avoidance	Minimal, modest impact on approach procedure routing	Reduced longitudinal spacing, and improved arrival-departure coordination
C9	Very closely spaced (750–2500 ft) parallel runway operations	Minimal, modest impact on approach procedure routing	Reduced longitudinal spacing

As discussed in section 6.1, system performance is influenced by many exogenous factors such as: runway geometry, airspace geometry, separation standards, traffic demand as a function of time, and operating conditions; constraints including weather, airspace, environmental, and uncertainties; and design parameters directly targeted to improve metroplex operations. Thus a two-pronged set of metroplex concept impact analyses was chosen. The first method was to conduct a quantitative parametric analysis of a Generic Metroplex that can be configured to span the range of geometries within the NAS to provide broadly applicable results. The second method was to conduct a quantitative analysis of a specific metroplex. As a result of previous studies and the site-survey and quantitative metrics analyses, the N90 Metroplex was selected as the site for the specific analysis. It is the most complex metroplex, and therefore, the one with the greatest expectation of potential metroplex concept benefits.

In the Generic Metroplex parametric analysis, the intention was to vary each parameter to span all the NextGen technologies as well as technologies that have been conceptualized by the metroplex team. In the specific N90 study, only those technologies that are indicated through the Generic Metroplex parametric study to be beneficial to N90 were studied.

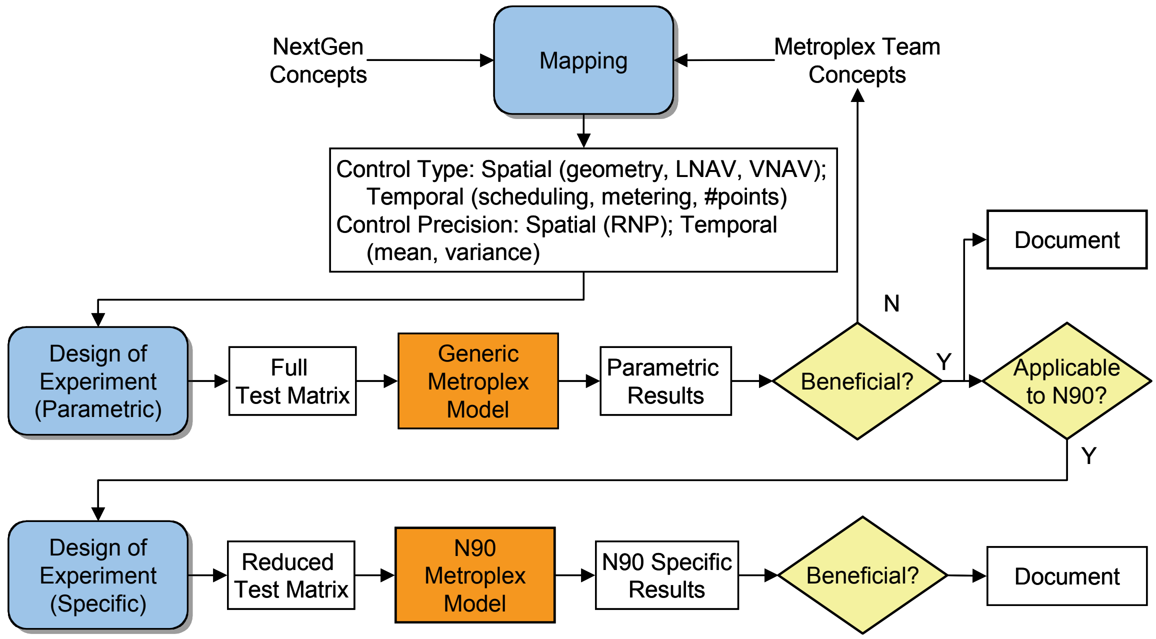


Figure 21. Metroplex experiment strategy.

As shown in the experiment strategy in Figure 21, all concepts are mapped to parameters that represent control types and control precision. As discussed earlier, there are two types of controls: spatial and temporal. Spatial control includes airspace geometry design and operational procedures employing lateral navigation (LNAV) and verical navigation (VNAV). Temporal control includes scheduling and coordination of arrivals and departures, metering of traffic into a given airspace volume, and the location and number of metering points. The spatial control accuracy can be presented by required-navigation-performance (RNP) values, both lateral and vertical (in the NextGen time frame), and their associated separation standards. The temporal control accuracy can be presented by metering accuracy in terms of the bias of the mean and variance of the arrival time relative to the ideal arrival time.

Control parameters were prioritized and cross-checked for compatibility and consistency to reduce the number of test cases that had to be executed. A full test matrix was developed for the Generic Metroplex assessment to span a wide range of parameter space to identify the most promising design points. The N90 assessment then focused on the reduced test matrix that analyzed only the identified design points that were identified as potentially suitable for improving N90 operations.

The experiments focused on operations under visual meterological conditions (VMC) because in the NextGen time frame, improved capabilities will enable VMC-type operations under today's instrument meterological conditions (IMC). Because of time and resource limitations, special weather conditions such as convection were deferred to future studies. Based on similar considerations, terrain and special-use airspace (SUA) were not considered in the current study.

6.4 Spatial Design and Control Parameters

Spatial design and control parameters fall into two basic categories:

- The spatial uncertainty/containment and minimum safe separation between aircraft and between aircraft and obstructions
- The geometric layout of the airspace, nominal procedure routes, and vertical profiles

The definition of the former category is driven by safety requirements; the definition of the latter is driven by capacity and efficiency needs, while satisfying all safety requirements.

In a traditional radio navigation environment, the spatial containment is defined using the along-track tolerance (ATT) and cross-track tolerance (XTT) [FAA-H-8261-1A]. For obstacle protection, the primary area width is 2 × XTT. RNP is a statement of the navigation performance necessary for operation within a defined airspace. With this concept, the lateral performance requirement associated with a given procedure is specified in terms of RNP values given in nautical miles. The required performance is obtained through a combination of aircraft capability and the level of service provided by the corresponding navigation infrastructure. A key feature of RNP is the concept of onboard monitoring and alerting, meaning the navigation equipment is accurate enough to keep the aircraft in a specific volume of airspace, which moves along with the aircraft. RNP levels are actual distances from the centerline of the flightpath, and they must be maintained for aircraft and obstacle separation. Longitudinally, this block is centered at the true longitudinal position known to the aircraft. The aircraft is expected to remain within this block of airspace for at least 95% of the flight time. Additional airspace outside the 95% area is provided for continuity and integrity, so that the combined areas ensure aircraft containment 99.9% of the time [FAA-H-8261-1A]. The route width, or containment airspace, is defined as 2 × RNP from the route central line on both sides. The current Federal Aviation Administration (FAA) RNP approach-procedure standard RNP values [FAA JO8260.52] are shown in Table 19. The ATT and XTT values and their corresponding RNP values for FAA RNAV departure-procedures standards [FAA JO8260.44A, FAA JO8260.46C] are shown in Table 20.

TABLE 19. STANDARD RNP VALUES FOR RNP APPROACH-PROCEDURE SEGMENTS

Segment	RNP Values (nm)		
	Maximum	***Standard***	***Minimum***
Feeder	2	2	1.0
Initial	1	1	0.1
Intermediate	1	1	0.1
Final	0.5	0.3	0.1
Missed approach	1	1	0.1

TABLE 20. STANDARD RNP VALUES FOR RNAV DEPARTURE-PROCEDURE SEGMENTS

Segment	RNP or ATT/XTT Values (nm)		
	Level 1	*Level 2*	*Level 3*
	RNP 1.0	RNP 2.0	RNP 0.3
Terminal (within 30 nm DME from airport)	ATT: 0.5 XTT: 1.0	ATT: 2.0 XTT: 2.8	ATT: 0.3 XTT: 0.6 (≤ 15,000 ft)
En Route (first fix beyond 30 nm DME[a] from airport and succeeding fixes)	ATT: 0.5 XTT: 2.0	ATT: 2.0 XTT: 2.8	Not used

[a]DME is distance-measuring equipment.

The criteria of levels 1 and 2 in Table 20 are for public RNAV departure procedures. Level 2 is the standard criteria. Level 1 is applied when narrower obstacle clearance areas than level 2 are required. Level 3 criteria are for special RNAV departure procedures only.

The minimum vertical clearance that must exist between an aircraft and the highest ground obstruction within the obstacle evaluation area of instrument procedure segments is the required obstruction clearance (ROC). For RNP arrivals, the minimum ROC value for the feeder segment is 1,000 ft (2,000 ft over designated mountainous terrain); for the initial approach segment, the ROC is 1,000 ft; and for the intermediate approach segment, it is 500 ft [FAA JO8260.52, FAA JO8260.3B]. For RNAV departures, the minimum ROC value over areas not designated as mountainous is 1,000 ft, and over mountainous areas it is 2,000 ft [FAA JO8260.3B]. Special requirements are in place for final approach and initial climb when aircraft are close to the ground.

Currently there are no standards for lateral separation between simultaneous use of RNP and RNAV routes in the terminal area. A 3-nm lateral separation (5 nm beyond 40-nm distance-measuring equipment (DME) from the radar site) and 1,000-ft vertical separation are the minimum requirements. In a multiple-airport environment, for the purpose of airspace design, the minimum lateral separation between parallel tracks to the same airport is required to be 3 nm. The lateral separation requirement between tracks to adjacent airports is 4 nm, or 3 nm for high-volume traffic with dual tracks for each airport, with the 3-nm area between adjacent tracks designated as a no transgression area [FAA JO7400.2G]. When the traffic pattern associated with an airport overlaps the airspace encompassed by a standard instrument approach procedure (IAP) for an adjacent airport, the minimum vertical separation between the traffic pattern and the affected portion of the adjacent IAP is 500 ft. If heavy jets are involved, the minimum vertical separation is 1,000 ft [FAA JO7400.2G].

Given the range of options already defined in the current RNP, standard values are shown in Table 19 and Table 20; no significant change to these standards is expected in the NextGen environment. The standard 1,000-ft vertical separation and the 500-ft vertical separation between traffic pattern and IAP are also likely to remain unchanged, partially because of the size of the “heavy” category of jet aircraft, and partially because of the wake vortex separation requirements. However, the application of these standards, especially the smaller RNP values, is expected to increase. Improved vertical navigation would increase the use of better-defined vertical profiles, and thus would improve airspace efficiency and capacity. Rigorous system analysis, multidisciplinary airspace optimization, and improved fleet-wide navigation performance would allow increased use of four-dimensional (4-D) trajectories decoupled from each other in a high-volume environment. The control parameters would be simplified to different route and vertical profile structures reflecting levels of increased decoupling of 4-D trajectories.

The route and vertical profile structures are defined by airspace design geometry parameters such as the number of entry and exit fixes, their lateral (distance from metroplex center and distance from each other) and vertical spacing (single altitude or stacked), the extent of shared common path segments (complexity vs. airspace efficiency), and turn radii at various segments. Details of these route and vertical profile structures are discussed more specifically in sections 7 and 8, where the Generic Metroplex experiment and N90 experiments are presented.

6.5 Temporal Design and Control Parameters

For the Generic Airspace Metroplex Sensitivity Analysis, the desired arrival and departure temporal uncertainty values are a set of temporal uncertainties for the generic airspace terminal-area boundary crossing (external to the terminal area) and a set of temporal uncertainties for the generic airspace terminal area (internal to the terminal area). Section 6.2 discussed qualitatively the impact of the NextGen and team-proposed new concepts and technologies on the reduction of the temporal uncertainties. Recommendations for the values of these uncertainties were deduced from numerous sources and are discussed in the following paragraph. Table 21 summarizes these recommended metroplex temporal uncertainty assumptions. These uncertainties are measured at points shown in Figure 22.

TABLE 21. RECOMMENDED METROPLEX TEMPORAL UNCERTAINTY ASSUMPTIONS SUMMARY

Temporal Uncertainty Category	Temporal Uncertainty	Bias	Grouping (2-sigma)
Arrival-boundary crossing	Current system-arrival–fix-crossing time	0 sec	60 sec
	Future 4-DT system-arrival–fix-crossing time	0 sec	12 sec
Departure-boundary crossing	Current system-departure takeoff time	-4.5 min	22 min
	Future SMS system-departure takeoff time	-2 min	15 min
	Future 4-DT system-departure takeoff time	0 min	5 min
Arrival-terminal area	Current system-arrival landing time	0.2 min	4.4 min
	Future 4-DT system-arrival landing time	0 sec	35 sec
Departure-terminal area	Current system-departure fix-crossing time	0 min	2 min
	Future 4-DT system-departure fix-crossing time	0 sec	12 sec

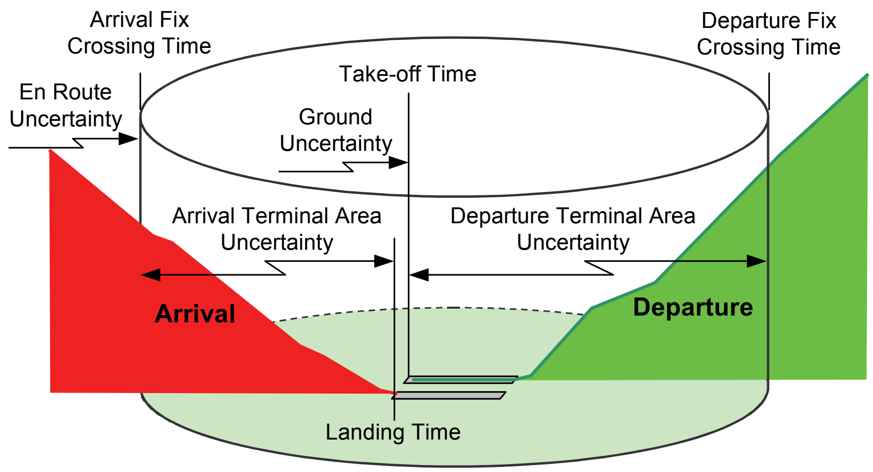


Figure 22. Temporal uncertainty measuring point.

In Table 21, the bias is defined as the difference between the mean and the nominal value; the grouping is defined as the spread of the uncertainty around the mean, given as 2 times the standard deviation.

The current system-arrival–fix-crossing time temporal uncertainty value is based on data for aircraft controlled by en-route air traffic controllers with the Multi-Center Traffic Management Advisor (MC-TMA) operating [LF03]. The future 4-DT system-arrival–fix-crossing time, future 4-DT system-arrival landing time, and future 4-DT system-departure fix-crossing time temporal errors were assessed based on recent controlled-time-of-arrival (CTA) research sponsored by Eurocontrol's Partnership Project: CTA-ATM System Integration Studies (CASSIS) [KAM09]. The current system-departure takeoff time temporal error was estimated by traffic flow management system (TFMS) expected-departure-clearance-time (EDCT) compliance accuracy data analysis [L09]. The future surface management system (SMS) system-departure takeoff time temporal uncertainty is based on SMS system prediction accuracy as measured in a series of operational trials at Memphis International Airport (MEM) [AJ04]. A future airport guidance and control system where aircraft would receive and use detailed 4-D trajectories for guidance, as well as a datalink for communication and full airport surface surveillance (both ramp and movement area), would provide higher levels of aircraft takeoff prediction accuracy. The values for future 4-DT system-departure takeoff time temporal error were chosen through team subject domain expert evaluation. The current system-arrival landing time temporal uncertainty is based on measurements from previous NASA Collaborative Arrival Planning research [QZ98]. Current system-departure fix-crossing time temporal uncertainty should be larger than the current system-arrival–fix-crossing time temporal uncertainty because of the lack of a current system such as Traffic Management Advisor (TMA) that provides scheduled times of arrival to which controllers try to control flights, the naturally increased variation in aircraft weight during the departure phase, and other similar factors. For this research, it is assumed that the current system-departure fix-crossing time temporal uncertainty is double the value for current arrival–fix-crossing time temporal error.

6.6 Discussion of Metroplex Scheduling Algorithms

Metroplex scheduling is a means to determine nominal entry fix-crossing times for flights destined to the metroplex airports or nominal departure takeoff times for flights originated from metroplex airports. Together with metering techniques and spatial control methods, the primary goal of metroplex scheduling is to maximize metroplex throughput. A secondary goal is to minimize the delays that occur within the terminal area; delays within the terminal area are more costly from the fuel-burn and emissions perspectives than delays that occur in the en-route environment. Reduced delays in the terminal area can also reduce the noise impact of aircraft operations. This section discusses a metroplex arrival scheduling algorithm. This scheduling algorithm was used in the Generic Metroplex simulation study described in section 7.5 and the N90 Airport and Airspace Delay Simulation Model (SIMMOD) simulation study in section 8. The Georgia Institute of Technology (GaTech) team also studied alternative scheduling algorithms. Details of these alternative scheduling algorithms and the analysis results are presented in section 7.4.

Architecture of the Metroplex Arrival Scheduling Algorithm

The arrival scheduling algorithms assume that the estimated time of arrival (ETA) at entry fixes and the runway assignments are known for all flights destined to the metroplex airports on an entire day. This assumption is not a requirement, but rather one for simplifying the implementation of the algorithm so that it can be easily applied to the simulation studies. In the real-world environment, the algorithm could be implemented to work on a rolling window of a given time horizon, within which the ETA and runway assignments may be reliably predicted.

A two-stage scheduling algorithm architecture is employed to generate a required time of arrival (RTA) for each aircraft. In the first stage, the time between successive aircraft destined for a given runway is minimized, thereby maximizing the throughput of that runway (thus achieving the primary goal). In the second stage, the impact on runway throughput of conflict resolution actions required at all the metering fixes is minimized (thus achieving the secondary goal without compromising the primary goal). These two stages are discussed in the following paragraph.

Maximizing Runway Throughput

The runway throughput is maximized by minimizing the time between successive aircraft that cross a given runway threshold subject to runway constraints only. In other words, the constraints at all the entry metering fixes are relaxed in this stage. Any potential conflicts that could occur between different traffic streams via a common entry fix are ignored, thereby treating the aircraft destined to a given runway as independent of aircraft destined to other runways. Using the ETA at the entry fix as the starting point, the earliest possible runway arrival time for each aircraft destined to a given runway is determined by using its future unimpeded trajectory, assuming it is able to conduct a continuous-descent arrival (CDA) at the optimal speeds. The result is a sequence of arrivals ordered by their earliest possible runway arrival time. In this sequence, time intervals between runway arrival times might actually be less than those corresponding to the minimum required separations between successive aircraft landing on the same runway. Because this sequence is determined from the earliest possible runway arrival time for each aircraft, the only way to resolve the conflict at the runway threshold is to push back the runway arrival times to satisfy runway separation constraints. The result is an ideal runway schedule that maximizes runway throughput subject to runway separation constraints. From the ideal runway schedule, runway-ideal entry fix-crossing times for aircraft destined to the same runway can be determined by back propagating each unimpeded CDA trajectory to its corresponding entry fix.

Minimizing Impact of Conflict Resolution at Metering Fixes

The runway-ideal schedule at an entry fix can be obtained by combining runway-ideal entry fix-crossing times for all aircraft destined to different runways at metroplex airports. Because the runway-ideal entry fix-crossing times are determined independently for different runways, the time intervals between consecutive aircraft in the runway-ideal schedule, given an entry fix, might actually be less than that corresponding to the minimum separation required at the fix (normally 5 nm). The impact on runway throughput of conflict resolution actions at entry metering fixes is minimized by minimizing the net increase in fix-crossing times that are required between different traffic flows. The runway-ideal fix-crossing times could be simply pushed back to satisfy minimum separation requirements at the fix, just like what is done currently at the runway. This push-back would result in additional gaps in the runway arrival stream beyond whatever gaps might exist because demand is less than capacity. It is thus determined to selectively advance the fix-crossing times from the runway-ideal fix-crossing times to achieve the minimum required separation at the fix. Any advance is limited not to be earlier than the corresponding original ETA. Because of the limit imposed, the minimum required separation might not be achieved for all consecutive aircraft pairs. If for an aircraft pair the minimum required separation is not satisfied, the entry fix-crossing time of the trailing aircraft is pushed back as little as possible to achieve the minimum required separation.

Application of Metroplex Arrival Scheduling Algorithm

The adjustment of the fix-crossing times is determined using a linear program. The net result is the schedule of desired runway fix-crossing times. The same algorithm can be applied to both the Generic Metroplex simulation and the N90 Metroplex simulation proposed in section 6.3. The algorithm takes sequences of ETA at entry fixes as input and outputs the schedule (sequences of RTA) at entry fixes, which will in turn be used in the corresponding simulation as the new input.

7.0 GENERIC METROPLEX ANALYSIS AND SIMULATION

The Generic Metroplex analysis and simulation were developed to systematically study the impacts of the spatial and temporal control parameters on metroplex operations. Two types of control parameters and metroplex performance metrics were analyzed to form the basis for the experimental methodology. An experiment process flow was developed to implement this methodology. Details of the experiment methodology are presented in section7.1. to provide background information for the discussions that follow. The Generic Metroplex Model was developed as the platform for all analyses and simulation studies in this section. This model includes four different airspace geometries with the area-navigation-system (RNAV) and required-navigation-performance (RNP) procedure to represent the broad range of spatial control parameters. To support the analysis and simulation, a demand model and an aircraft traffic spacing model were also developed, as described in section 7.2.

Four separate analysis and simulation tasks were conducted to test the Generic Metroplex system performance. The first task was an airspace interdependency and complexity analysis referred to as the Intersect Flow analysis, as described in section 7.3. Using the developed intersect flow metrics, the analysis compared the four different airspace geometries under the demand set described in section 7.2.2. The second task was an analysis of a set of alternative scheduling algorithms (different from the one described in section 6.6) and their impact on metroplex delays. This study analyzed the performance of different geometries and different airports in the Generic Metroplex when the proposed scheduling algorithms were applied. It identified some issues that warrant further examination in the future. The proposed scheduling algorithms and the analysis results are presented in section 7.4. The third task, also the most important of part of the Generic Metroplex study, was a linked node queueing process simulation. Different demand levels, the scheduling algorithm described in section 6.6, and different temporal control accuracy values were tested. Details of the linked-node queueing-process model, the test case design, and simulation results are presented in section 7.5. The last one of the four tasks was an environmental analysis of different Generic Metroplex geometries. The analysis methods, fuel burn, and emissions results of this task are presented in section 7.6.

7.1 Experiment Methodology

7.1.1 Experiment Hypotheses and Experiment Metrics

According to the metroplex evaluation framework discussed in section 6, there are two basic categories of strategies for managing air traffic flows in a metroplex. The first category is temporal strategies, which involves de-conflicting traffic flows to and from multiple airports sharing points, routes, or volumes of airspace by controlling flight-by-flight arrival times at the shared resource to maintain separation. The separation allows flights to take direct routes between their origin/destination airports and within the metroplex terminal area, but might lead to excess delays. The second category is spatial strategies, which involve de-conflicting traffic flows to and from multiple airports by using different routes that are separated either vertically or laterally. In this second category, controllers do not have to worry about temporal separation between any two traffic flows going to/coming from two different airports. However, this scenario might lead to extra distance flown, which in turn can be translated into additional flying time. In most cases, the control of interweaving traffic flows might involve a combination of these two de-confliction strategies. In addition, the benefits of advanced metroplex spatial or temporal control strategies might diminish with increased levels of uncertainty or decreased levels of control accuracy.

To systematically test these two types of strategies, the metroplex operational environment and the control strategies were mapped into a set of variables. These variables form a multidimensional design space. Each point in the design space represents a specific metroplex and a set of specific control strategies and their associated performance. Exogenous variables are those defining a specific metroplex environment that the metroplex operations depend on. Theoretically, some of these exogenous variables can be adjusted to influence metroplex operations, but these changes may take decades to implement. Typical exogenous variables include:

- Number of airports in the metroplex
- Relative location and distance between metroplex airports
- Orientation of runways and distance between them at the metroplex airports
- Traffic-demand levels and priorities of different airports
- Internal and external airspace constraints (terrain, special-use airspace (SUA), etc.)
- Weather phenomena
- Environmental constraints
- Facility evolution (airspace jurisdiction)

Following the temporal-spatial framework, design variables and control variables are divided into spatial control variables and temporal variables. Spatial design and control variables include:

- Size and shape of the metroplex terminal-area airspace
- Number of entry and exit fixes at the metroplex terminal-area airspace boundary
- Use of the entry and exit fixes (shared or segregated)
- Terminal-area arrival and departure-route structure (shared common path segments or fully segregated)
- Turn radii at various route segments
- Terminal-area arrival and departure vertical profiles (step down or optimized profile)
- Lateral containment and minimum safe separation (see section 6.4)
- Vertical containment and minimum safe separation (see section 6.4)

Temporal design and control variables include:

- Arrival and departure scheduling (with or without metroplex scheduling)
- Metering strategy (truncation to ensure minimum separation or target seeking to achieve required time of arrival (RTA))

- Longitudinal containment and safe separation (radar, visual, wake vortex)
- Temporal control accuracy (see section 6.5)

Selected Experiment Variables

Because of time and resource limitations, only a subspace of the whole design was tested. Parameters were prioritized and cross-checked for compatibility and consistency to reduce the number of test cases that had to be executed. The subspace was defined by the following grouped variables:

Generic Metroplex airspace design:

The Generic Metroplex airspace design is detailed in section 7.2.1. This design was defined by two airports in the metroplex, each with two parallel runways; four alternative route structures representing different numbers of entry and exit fixes, and the use of fixes and routes by traffic flows at the two airports; continuous-descent arrival (CDA)-type arrival vertical profiles and unrestricted departure profiles; and the use of maximum RNAV/RNP design standards that reflect minimum spatial containment achievable by best-equipped aircraft.

Metroplex demand model:

Two separate demand models were tested. A Poisson arrival model with varying arrival rates was used to test system performance under different traffic volumes. A Generic Metroplex demand model to represent arrivals and departures on a typical day was used for all other analysis. The future demand model is described in section 7.2.2.

Scheduling algorithms:

Several different prototype scheduling algorithms were developed, including the ones described in sections 6.6 and 7.4. The baseline nonscheduling case was the arrival and departure times derived directly from the Generic Metroplex demand model.

Metering strategies and temporal control accuracy:

As an attempt to realistically model metering strategies and temporal control accuracy, an inter-aircraft spacing model was developed (see section 7.2.3). This model was used to adjust the nominal fix crossing times and takeoff times for the metroplex demand model. A range of temporal control accuracy values, defined by the standard deviation of entry fix-crossing times relative to the nominal fix-crossing times, were tested. Details of these temporal control accuracy values and the simulation results are presented in section 7.5.5 following.

Delay was selected as the primary metric for the Generic Metroplex study. A set of metroplex intersect flow metrics was also developed to measure the metroplex flow complexity. For energy metrics, fuel burn was used. Emissions were used as the environmental metrics. Noise was omitted because it is an issue directly related to populations distribution, which was not considered in the Generic Metroplex model for the sake of simplicity.

7.1.2 Generic Metroplex Experiment Process Flow

It is assumed that arrivals and departures are operationally independent in the initial Generic Metroplex studies, so they are assessed separately. Figure 23 depicts the Generic Metroplex simulation process for assessing arrivals to or departures from the Generic Metroplex airports. The general data inputs to the process include *airspace geometry*, the *spatial precision* of aircraft navigation and guidance, probability density functions of *spacing* at the arrival fixes or departure runways, *minimum required spacing* values at the *arrival fix*, *procedure merge points*, *airport runways*, and *temporal precision* in delivering aircraft at scheduled times. Data outputs are *delay*, *fuel burn*, *emissions*, and other possible *cost metrics*. Computational elements are metroplex traffic *demand generation*, metroplex *airspace design*, *traffic spacing*, *sequencing/scheduling*, and *queueing model*.

The simulation process is as follows. Airspace geometry specifies the number of metroplex arrival and departure fixes and their locations, as well as exogenous variables, including the number of metroplex airports and their locations, runway orientations, and capacities. Data from this step are inputs to both the demand-generation and airspace-design process.

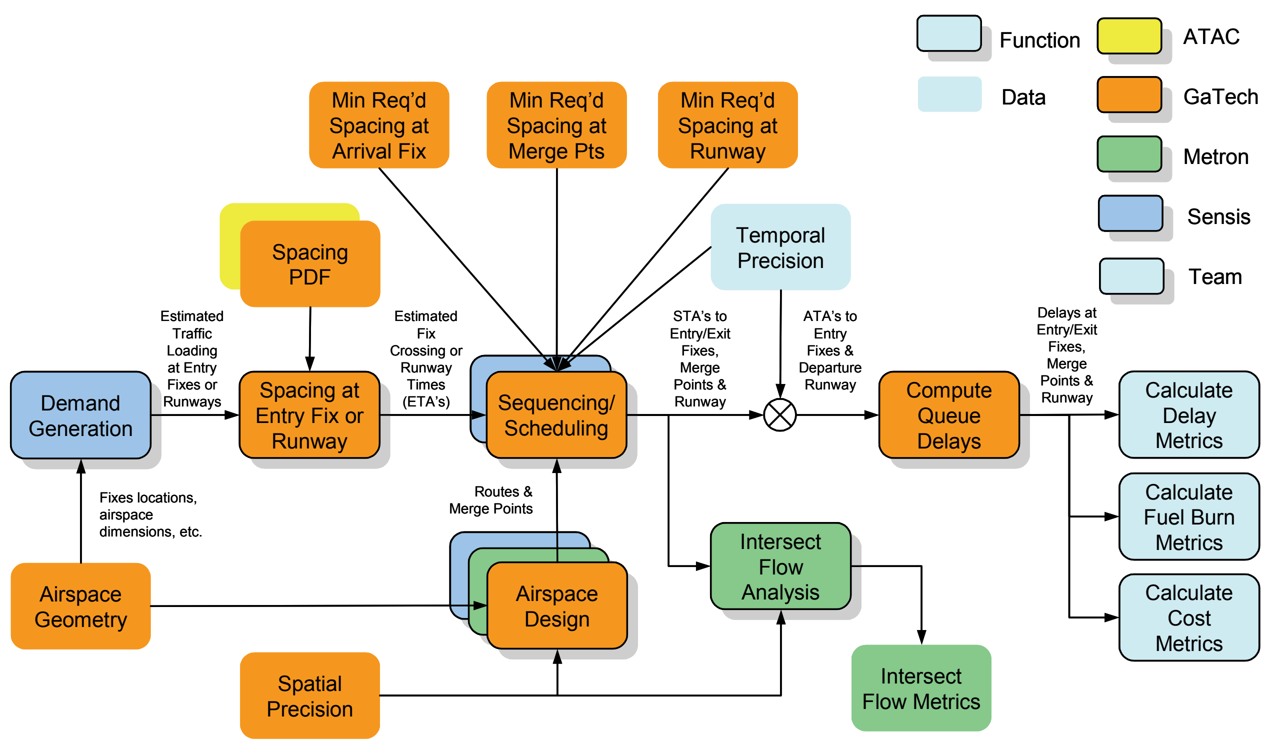


Figure 23. Generic metroplex assessments process flowchart.

Demand generation creates an initial schedule of arrivals to and departures from each Generic Metroplex airport according to the specified arrival and departure capacities and demand-to-capacity ratio of the airport. This process includes assigning each flight to an arrival or departure fix and estimating its time of arrival to that fix. Merging the arrivals schedules of the metroplex airport yields the raw scheduled demand for each arrival fix. Traffic spacing adjusts spacing at arrival fixes or departure interval at runways in accordance with an empirically derived inter-flight probability distribution and the implied traffic volume. This adjustment yields realistic fix-crossing times or runway departure times. If metroplex sequencing and scheduling is applied, the fix-crossing times or runway departure times will be provided as input to that module.

Airspace design creates a set of arrival and departure procedures coupling each metroplex airport with its associated arrival and departure fixes. Merge points or other points of interaction between different procedures are also defined. Additional input to airspace design is the spatial precision and the anticipated lateral and vertical navigation performance of the aircraft executing the procedures. The outputs of airspace design are the Generic Metroplex terminal airspace procedures and their merge or interaction points.

Provided with nominal arrival transit times and initial crossing times at arrival fixes, the arrival sequencing and scheduling determine the new sequence and new arrival–fix-crossing times that satisfy minimum required spacing and minimize delay. Provided with nominal departure transit times and initial runway departure times, the departure sequencing and scheduling algorithm determines the new sequence and new runway departure times that satisfy minimum required spacing and minimize delay. In addition, the sequencing and scheduling may account for the temporal precision in estimating aircraft transit times and in meeting scheduled times of crossing at control points.

The scheduled arrival–fix-crossing times or runway departure times are then in turn perturbed as per the temporal precision to yield actual times at these points. These inputs are fed into the queueing network (referred to as linked-node queueing-process model) to simulate queueing delays that may incur during the execution of arrival or departure procedures. The computed flight delays at fixes, merge points, and runways are then used to compute total delay, fuel burn, and cost metrics. Key components of this process are described in the following sections.

7.2 The Generic Metroplex Model

This section presents the Generic Metroplex model. Key components of the model include Generic Metroplex airspace design, the demand generation, and the inter-aircraft spacing model. These components are described in the following sections. Some other factors, which could be considered in a thorough Generic Metroplex experiment study, are skipped in the current research because of time and resource limitations. Those other factors are discussed briefly for the completeness of the subject.

7.2.1 Generic Metroplex Airspace Design

The Generic Metroplex airspace design started with a set of four basic airspace design geometries. The team first conducted discussions on the notional procedure design and identified major issues that needed to be considered in the procedure design: vertical profiles, lateral path, potential trajectory conflicts, separation standards, and optimization of trajectory spatial displacement. The purpose of spatial displacement of trajectories is to reduce temporal coupling between trajectories to improve overall throughput, efficiency, and safety.

The initial Generic Metroplex model explored in this study consists of two airports, A and B, located 20 nm apart. Airport elevation is assumed to be at mean sea level (MSL) for the sake of simplicity. Each airport has two parallel runways that are separated by 5,000 ft, permitting independent simultaneous parallel operations. Runways are oriented perpendicular to the north-south straight line connecting the two airports. Each runway is 9,000 ft, assumed sufficient for today's heavy commercial jets. The layout of this initial metroplex model is shown in Figure 24, where the most direct routes are presented. The four basic airspace design geometries are designed to represent the different levels of route efficiency outside the terminal area and the spatial segregation that can be achieved within the terminal area. These four geometries are briefly discussed as follows:

- **Airspace geometry 1**: There are four equally spaced arrival fixes and four departure fixes located at the 40-nm ring from terminal radar approach control (TRACON) center. Each fix is shared by both airports.
- **Airspace geometry 2**: There are four equally spaced arrival fixes and four departure fixes located at the 40-nm ring from TRACON center. Each fix is shared by both airports. In addition, arrival and departure paths are maximally shared by aircraft sharing the same entry or exit fix. This geometry represents the use of common standard terminal arrival routes (STARs) and standard instrument departures (SIDs).
- **Airspace geometry 3**: There are four pairs of arrival fixes and four pairs of departure fixes at the 40-nm ring. Each fix in the pair is used by only one airport.
- **Airspace geometry 4**: There are 16 arrival fixes and 16 departure fixes. Arrival fixes and departure fixes are alternately distributed on the 50-nm ring. Each fix is used by only one airport.

Unrestricted arrival and departure profiles are important reference design solutions as they present the most fuel-efficient design. The unrestricted arrival profile represents a continuous-descent-arrival (CDA)-type vertical profile. In this profile, the aircraft descend from high altitudes along a performance-based vertical profile such that the thrust setting remains in idle for as long as operational conditions permit. The unrestricted departure profile represents a profile in that the overall efficiency is optimized, although the optimization objectives may be operator-specific. Reduced-rate departures may also be employed to save fuel, to reduce aircraft noise impact to the community below the flightpath, or to save engine maintenance cost. An example of arrival and departure profiles is shown in Figure 25.

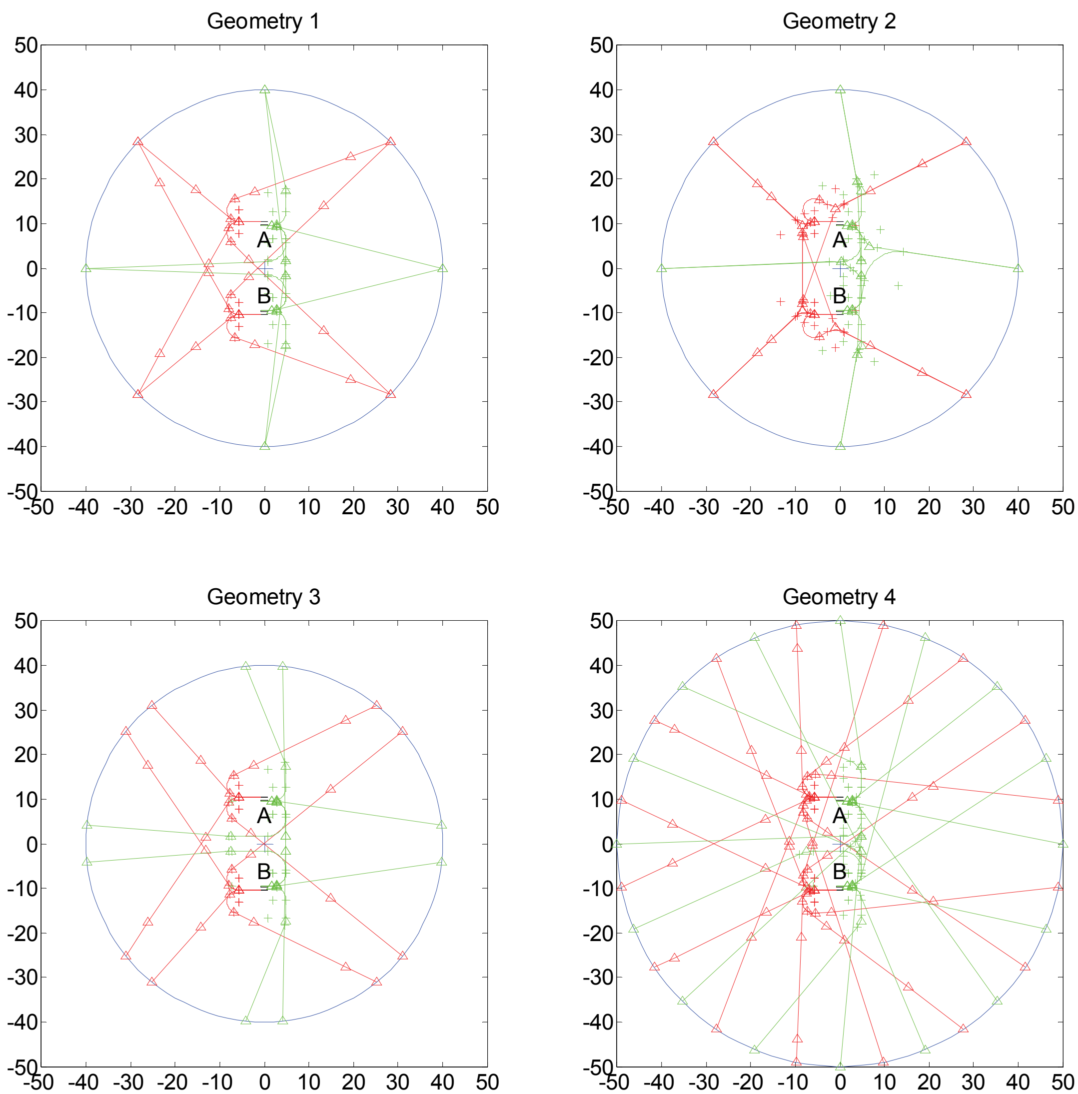


Figure 24. Most-direct-route structures for Generic Metroplex.

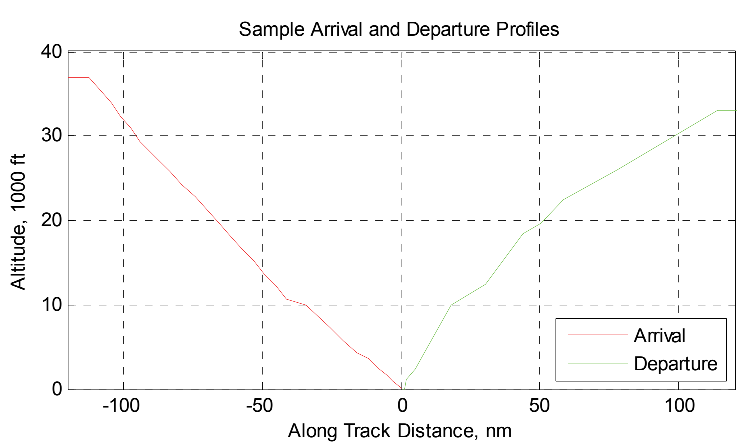


Figure 25. Example of unrestricted arrival and departure profiles.

Per the current design standard, an RNP arrival procedure would provide the possibility for the most direct routes for different airspace setups. Lower RNP values may reduce lateral separation minima and help de-conflict traffic flows in the metroplex, but would limit the availability of procedures to the minority of current-day fleet mix equipped with that capability. Within the current RNP procedure design standards, a wide range of arrival procedures can be developed. The availability of new capabilities and technologies in the future would mostly tend to enable expanded use of RNP procedures by more aircraft and in a wider range of external conditions. The availability of new capabilities in the future, however, probably would not tend to dramatically reduce the RNP values from today's standards. The radius of turn is determined by indicated airspeed, tailwind component, maximum segment altitude, and the design of the turn arc. With a reduced radius of turn, design flexibility can be improved, and it would help separate different paths. However, if the selected radius of turn is too small, it may reduce efficiency because the aircraft have to decelerate to a slow speed early and the availability of such routes may be limited to certain aircraft types. Based on these assumptions, a set of procedure design parameters were selected to develop a set of most-direct-route structures based on the four basic geometries. These route structures are shown in Figure 24.

In Figure 24, the red routes are arrivals and the green routes are departures. The four route structures are the bases for the Generic Metroplex simulation analysis.

7.2.2 Generic Metroplex Demand Generation

Metroplex demand generation is the process for creating a traffic demand set (set of scheduled arrivals and departures) for Generic Metroplex airports to support simulation-based evaluation of hypothetical terminal airspace configurations. Demand-generation process inputs comprise a current-day traffic demand set; a user-specified National Airspace System (NAS) airport after which to model traffic demand to a particular metroplex airport, and an hourly capacity value; and target 24-hour demand–to–16-hour capacity ratio for the airport. The demand-generation process comprises the following computational steps:

1. The traffic demand set is processed using the AvDemand tool to grow the traffic to a specified volume and to estimate gate arrival times for each flight [HS07].
2. Those flights to/from the specified NAS airport are captured.
3. A portion of the flights of interest are removed to achieve the specified demand-to-capacity ratio as per the specified generic airport hourly capacity [WL01].
4. The remaining flights—i.e., the arrival flights to and departure flights from the generic airport—are assigned to a peripheral source/sink airport at a specified radius beyond the terminal airspace.
5. Each metroplex airport arrival and departure flight is assigned to an arrival or departure fix on the hypothetical terminal airspace boundary with the en-route airspace.
6. The terminal and en-route transit times of each flight are updated to reflect the airspace geometry.
7. After transit times are computed, distinct, randomly generated gate departure times are assigned to all the generic airport flights in order to eliminate coincident scheduled takeoffs.

Finally, the generated schedule of generic airport arrivals and departures is written to a simulation input file of the appropriate format. The following input parameters are used to generate traffic demand sets for airports A and B in the Generic Metroplex assessments. The seed traffic dataset is an enhanced traffic management system (ETMS)-derived record of instrument-flight-rules (IFR) flights for September 26, 2006 [ETMS]. The seed traffic dataset was "grown" using AvDemand to three times the total traffic volume in accordance with 2008 terminal-area-forecast (TAF) forecasts [TAF08]. From the grown traffic demand set, ATL traffic is used to create traffic demand sets for both Generic Metroplex airports A and B. Arrival and departure traffic volumes for Generic Metroplex airports A and B are in accordance with capacity of each airport of 60 arrivals/hour and 60 departures/hour (each airport has two operationally independent parallel runways) and their respective demand/capacity ratios, 0.7 for airport A and 0.35 for airport B [N04]. Figure 26 depicts the generated traffic-demand profile with total capacity for Generic Metroplex airports A and B.

The metroplex demand-generation process is effective in preserving the directional distribution of scheduled traffic to the specified reference NAS airport. The directional traffic distribution determines the relative loading of the metroplex arrival and departure fixes, in turn impacting controller workload and possibly requiring airspace configurations and traffic-management strategies to accommodate it. Figure 27 depicts the directional distributions of of Generic Metroplex airports A and B from the metroplex demand-generation process. The heavy ATL scheduled demands in the 45- to 60-degree and 15- to 165-degree ranges are preserved in the Generic Metroplex demand set.

7.2.3 Inter-Aircraft Spacing Model

One of the research questions in modeling temporal control variables is how the metering strategies are practiced in the existing environment and how this practice would change in the future environment when traffic levels are significantly increased. Uncertainties in spacing are one of the major sources of queueing delays. Accurate modeling of spacing is thus important to simulate current system performance and to develop and test future concepts and automation. This research explores the problem of modeling the probability distribution of spacing under different traffic levels and the separation minima in effect.

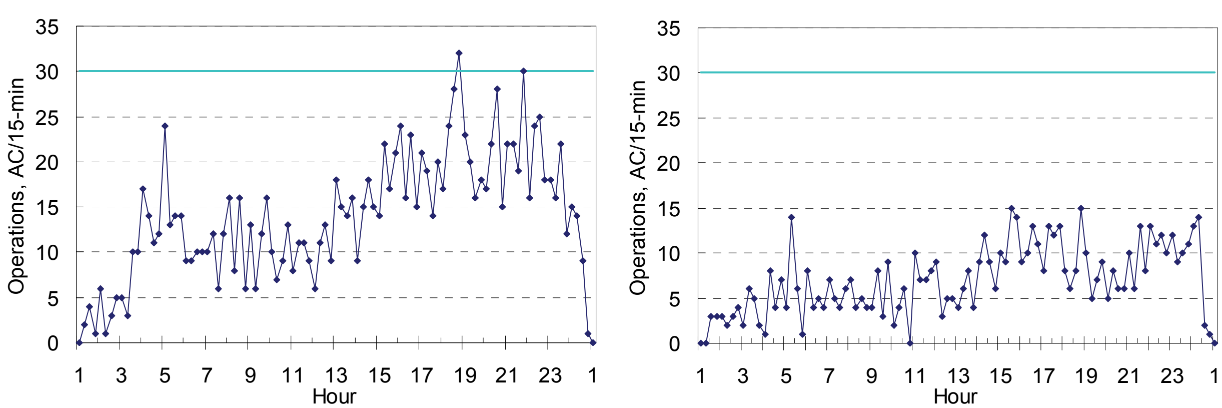


Figure 26. Generic Metroplex airport A (left) and airport B (right) traffic-demand profiles and capacities.

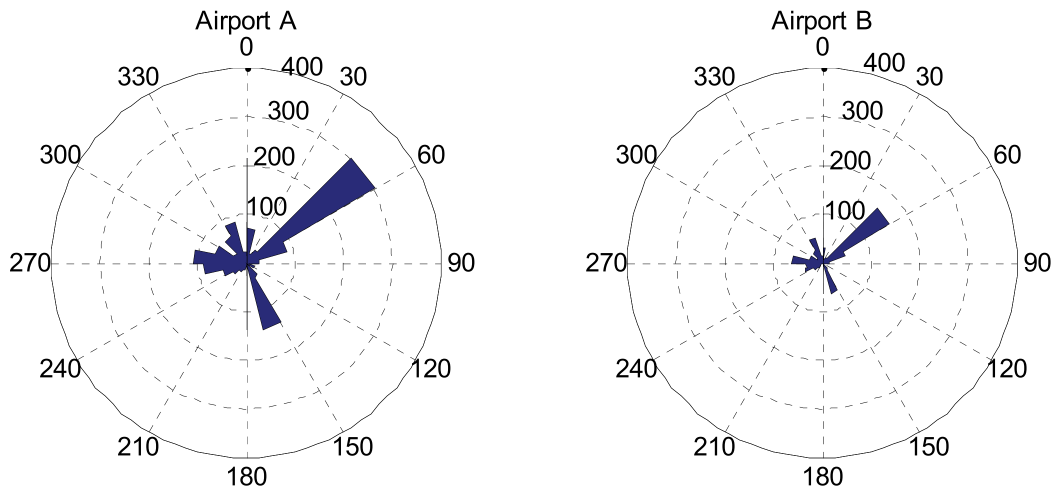


Figure 27. Directional traffic distribution for ATL and Generic Metroplex airport A.

Spacing is usually measured in terms of time or distance, depending on the purpose of the study. One of the efforts is to characterize the probabilistic distribution of the time interval between two successive flights at arrival fixes and departure runways under various traffic levels through analyzing data collected from real-world operations. This work is motivated by the need to provide realistic inputs to the metroplex experiments for current and future traffic scenarios.

Most inter-arrival time probability distribution models fit in the exponential family. Mathematical manipulation of the exponential family of models can be facilitated through parameterization of canonical and mean values. A specific model can be characterized by a location parameter γ, a dispersion parameter β , and a shape parameter α . The location parameter has a one-to-one transformation of the mean; normally it is a shift from the mean. The dispersion parameter measures the spread of the distribution and may correlate with the shape parameter that normally controls the skewness of the distribution. It is intuitive to expect that under high traffic conditions the inter-arrival time would concentrate towards the minimum separation in effect as controllers would keep spacing as small as possible while maintaining separation requirements. Spacing under low traffic conditions is expected to have a larger dispersion. The corresponding probability density function would shift to the right (longer time between arrivals) with a larger mean as the observed spacing intervals would be more likely driven by random events.

The following sections discuss the modeling approach, the calibration of the model, and modeling results.

Modeling Approach

In this work, models of inter-arrival time probability distribution at TRACON entry fixes and models of inter-departure time probability distribution at the runways were developed. Inter-arrival time is selected to represent spacing because it can be directly used in metroplex queueing simulations.

One day's worth of archived performance-data-analysis-and-reporting-system (PDARS) data from October 2, 2008, representing typical west-flow operations at ATL were used for model development. The arrival fixes for A80 are along an approximately 40-nm radius from ATL. For each arrival flight, the intercept point at the 40-nm radius was calculated from the PDARS track, along with the crossing time. PDARS data were also used to determine the runway usage and runway times for both arrivals and departures.

To examine the distribution of inter-arrival time under different traffic conditions while maintaining reasonable sample sizes, the arrival rates at the entry fixes were divided into four discrete levels (see Table 22). The full day's worth of data were divided into 24 one-hour bins. The arrival rate for each one-hour bin was calculated for each entry fix. Assuming sufficient data points exist within each time bin, one model can be developed for each such bin. With the resulting 24 models from one day's worth of data, a good estimate of the variability of probability distribution parameters can be developed as a function of traffic levels. However, for each one-hour bin, the available data points are limited, especially for the one-hour bins with low arrival rates or departure rates that contain fewer observations. This issue is resolved by grouping the one-hour bins into the defined four traffic levels.

Because of the limited data available for the analysis, the modeling process was simplified based on the following assumptions:

1. The probability distribution function of spacing remains in the same form under different traffic levels, with only the values of (some of) its parameters varying with the traffic level.
2. Observations within a time bin during a typical day are representative subgroups of the population.
3. The arrival process at primary arrival fixes or the departure process at runways is homogeneous for all such arrival fixes or runways. The homogeneity applies to entry fixes and runways as if the operations are conducted independently, but at the same fix or runway.
4. Instead of performing statistical tests to identify subpopulations within each discrete traffic level, it is assumed that the sample mean arrival rate corresponding to the discrete traffic level is representative of all the data points grouped into the same traffic level. This assumption helps to maintain a reasonable sample size for each traffic level.
5. The parameters of the statistical model are determined only by the mean spacing, or arrival rate and departure rate.

From these assumptions, making an inference to the distribution under any given traffic condition depends on the model parameters. The maximum-likelihood estimator (MLE) [LK07] was selected to estimate the parameters from the independent and identically distributed (IID) data for each selected traffic level. The relationship between model parameters was established through the fundamental parameter for the exponential family known as the mean of time intervals. In other words, the parameters of the statistical model can be written as a function of average arrival or departure rate for the given traffic level. With model parameters determined for the four defined traffic levels, the trending of model parameters with arrival or departure rate can be determined using regression.

Model Development Results

For arrivals, the 40-nm radius crossing times were first grouped according to the existing arrival fixes, i.e., DIRTY, CANUK, HONIE, and ERLIN. This grouping was done by comparing the bearing of the crossing point and the bearing of each arrival fix, both relative to ATL.

Data points with time separation less than 1.07 minute (assuming a ground speed of 280 kt, this separation is equivalent to a 5-nm longitudinal separation) were simply excluded, as these flights might have been laterally or vertically separated. Close examination of flights with similar characteristics would be conducted in future analysis when more data are processed to assure this assumtion is valid. For departures, only operations from runways 26L and 27R were analyzed. The number of departures from runway 28 was too small to be used. The effect of wake vortex separation minima was considered for the departure process.

Categorizing data into four traffic levels for both arrivals and departures was done in a way to allow relatively equal sample sizes among the levels. Lower-frequency data were placed in levels with a wider range of arrival/departure rates, increasing the variation in the model for those levels. It is an iterative process to obtain a balance between sample size and population segregation, as both are important to the accuracy of the model.

The hypothesized distributions for both arrival and departure were selected to be Weibull distributions [KS08], which have an overall better fit. The Weibull distribution has the probability density function

$$f(x) = \begin{cases} \alpha\beta^{-\alpha}(x-\gamma)^{\alpha-1}\exp\left[-(\frac{x-\gamma}{\beta})^{\alpha}\right], & \text{if } x > \gamma \\ 0, & \text{otherwise} \end{cases}$$

where $\alpha, \beta > 0$.

The Weibull distribution reduces to the exponential distribution when $\alpha = 1$. It appears to be a bell-shape and a reversed J-shape distribution for $\alpha > 1$ and, $\alpha < 1$ respectively. Table 22 shows estimated Weibull distribution parameters using the MLE for different traffic levels, along with the corresponding traffic levels given in terms of mean time intervals between flights, and average arrival or departure rate.

TABLE 22. MAXIMUM-LIKELIHOOD ESTIMATION FOR DIFFERENT TRAFFIC LEVELS

Traffic Level		Average Arrival/Departure Rate	Location, γ	Scale, β	Shape, α	Mean, min	Standard Deviation, min
Arrival	LEVEL1	10.526	1.1999	4.1519	0.855	5.7004	6.0846
	LEVEL2	19.032	1.0833	2.0582	0.9875	3.1526	2.2851
	LEVEL3	26.510	1.0831	1.1335	0.9178	2.2633	1.4399
	LEVEL4	33.442	1.1485	0.6500	1.0163	1.7941	0.6744
Departure	LEVEL1	11.925	0.88299	2.1571	0.51094	5.0315	7.6210
	LEVEL2	24.621	0.84999	0.9700	0.56475	2.4369	2.9548
	LEVEL3	33.065	0.84996	0.5223	0.52299	1.8146	1.2896
	LEVEL4	44.895	0.84992	0.2913	0.55694	1.3365	0.5966

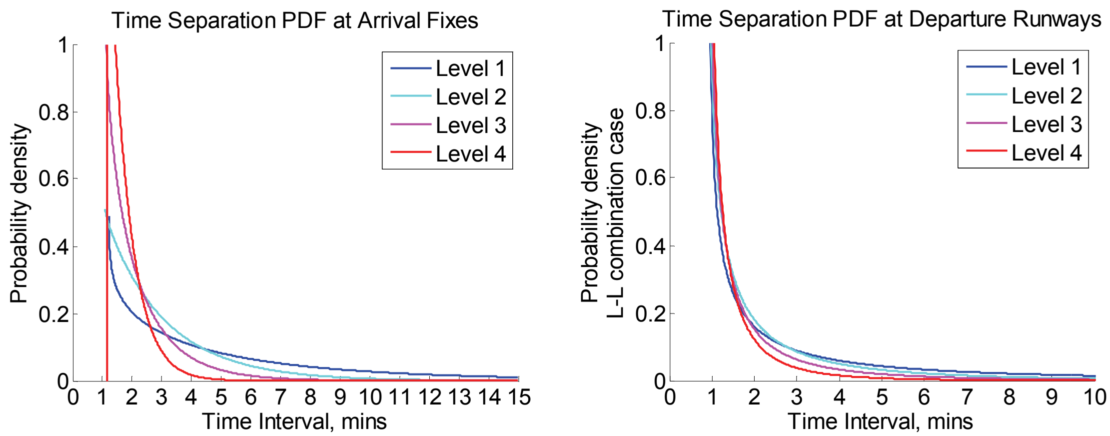


Figure 28. Probability density function for arrival and departure operations at ATL.

The probability density functions (PDFs) generated from the model parameters listed in Table 22 are shown in Figure 28, with arrivals on the left and departures on the right. Note that for departures, the wake vortex separation is applied; thus the minimum time interval varies with the aircraft pair. Because of the low proportion of heavy jet operations at ATL, sufficient data were not available for aircraft pairs involving a heavy jet. The departure data listed in Table 22 and the departure PDFs shown in Figure 28 are for large-large aircraft pairs only. From the PDF curves, it can be seen that the dispersion of time interval between departure flights at the runway threshold was less than that for arrivals, implying that controllers had more precise control over departures times. The dispersion of time intervals between flights for arrivals at the TRACON entry fixes was greater than for departures, implying the strong influence of random events. For both arrival and departure operations, the dispersion becomes greater at lower traffic levels, reflecting less restriction to operations and more random-event–type behavior. The dispersion or uncertainty, especially for arrivals at high traffic volume, is a measure of traffic-flow efficiency.

With the model parameters determined from the data, the distribution of arrival or departure rates other than those listed in Table 22 can be obtained through a trending analysis. The trend of parameters describes how a family of statistical models varies as traffic load varies. The mean of the Weibull distribution can be determined by parameters α, β, γ using the following equation:

$$E(X) = \gamma + \frac{\beta}{\alpha}\Gamma(\frac{1}{\alpha})$$

For consistency, the model parameters for a given arrival or departure rate must satisfy this equation. If all three Weibull distribution parameters were to be determined through trending for a given arrival or departure rate, the resulting mean time interval may be different from that corresponding to the given arrival or departure rate. It was thus determined that only estimated parameters $\widehat{\beta}$ and $\widehat{\gamma}$ are determined from trending, and the estimated $\widehat{\alpha}$ parameter is determined from solving the nonlinear equation. It should be noted that, per the definition of Weibull distribution, both $\hat{\alpha}, \hat{\beta}$ must be positive. Such determined parameter trending results are shown in Figure 29, with arrivals on the left and departures on the right.

Although the model parameters were determined from the ATL data for the four selected traffic levels, the same principle can be applied to a different set of traffic-level definitions. If additional data can be obtained, model accuracy can be improved. With the parameter trending, traffic levels above the current level can be simulated, especially in a future increased traffic-demand scenario.

From the investigation, and from observations of metroplex operations, the system does not always grow in the same form. However, the proposed spacing models could still be used as reference indicators to make inferences and perform comparisons across different types of metroplex operations. For arrival operations, the model is based on the flow crossing times at a cylindrical boundary around the metroplex terminal area. The spacing information can be interpreted as a result of traffic coordination before flights arrived at the boundary. Data from different facilities could be used to identify additional independent variables such as traffic-flow coordination usage. For departure operations, spacing characteristics could also be correlated with the runway configuration used. Separation models written as a function of runway configuration would be more intuitive in this case.

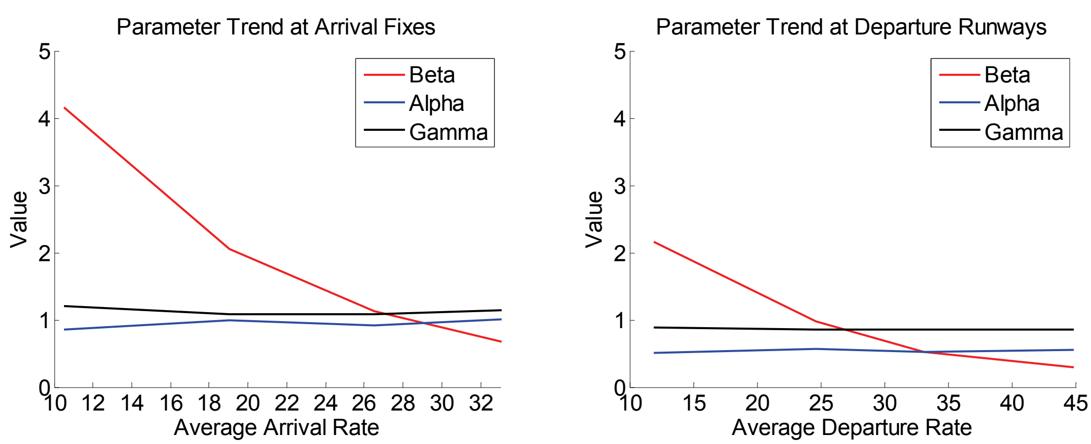


Figure 29. Parameter trend for arrival and departure operations at ATL.

7.2.4 *Other Factors*

Airspace Restrictions

Special-use airspaces (SUAs) or terrain features impose airspace restrictions on metroplex operations. These restrictions can be modeled as blocked (i.e., unusable) volumes of cylindrical airspace defined laterally by a polygon and vertically by an altitude range given the bottom and the top of each cylindrical volume. Following this definition, the difference between a SUA and a terrain feature is not distinguishable except that a SUA becomes hot (the restrictions are enforced) only during a certain period, while the terrain restrictions are always enforced. For the Generic Metroplex model, SUAs and terrain features can be modeled parametrically, following samples from metroplexes in the NAS. Existing SUAs can be found in the Federal Aviation Administration (FAA) National Flight Data Center (NFDC) publications. Terrain features can be also found in the NFDC publications. The minimum vectoring altitude (MVA) used by air traffic control (ATC) can be used as definitions of large terrain features such as mountains.

Because of limited resources, in the initial Generic Metroplex model described in section 7.2.1, the effect of SUAs is not considered and the MSL is used as the Earth's surface.

Weather Conditions

The two basic elements of the weather model are wind profiles and temperature profiles. Typical wind and temperature profiles can be used to explore the range of trajectory variations and their impact on the separation between trajectories, and consequently minimum displacements and travel times. For the sake of simplicity, standard atmosphere and zero wind were assumed in this study. Stochastic wind short-term wind variations [RC08], however, were used in the simulation study.

7.3 Metroplex Intersect Flow Analysis

7.3.1 *Metroplex Intersect Flow Metrics*

This section introduces two metrics for quantifying the complexity of metroplex airspaces. Complexity of the airspace surrounding two or more closely spaced airports will increase with the amount of overlap between their *aircraft flows*, defined as aggregations of flights following a perceptible pattern. Flights are grouped into flows by the proximity of their tracks in space and time.

In order to quantify the interaction of flows, the notion of an *aircraft flow envelope* is developed and used to define two metrics for flow interactions: *flow envelope intersections* and *flight pairs*.

Aircraft Flow Envelopes

For analysis of existing metroplexes, historical track data can be used to define aircraft flows. All of the tracks occurring during a specified window of time can be displayed in three dimensions using Metron Aviation's Airspace Design Tool (ADT). The grouping of tracks into flows can be determined visually or in an automated way using clustering algorithms within ADT [WC04].

For future metroplex design studies, the planned three-dimensional (3-D) paths from the arrival and departure fixes to the runways are employed to define the metroplex flows.

The *aircraft flow envelope* is a "minimal" volume of airspace encompassing most or all of the traffic in a flow. For existing metroplexes, ADT is used to define these envelopes by creating low- and high-altitude "backbones" for each flow. These backbones follow the lateral center of the tracks in each flow, and either the lowest or the highest altitude track, using a series of nodes along the tracks with lateral "dispersions" that encompass all of the tracks. For future metroplex design, flow envelopes are created by first dividing each arrival and departure path into equal-length sections, defining "nodes" along the path, and assuming the paths are linear between these nodes. Vertical and horizontal dimensions are then added to each node in accordance with a specified RNP standard.

In order to find the intersections of these flow envelopes using the Intersect Flows algorithm, they must first be divided into convex polyhedra. The method for dividing them is already suggested by the division of the centerline paths into linear segments divided by nodes, as described previously. In the case of an existing metroplex, the low- and high-altitude backbones for each flow use identical latitudes and longitudes so they can be used to define the set of convex polyhedra. Similarly, in the future metroplex design case the RNP vertical and horizontal designations at each node along the path naturally define the division of the flow into convex polyhedra. Figure 30 shows the overhead view of a set of flow envelopes that have been divided into convex polyhedra using this method.

Flow Envelope Intersections Metric

The **Flow Envelope Intersections Metric** is simply the sum of all pairwise intersection volumes of distinct flow envelopes in the metroplex. The formula for the intersection of one such pair of flows is given by the following:

- Let $I(j,k)$ be the volume of the intersection of the jth and kth convex polyhedra from Flow1 and Flow2, respectively.
- The envelope intersection is defined as $\Sigma_j \Sigma_k I(j,k)$.

The sums are taken over the polyhedra of Flow1 and Flow2, respectively.

The total Flow Envelope Intersections Metric for a metroplex is the sum of all volume intersections of distinct pairs of flow envelopes in the metroplex, shown as green volumes in Figure 30.

Static and Temporal Flight-Pairs Metrics

The **Flight-Pairs Metric** utilizes the idea of flow envelopes described previously, but creates a conceptually more realistic metric describing interactions of flights rather than volumes of airspace. The difference is that instead of computing the volume of airspace in the intersection of two convex polyhedra, the "expected" number of "flight pairs" contained in the intersection is calculated. The idea of flight pairs is to count the expected number of flights from Flow1 and Flow2 that are in proximity.

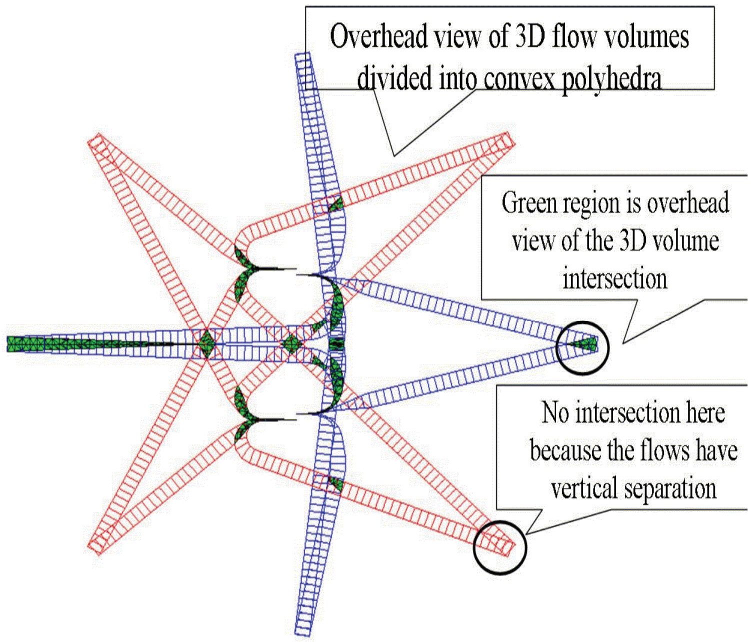


Figure 30. Plan view of 3-D flow envelope intersection shown in green.

Static and Temporal Flight-Pairs Metrics

The **Flight-Pairs Metric** utilizes the idea of flow envelopes described previously, but creates a conceptually more realistic metric describing interactions of flights rather than volumes of airspace. The difference is that instead of computing the volume of airspace in the intersection of two convex polyhedra, the "expected" number of "flight pairs" contained in the intersection is calculated. The idea of flight pairs is to count the expected number of flights from Flow1 and Flow2 that are in proximity.

The calculation is done by intersecting each pair of convex polyhedra coming from Flow1 and Flow2 as previously, but instead of taking the volume intersection, the expected number of flights from Flow1 contained in that volume intersection is computed, as well as the expected number of flights from Flow2 in the volume intersection. Multiplying these numbers together yields the expected number of flight pairs for this intersection.

To be explicit, this metric finds the number of expected flights in the intersection coming from polyhedron j as the number of flights in j multiplied by the proportion of the volume of j included in the intersection. It then finds the product of the number of flights coming from each pair of polyhedra, and sums them over all possible pairs coming from Flow1 and Flow2. Formally, define:

$V(i,j)$, the volume of the jth convex polyhedron for Flow i, $i = 1,2$.

$T(i,j)$, the number of tracks in the jth convex polyhedron for Flow i, $i = 1,2$.

$I(j,k)$, the volume intersection of the jth and kth convex polyhedra from Flow1 and Flow2, respectively.

Then the *Flight-Pairs Metric* is defined as:

$$\Sigma_j \Sigma_k \, [T(1,j) \cdot I(j,k)/V(1,j)] \cdot [T(2,k) \cdot I(j,k)/V(2,k)]$$

The sums are taken over all polyhedra in Flow1 and Flow2, respectively. The total Flight-Pairs Metric for a metroplex is the sum of all the flight pairs for distinct pairs of flows in the metroplex.

The flight-pairs definition given previously is "static" in the sense that it uses a single set of track data. This concept can naturally be extended to define a **Temporal Flight-Pairs Metric** by dividing the scheduled flight traffic demand into time bins, computing the static Flight-Pairs Metric for each time bin, and summing them.

7.3.2 Metroplex Intersect Flows Analysis Results

This section presents the airspace complexity comparison between the four Generic Metroplex geometries, as measured by the Flow Envelope Intersections Metric and the Flight-Pairs Metric described earlier. Previous preliminary analyses of airspace complexity have been conducted on existing airports in A80 [CTWDL09] using these metrics with the flows defined by bundling historical flight tracks.

Generic Metroplex Flow Shapes

For the Generic Metroplex study, aircraft flow envelopes are defined starting with the 3-D paths for each geometry as given in section 7.2.1 and adding width and height dimensions to each path in accordance with the horizontal and vertical parameters in section 6.4. In particular, take the parameters shown in Table 23 as the maximum width and height, defining four flow shapes:

TABLE 23. FLOW-SHAPE PARAMETERS

Flow Shape	1	2	3	4
Maximum width, nm	3	2	2	0.6
Maximum eeight, ft	1000	1000	200	200

Then the width and height at each point along the path is given as a function of distance from the runway by linear interpolation between the values shown in Table 24.

TABLE 24. FLOW WIDTH AND HEIGHT AS FUNCTIONS OF DISTANCE FROM THE RUNWAY

Distance from Runway	Flow Width	Flow Height
0 nm	100 ft	100 ft
5 nm	0.3 nm	Maximum height
> 10 nm	Maximum width	Maximum height

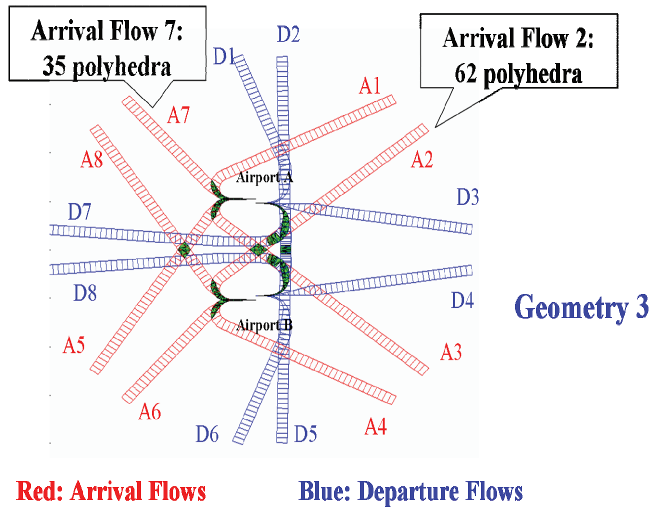


Figure 31. Plan view of 3-D aircraft flow envelopes for Generic Metroplex geometry 3.

Each flow envelope is then divided into convex polyhedra having length 1 nm along the path centerline. Figure 31 shows a plan view of the result for geometry 3 using flow shape 2. Intersections of the flow envelopes are colored in green. The number of polyhedra in each flow envelope are determined by the length of the path from arrival or departure fix to runway.

Application of Generic Metroplex Demand Set

The traffic demand set for the Generic Metroplex described in section7.2.2 is used in calculating the Flight-Pairs Metric. For this study the demand traffic was divided into 15-minute time bins by the scheduled "time in flow": the arrival or departure fix crossing time, adjusted by adding 5 minutes for arrivals and subtracting 5 minutes for departures. The Static Flight-Pairs Metric for each time bin (see section 7.3.1) is then computed and added together to obtain the Temporal Flight-Pairs Metric.

Intersect Flows Results for the Generic Metroplex Models

Airspace complexity for the four Generic Metroplex Geometries was compared using each of the four flow shapes defined previously. This analysis uses only the original demand as described in section7.2.2. Analyses on the demand set with scheduling (for geometries 1, 2, and 3; see section 7.2.1) were conducted, but no significant difference from the original schedule results was found, undoubtedly because the time-bin size of 15 minutes is too large to be sensitive to the small adjustments in arrival and departure fix-crossing times given by the optimized schedule.

Conclusions

Table 25 shows that the four flow shapes have dramatically different Flow Envelope Intersection and Flight-Pairs Metrics for the same Generic Metroplex geometry. Table 26 through Table 29 show that no matter which flow shape is used, geometry 3 shows an improvement in both Flow Envelope Intersection and Flight-Pairs Metrics, while geometries 2 and 4 show increases in both metrics over the baseline geometry 1.

TABLE 25. INTERSECT FLOWS RESULTS FOR GENERIC METROPLEX GEOMETRY 1

Flow Shape	Total Flow Envelope Volume, nm^3	Flow Envelope Intersection Volume, nm^3	Flight Pairs Using 15-Minute Time Bin
1	320.5	25.0	23349.2
2	214.6	13.5	22852.7
3	43.3	2.3	21496.9
4	13.4	0.8	20759.2

TABLE 26. INTERSECT FLOWS CHANGES FROM BASELINE (GEOMETRY 1) FOR FLOW SHAPE 1

Geometries	Total Flow Envelope Volume, %	Flow Envelope Intersection Volume, %	Flight Pairs Using 15-Minute Time Bin, %
2 vs. 1	4.6	19.5	6.5
3 vs. 1	-1.2	-42.9	-6.4
4 vs. 1	149.4	240.7	26.0

TABLE 27. INTERSECT FLOWS CHANGES FROM BASELINE (GEOMETRY 1) FOR FLOW SHAPE 2

Geometries	Total Flow Envelope Volume, %	Flow Envelope Intersection Volume, %	Flight Pairs Using 15-Minute Time Bin, %
2 vs. 1	4.5	34.2	7.7
3 vs. 1	-1.2	-34.1	-4.6
4 vs. 1	149.2	275.8	28.1

TABLE 28. INTERSECT FLOWS CHANGES FROM BASELINE (GEOMETRY 1) FOR FLOW SHAPE 3

Geometries	Total Flow Envelope Volume, %	Flow Envelope Intersection Volume, %	Flight Pairs Using 15-Minute Time Bin, %
2 vs. 1	5.2	3.1	7.0
3 vs. 1	-1.2	-38.9	-3.7
4 vs. 1	148.8	278.6	26.6

TABLE 29. INTERSECT FLOWS CHANGES FROM BASELINE (GEOMETRY 1) FOR FLOW SHAPE 4

Geometries	Total Flow Envelope Volume, %	Flow Envelope Intersection Volume, %	Flight Pairs Using 15-Minute Time Bin, %
2 vs. 1	4.4	22.6	8.5
3 vs. 1	-1.2	-12.3	-1.2
4 vs. 1	147.1	391.3	29.7

7.4 Delay Comparison Based on Analysis of Scheduling

The Generic Metroplex airspace design (section7.2.1) presented in detail the different spatial de-confliction strategies (metroplex airspace geometries 1 through 4) that were tested. Section 6.6 presented a metroplex arrival scheduling algorithm that was used in the Generic Metroplex simulation study described in section 7.5 and the N90 Airport and Airspace Delay Simulation Model (SIMMOD) simulation study in section 8. This section presents in detail a set of alternative temporal de-confliction strategies (scheduling algorithms) and a delay comparison analysis based on these strategies. Because of the time available for this project, only arrival algorithms that assumed departure flows would be spatially separated from arrival flows were considered. Departure scheduling algorithms should be studied in future research activities in this area.

7.4.1 Candidate Generic Metroplex Arrival Scheduling Algorithms

In this study, two options for arrival scheduling algorithms were studied. One option was a "no intelligent scheduling" option, which served as the baseline for comparing against all other scheduling options. Also studied was an "optimal scheduling" algorithm that minimizes overall delay cost by giving higher priority to flights belonging to the busier of the queues (among the queues at the arrival fix and queues at the runway). Following is a brief description of these two scheduling options.

No Intelligent Scheduling Option

Under this option, it was assumed that the TRACON arrival controller has no prior information about the estimated arrival–fix-crossing time or estimated runway landing time for incoming flights until they reach the TRACON boundary. Because of a lack of information, whenever a flight enters the TRACON (i.e., crosses the arrival fix), the TRACON arrival controller basically assigns it to land right after the latest flight (going to the same airport) that crossed the TRACON boundary just before the current flight. This strategy was a first in, first out (FIFO) strategy.

Optimal Scheduling Option

Under this option, it was assumed that the TRACON arrival controller and the upstream en-route controller would have information about the estimated arrival-fix crossing time and the estimated runway landing time for incoming flights at some look-ahead time before the flights reach the TRACON boundary. Because of the availability of this information, the en-route controller would have some flexibility in changing the sequence of arrival-fix crossings and the TRACON controller would have some flexibility in changing the sequence of runway landings. The optimal scheduling algorithm utilizes this flexibility to compute the optimum sequence of arrival-fix crossings and runway landings among leading flights going from each arrival fix to each runway such that an overall delay cost is minimized.

In this algorithm, a set of leaders to each airport is picked at each arrival fix. Sequence changes between leader flights are allowed at the arrival fix and also at the runway. If any leader is not within a user-specified time window (default: 2 min), starting at the earliest estimated arrival-fix crossing time among the leaders, then it is dropped from the leaders' set. Each possible combination of arrival–fix-crossing orders and runway landing orders is evaluated for the flights in the leaders' set. The minimum cost combination is picked and the leading flights to each runway among the picked combination are scheduled (i.e., their arrival-fix and runway times are fixed). Here, delay cost is equal to the sum over the leader flights of

$$\textit{Flight Delay} \times \textit{Queue-delay factor}$$

where *Queue-delay factor* for flight *i* = Number of flights following flight *i* within a user-specified time window (e.g., 2 min) of its estimated arrival–fix-crossing time.

The scheduled flights are removed from the leaders' set, a new leaders' set is formed, and the process is repeated until all flights are released.

7.4.2 Implementation of Scheduling Algorithms

The following paragraphs describe different pieces of the implementation that were used to test the scheduling algorithms.

Assumptions

The following assumptions were implicit in the modeling/assessment process:

- Estimated runway-landing time is computed as the estimated arrival–fix-crossing time (taken from the input demand set) plus the nominal TRACON transit time, assuming a CDA profile (taken from a table of transit times as a function of the distance from the runway per aircraft weight class, generated by the Tool for Analysis of Separation and Throughput (TASAT) [RC08]).
- Nominal arrival-fix crossing speeds and runway landing speeds are taken from aircraft weight class–dependent tables (source: Airspace Concept Evaluation System (ACES) data).
- There are only two de-confliction points—the arrival fix and the runway. It is assumed that between these two points controllers will keep flights separated and try to meet the scheduled times at the runway.
- The arrival-fix minimum spacing requirement between consecutive arrival-fix crossings is 5 nm.
- The runway spacing requirement between consecutive runway landings is taken from an aircraft weight class–dependent matrix of distance spacing requirements (source: ACES data).

Realization of the Algorithms

MATLAB [MW09] was used as the platform for developing the implementation of the FIFO and optimal scheduling algorithms. Input demand sets processed by the MATLAB script consisted of initial estimated arrival–fix-crossing time, initial estimated runway landing time, aircraft weight class, landing runway/airport identifier, and arrival-fix identifier for each flight. The MATLAB script processes the initial estimated arrival times of the flight by applying processing in line with FIFO or optimal scheduling to compute the scheduled arrival-fix and runway times. En-route, TRACON, and total delay per flight are computed as the difference between the initial and scheduled times. Delay metrics for each generic airspace geometry under both scheduling options were collected and compared. The results of delay comparison are presented in the next subsection.

7.4.3 Scheduling-Analysis Results

This section presents results of the Generic Metroplex analysis based on the alternative scheduling options. The metrics collected during initial simulation runs were:

- En-route delay per flight (= Delay absorbed before reaching the arrival fix)
- TRACON delay per flight (= Delay absorbed between the arrival fix and the runway)
- Total delay per flight (= Sum of en-route and TRACON delays)
- Distribution of the delay across flights going to airport A vs. airport B vs. overall delay

Generic Metroplex Geometries 1 and 2

Figure 32 shows the total delay distribution for airport A, airport B, and overall for geometry 1 or 2 (shared arrival fixes/shared arrival fixes and terminal arrival routes). It is seen that the total delay at an airport/runway was roughly correlated to the number of operations at the airport/runway, but the relationship was not linear. Airport A had twice as much traffic as airport B, hence it had a much larger amount of delay. Also, it is seen that optimal scheduling (green bar) saves approximately 12% delay overall as compared to the no scheduling (FIFO) option (red bar).

Figure 33 shows the distribution of delay between TRACON and en-route for geometry 1 or 2. It is seen that most of the delay was absorbed within the TRACON, because excess arrival-fix spacing was not provided between successive arrival flights and that lack of spacing led to significant congestion inside the TRACON and at the runways. Also, it is seen that optimal scheduling tended to transfer some delays from TRACON to en-route delays while minimizing total delays.

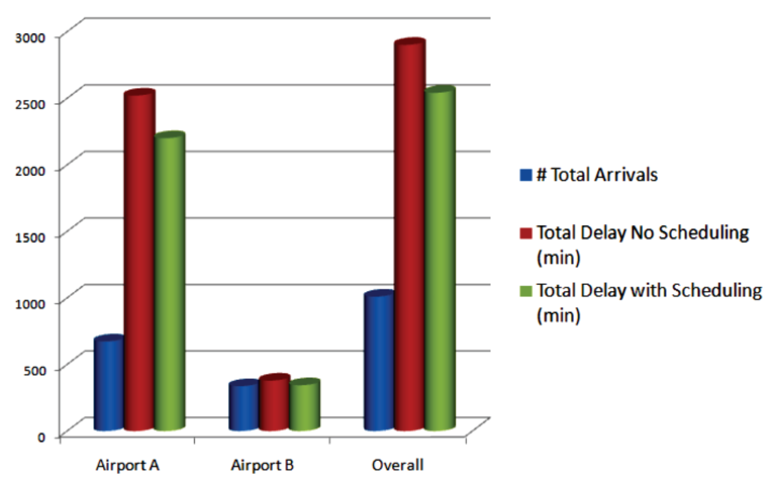


Figure 32. Geometry 1 or 2 – Distribution of total delay across airports in the Generic Metroplex.

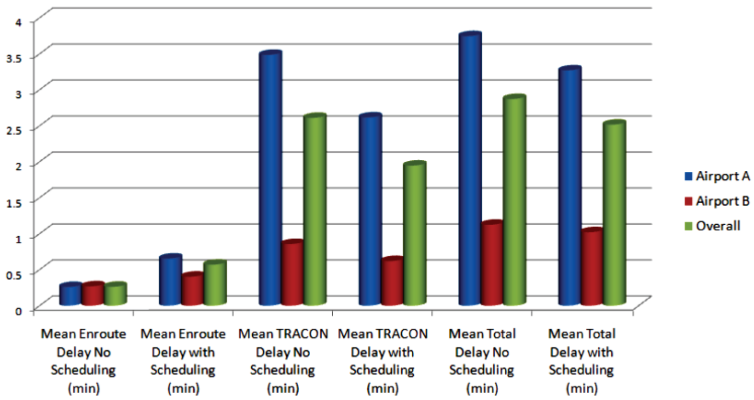


Figure 33. Geometry 1 or 2 – Distribution of delay between en-route and TRACON.

Generic Metroplex Geometry 3

Figure 34 shows total delay distribution for airport A, airport B, and overall for geometry 3. Again delay was roughly correlated with the number of operations at each runway. The optimal scheduling saved approximately 10% delay over no scheduling here.

Figure 35 shows the distribution of delay between TRACON and en-route for geometry 3. Again, it is seen that most of the delay was absorbed within the TRACON. The imbalance between en-route and TRACON delays was more severe here because in geometry 3 each arrival fix served only one airport and hence flights going through the fix did not have to be spaced with respect to flights going to the other runway. This situation created an excess influx of flights into the TRACON that the busier runway could not handle without excessive TRACON delay.

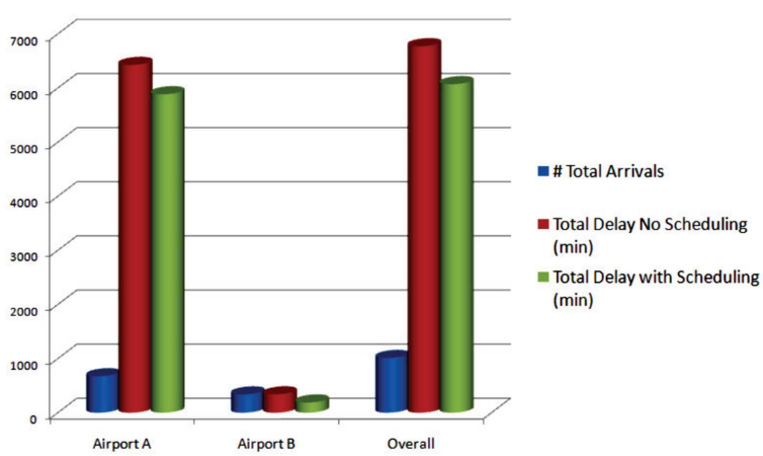


Figure 34. Geometry 3 – Distribution of total delay across airports in the Generic Metroplex.

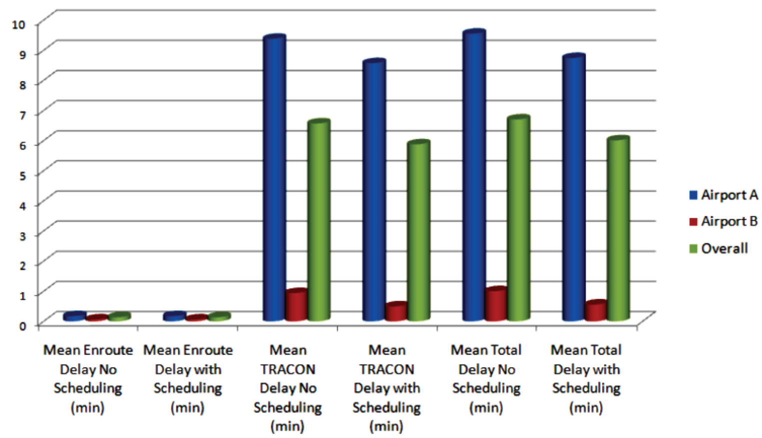


Figure 35. Geometry 3 – Distribution of delay between en-route and TRACON.

Comparison and Conclusion

Finally, Figure 36 shows a comparison of total airport/runway delay with the optimal scheduling and without scheduling for both geometries 1 and 3. It is seen that both with and without scheduling, total arrival delays were 57% lower in geometry 1 airspace than in geometry 3 airspace. However, with scheduling, arrival delay at airport B for geometry 3 was 45% lower as compared to geometry 1, while with scheduling, arrival delay at airport A for geometry 3 was 62% higher as compared to geometry 1.

From this analysis, it was shown that geometry 3 (exclusive arrival fixes per metroplex airport) was better as compared to geometry 1 (shared arrival fixes) only for airports with a low demand/capacity ratio. For airports with high demand/capacity ratios the runway was the main constraint. The analysis based on the scheduling algorithms described in sections 7.4.1 and 7.4.2 shows that it might be better to have shared arrival fixes across multiple metroplex airports. This observation is worth further examination in the future; factors that could be considered include traffic volume at each arrival fix and possible enhancements to the scheduling algorithms presented in this section to improve the handling of shared arrival fixes. In any case, the optimal scheduling saved around 12% delay over no scheduling for geometry 1 generic airspace and around 10% for geometry 3 generic airspace.

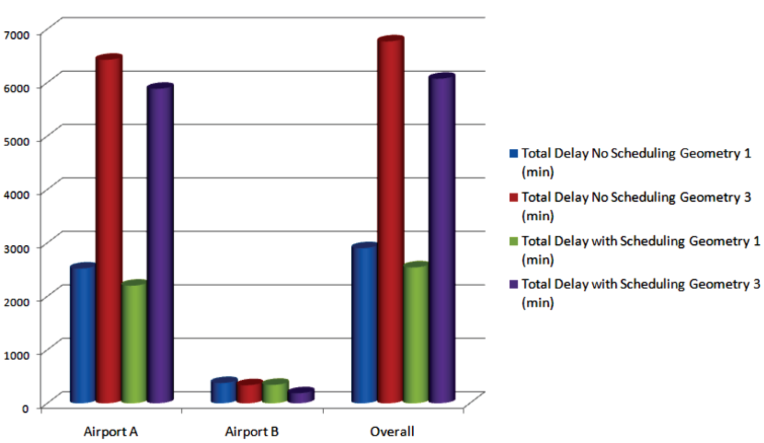


Figure 36. Comparison of total delay between geometry 1 (or 2) and geometry 3.

7.5 Generic Metroplex Queueing Simulation

To thoroughly evaluate the impact of future metroplex concepts and identify the most promising concepts, a linked-node queueing-process–based simulation was created to determine the delay of arrival operations. In this simulation study, the intention was to vary each parameter to span the range of all the Next-Generation Air Transportation System (NextGen) capabilities as well as technologies that have been conceptualized by the Georgia Institute of Technology (GaTech) team.

Details of the linked-node queueing-process model and the associated assumptions are presented in the next subsection. The parameters tested and their ranges of variation, the test conditions, and specific test cases are described in section 7.5.2. Results from each test case are presented as a separation subsequent subsection.

7.5.1 Linked-Node Queueing-Process Model

Because of limited time available for this project, only arrival operations were studied. As illustrated in Figure 37, two types of shared resources are modeled in the linked-node queueing process: entry fixes and runways at metroplex airports. Theoretically, points where traffic flows merge or cross (at the same altitude) could also be modeled, but they are omitted for the sake of simplicity. The model is reconfigurable to have any number of entry fixes and any number of runways. Each entry fix is modeled as a single-server FIFO queue with infinite capacity. The service time is a random variable corresponding to minimum required separation at the arrival fix (i.e., 5 nm) because of the random fix-crossing speed. If an aircraft arrives at the entry fix when the queue is empty and no aircraft is being served (meaning the spacing from the previous aircraft is greater than the minimum required separation), it is released to enter the metroplex terminal area immediately, thus no queueing delay is incurred. When another aircraft is being served, regardless of queue length, the aircraft has to wait until the server is free. The waiting time in the entry fix queueing is referred to as the entry delay.

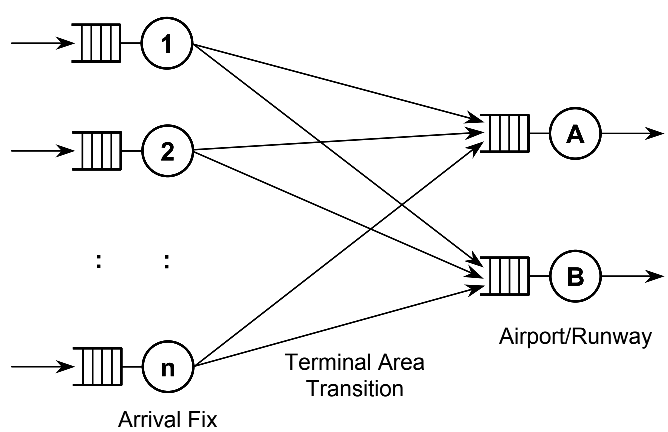


Figure 37. The linked-node queueing-process model.

Each runway at a metroplex airport is also modeled as a single-server FIFO queue with infinite capacity. Note that the runway queue capacity is physically limited because of the limited volume of airspace within the terminal area. When runway queue is full, holding may be implemented at the entry fixes. Assuming an infinite runway queue capacity simplifies the coding of the simulation, it also allows schematic trend analysis as the arrival-rate approaches very large values, as discussed in section 7.5.3. The service time is a random variable corresponding to minimum required separations at the runway threshold (i.e., wake vortex separation as a function of aircraft weight class) and the random final approach speed. Similar to entry fixes, queueing delays may incur at the runway threshold. This delay is referred to as the runway delay. In the real world, this delay may be incurred anywhere between the entry fix and the runway through path stretching or speed adjustment. Based on the temporal-spatial displacement concept, the delay is assumed to incur at the runway threshold without losing generality. Potential ground infrastructure limitations are ignored in the model, assuming that no other runway delays will incur except the queueing delays due to the required wake vortex separation.

Inputs to the linked-node queueing-process model are aircraft arriving at entry fixes and destined to predefined runways. For each aircraft the aircraft type is specified. The arrival aircraft sequence at an entry fix can be specified either by an arrival rate with a specified inter-arrival time distribution or by a sequence of arrivals (normally one day's worth of traffic) with the fix arrival time for each aircraft specified.

The links between the entry fix nodes and the runway thresholds are reconfigurable, ranging from each entry fix linked to a specific runway (fully segregated traffic flows, e.g., Generic Metroplex geometry 3) to every entry fix linked to every runway (fully shared entry fixes, e.g., Generic Metroplex geometry 1). The link between an entry fix and a runway threshold is a terminal-area arrival transition assuming a CDA-type vertical profile and speed profile overlaid on the lateral path given in the Generic Metroplex airspace design. A large pool of CDA trajectories were simulated for different aircraft types using TASAT [RC08] with uncertainty factors such as random aircraft weight, short-term wind variations, and random pilot-action delays. For a specific aircraft, a trajectory is randomly sampled from the pool. As such, the transition time from an entry fix to a runway threshold is a random variable. The arrival time at the runway queue is thus a random variable determined by the release time at the entry fix and the random terminal-area arrival transition time.

The linked-node queueing-process model is implemented as a discrete-event simulation in SimPy—an object-oriented, process-based discrete-event simulation language based on standard Python [MV03]. The output of the simulation is a log of events associated with each aircraft, including aircraft identification, entry fix, entry delay, entry fix-crossing time, runway, runway delay, and runway threshold-crossing time. The system performance can then be measured by entry delay, runway delay, and total delay on a per-aircraft basis or as a cumulative system-wide total.

7.5.2 Generic Metroplex Test-Case Design

In this simulation study, the intention was to vary each parameter to span the range of all the NextGen capabilities as well as technologies that have been conceptualized by the GaTech team. Parameters considered include traffic demand, airspace geometry, arrival scheduling, and metering accuracy. The variations of these parameters were grouped into three test cases. Delays were the output metrics being measured. The parameter setup of the three test cases is described as follows.

Delay vs. Arrival Rate

Hypothesis

The hypothesis of this test case was that as the arrival rate (i.e., traffic volume) increases the chokepoint of the Generic Metroplex system might shift from runways to entry fixes and, in addition, different Generic Metroplex geometries might behave differently under different arrival rates.

Control Variables

In this test case arrival rate was the major control variable. The total metroplex arrivals were equally divided as independent Poisson processes among the available entry fixes for the Generic Metroplex geometry being tested. Arrivals at each entry fix were modeled as a Poisson process that was fully defined by the arrival rate at the fix. The total metroplex arrival rate varied from 0 aircraft per hour (AC/hour) to a theoretical value of 2,000 AC/hour. The same arrival-rate range applied to all geometries tested.

The airspace geometry was the second control variable. Generic Metroplex airspace design geometries 1, 3, and 4 were tested. Geometries 2 and 1 have the same number of entry fixes. Because merge points within the Generic Metroplex terminal area were not modeled, geometries 2 and 1 were thus viewed as the same for all three test cases.

For this analysis, arrival scheduling was not implemented and the metering accuracy was assumed perfect to eliminate any possible nuisance effect on the output. This is to say, no additional uncertainty was applied to the entry fix arrival times generated by the Poisson process.

Execution of Test Runs

The number of test runs for this test case was given by

$$\textit{Number of Geometries}\ (3) \times \textit{Number of Arrival Rate Values}$$

For each test run, i.e., a given airspace geometry at a given arrival rate, the simulation lasted for 24 hours. The 24-hour simulation time assured that the queueing system reached the steady state for the major part of the entire simulation time. The results of this test case are presented in section 7.5.3.

Impact of Arrival Scheduling

Hypothesis

The hypothesis of this test case was that with the scheduling algorithm runway delays might be significantly reduced, while at the same time the increase in entry delays might be limited, resulting in reductions in overall delay; additionally, the effectiveness of the scheduling algorithm might vary with the specific Generic Metroplex airspace geometry being used.

Control Variables

In this test case, the Generic Metroplex demand sets described in section 7.2.2 were used. A demand set was generated for each of the Generic Metroplex airspace geometries. In each demand set, the inter-aircraft time interval at each entry fix was adjusted per the spacing model described in section 7.2.3 to emulate the spacing effort by Center controllers. Each demand set covers a 24-hour period.

The arrival scheduling was the major control variable. When no scheduling algorithm was used, the sequences of estimated time of arrival (ETA) at the entry fixes given by the demand set were used as the aircraft arrival times at the entry fixes. When the scheduling algorithm (as described in section 6.6) was used, the sequences of ETA were adjusted by the scheduling algorithm to generate sequences of RTA that were then fed into the simulation as arrival times at the entry fixes.

The airspace geometry was the second control variable. In this test case, only Generic Metroplex airspace design geometries 1 and 3 were tested. Geometry 4 was not tested because: the intersect flow analysis (see section 7.3) indicated a significant increase of traffic flow complexity for geometry 4 over geometry 1and the sensitivity analysis of delay vs. arrival rate indicated that without a sophisticated scheduling algorithm, all delays would be incurred within the terminal area, resulting in significant inefficiencies.

The metering accuracy was assumed perfect, i.e., no additional uncertainty was applied to the original entry fix arrival times generated by the demand set or the new entry fix arrival times adjusted by the scheduling algorithm.

Execution of Test Runs

The number of test runs for this test case was given by

$$\textit{Number of Geometries}\ (2) \times \textit{Number of Scheduling Options}\ (2)$$

For each test run, i.e., a given airspace geometry with or without scheduling, the simulation started when the first flight in the demand set arrived at the entry fix and ended when the last flight in the demand set crossed the runway threshold. The results of this test case are presented in section 7.5.4.

Impact of Temporal Control Accuracy

Hypothesis

The hypothesis of this test case was that en-route temporal control (metering) accuracy might have a significant impact on delays. The lower the metering accuracy the higher the delay might be. The metering accuracy might impact the delay more when scheduling was used because the metering accuracy would negate the performance of scheduling and the impact might be dependent on Generic Metroplex airspace geometry.

Control Variables

As in the previous test case, the Generic Metroplex demand sets described in section 7.2.2 were used. Again, each demand set covers a 24-hour period.

The metering accuracy was the major control variable. The metering error was defined by the difference between the actual time of arrival and the nominal time of arrival. The nominal times of arrival were the original sequences of ETA for arrivals without scheduling and the adjusted sequences of RTA for arrivals with scheduling. The metering error was assumed to follow normal distributions with a bias of zero sec and a standard deviation ranging from zero (perfect metering) to 30 sec with a 6-sec step size.

The airspace geometry was the second control variable. As in the previous test case, the Generic Metroplex airspace design geometries 1 and 3 were tested.

The arrival scheduling was the third control variable. For each geometry tested the metering accuracy was tested with arrival scheduling and then without arrival scheduling. Again, the scheduling algorithm described in section 6.6 was used for this purpose.

Execution of Test Runs

The number of test runs for this test case was given by

Number of Geometries (2) × *Number of Scheduling Options* (2) × *Number of metering error values* (10)

For each test run, i.e., a given airspace geometry with or without scheduling and a given metering accuracy, the simulation started when the first flight in the demand set arrived at the entry fix and ended when the last flight in the demand set crossed the runway threshold. The results of this test case are presented in section 7.5.5.

7.5.3 Sensitivity Analysis of Delay versus Arrival Rate

As specified in the test-case design, this analysis was conducted to study the effects of the arrival rate on Generic Metroplex system-wide delays. The results of this analysis are shown in Figure 38, Figure 39, and Figure 40 for the Generic Metroplex airspace design geometries 1, 3, and 4, respectively. As mentioned before, geometries 2 and 1 have the same number of entry and exit fixes. They thus were viewed as the same for this analysis. In each of the figures average queueing delay per aircraft at the entry fix, average queueing delay per aircraft at the runway, and the total delay per aircraft (sum of the previously mentioned two) are plotted versus metroplex total arrival rate on the left and versus metroplex mean time between arrivals (MBA) on the right. Because there are only two airports within the Generic Metroplex model, high arrival rates such as those greater than 500 AC/hour would be way beyond the runway capacity. Data at those values are presented to highlight the general trend.

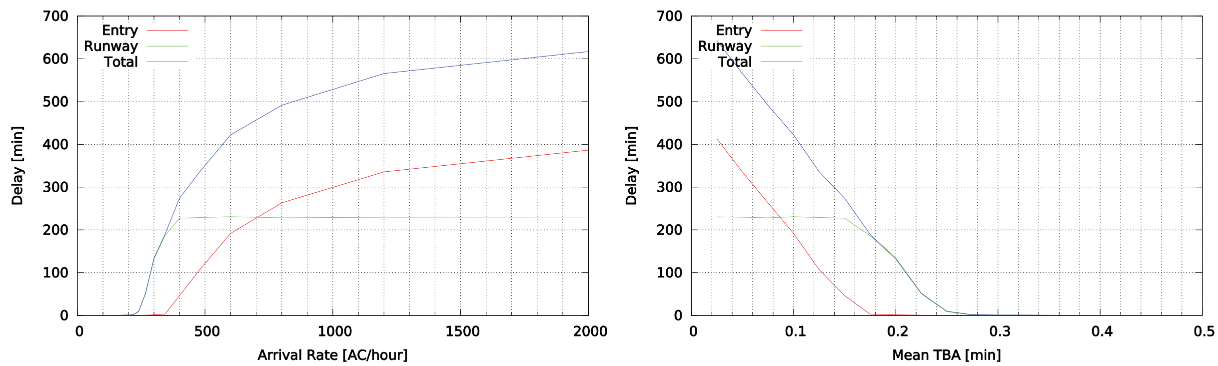


Figure 38. Total delay per aircraft versus arrival rate and MBA for geometry 1.

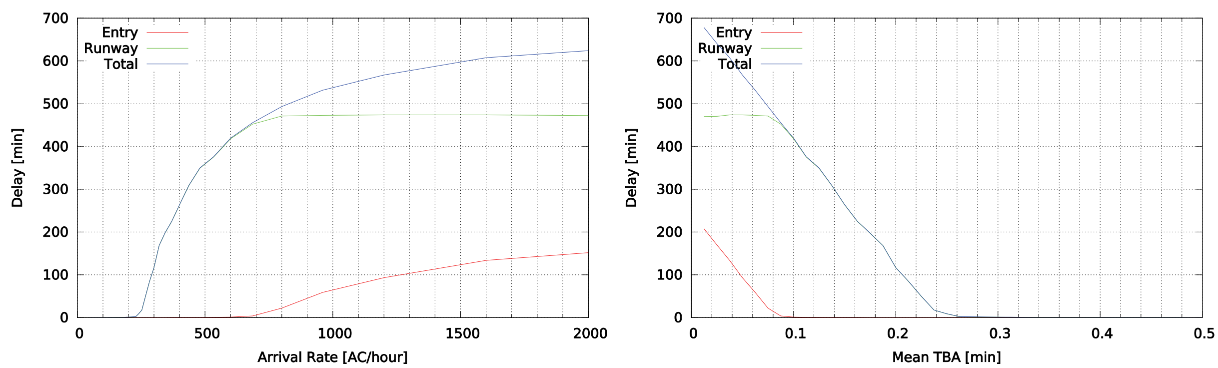


Figure 39. Total delay per aircraft versus arrival rate and MBA for geometry 3.

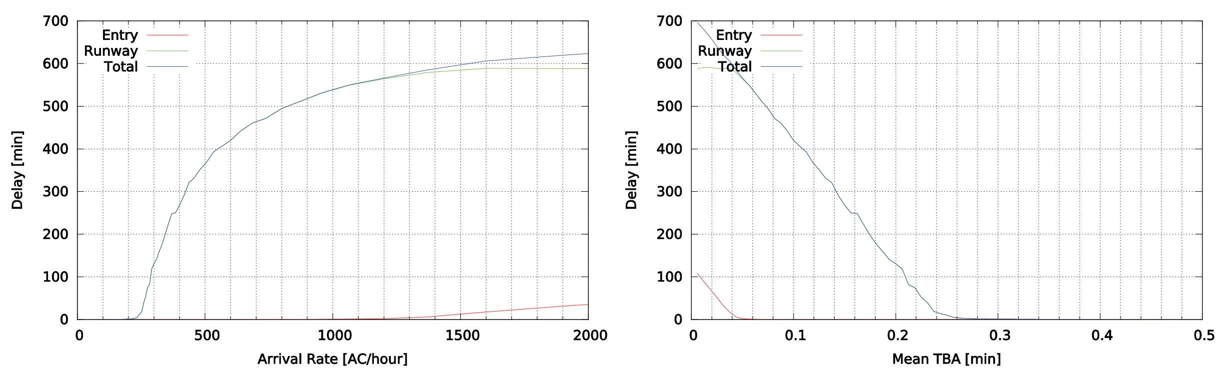


Figure 40. Total delay per aircraft versus arrival rate and MBA for geometry 4.

Figure 38, Figure 39, and Figure 40 show that for all three airspace geometries, delays at runways started to diverge much earlier than delays at entry fixes. There were several reasons behind this observation. The ground speed during approach is normally much lower than that at entry fixes. The compression effect requires spacings larger than separation minima in effect at entry fixes. If only the separation minima were enforced at entry fixes, delays would have to be absorbed within the TRACON as traffic volume increased. In the Generic Metroplex model there were only two arrival runways, one at each of the two airports, while there were 4 entry fixes for geometry 1, 8 for geometry 3, and 16 for geometry 4. Aircraft from different fixes would have to be merged to the runway at each airport. Even if proper spacings were enforced at entry fixes, issues would likely rise at the runways.

Another connected observation is that as the number of entry fixes increased from 4 for geometry 1 to 16 for geometry 4, and the divergence of delays at entry fixes occurred at a later time and at a slower rate as the total metroplex arrival rate increased. Because the same volume of metroplex total traffic was divided into more fixes, delays incurred because spacings in the traffic stream at each entry fix were lower. In addition, because more entry fixes existed, the ripple effect at entry fixes due to runway congestion was weaker.

As the arrival rate continued to increase, the delays at runways reached a saturation value. From that point on, even if the injected arrival rate continued to increase, the runway delays remained the same. The transition from the increasing runway delay to constant runway delay occurred when the entry fixes reached their capacities; thus the rate of aircraft entering the TRACON airspace remained constant from that point on. Any additional aircraft injected at the entry fixes were held at the entry fix. Delays at entry fixes started to rapidly diverge at the same time. As the number of entry fixes increased, the metroplex total arrival rate corresponding to entry fix saturation point became larger. As a result, the maximum delay per aircraft at runways increased. The transition point was about 400 AC/hour for geometry 1, 800 AC/hour for geometry 3, and 1,600 AC/hour for geometry 4, corresponding to 100 AC/hour/fix.

Figure 38, Figure 39, and Figure 40 also show that the average total delay per aircraft remained roughly the same for the three Generic Metroplex geometries studied. This result indicates that, without arrival coordination (as was the case with this analysis), making more entry fixes available for the metroplex would allow some delays that previously were absorbed in en-route airspace during very busy periods to be transferred to terminal-area airspace. Delays within the terminal-area airspace normally cost more than the same amount of delays within the en-route airspace because aircraft are more efficient in the en-route airspace when aircraft are at higher altitudes and cleaner configurations. Thus, extra entry fixes may not always be beneficial under high traffic conditions, unless existing arrival fixes are identified as the bottleneck (not the case with this analysis), or when arrival coordination capabilities are in place. As seen in Figure 25, with 16 arrival fixes and 16 departure fixes, the airspace structure is very complex. Managing and coordinating traffic flows under high traffic conditions would be a very challenging task. Additionally, any airspace geometry design change would likely face different environmental issues.

In interpreting the results, one must note that with multiple entry fixes, such as in geometry 4, arrivals can fly routes that are more direct as compared to the four-corner-post design such as geometry 1. Under relatively light traffic conditions, the benefits of flight time and fuel savings from flying short routes will out-weigh possible delays in the terminal area. In this case, however, a large number of predefined entry fixes may not be essential. In fact, at light traffic conditions, arrivals are often cleared “direct to” the airport without going through the predefined arrival gates that have to be used during busy periods.

Based on these discussions,only geometries 1 and 3 are discussed in the analyses to be presented in the next few sections.

7.5.4 Impact of Arrival Scheduling

As specified in the test-case design, this analysis was conducted to study the effect of scheduling. For the given demand generated for the Generic Metroplex model, simulation was first done without applying the scheduling algorithm to the arrival traffic and then repeated with the scheduling applied. To compare system performance of each airspace geometry design, the cumulative delay is plotted against cumulative aircraft count for the entire day of traffic, as shown in Figure 41. In these plots, the instantaneous slope at each point indicates the throughput per unit delay; the shallower the slope, the better the system performance. The overall position of the curve indicates system performance over time; the lower the curve, the better the performance. As shown in the figure, both entry delays and runway delays were significantly reduced by arrival scheduling. In terms of cumulative total delay, a 75% reduction was achieved. Similar delay reductions results were observed for both geometries 1 and 3.

Another interesting observation from Figure 41 is that, without scheduling, the cumulative entry delay was slightly lower for geometry 3 than for geometry 1, apparently because of the increased number of entry fixes available. However, the cumulative runway delay was slightly higher for geometry 3 than for geometry 1. Because traffic flows at entry fixes were less constrained in geometry 3, the runway thus had to absorb more delays than the runway in geometry 1. The cumulative total delay, however, remained roughly the same. With scheduling, the cumulative total delay was much lower for geometry 3 than for geometry 1, indicating improvements resulted from the combination of temporal control and spatial control.

Figure 41 also shows that, regardless of Generic Metroplex geometry and scheduling, the cumulative runway delay was always much higher than the cumulative entry delay. In the initial Generic Metroplex design, there were only two airports, each having only one arrival runway. The demand capacity ratio of 0.7 at airport A was actually relatively high, close to the demand capacity ratio of ATL [RC09b]. This setup determined that runways were choke points in the system and consequently the majority of delays were incurred at runways. The high delay reductions from arrival scheduling reflect the necessity of scheduling for managing critical shared resources. In addition to segregating traffic flows from and to different airports, the increased number of entry fixes increases the total entry fix capacity. As the number of airports increases, the capacity at entry fixes may become more critical, and consequently entry delay will increase. The benefits of airspace geometries with more entry fixes, such as geometry 3, would be higher.

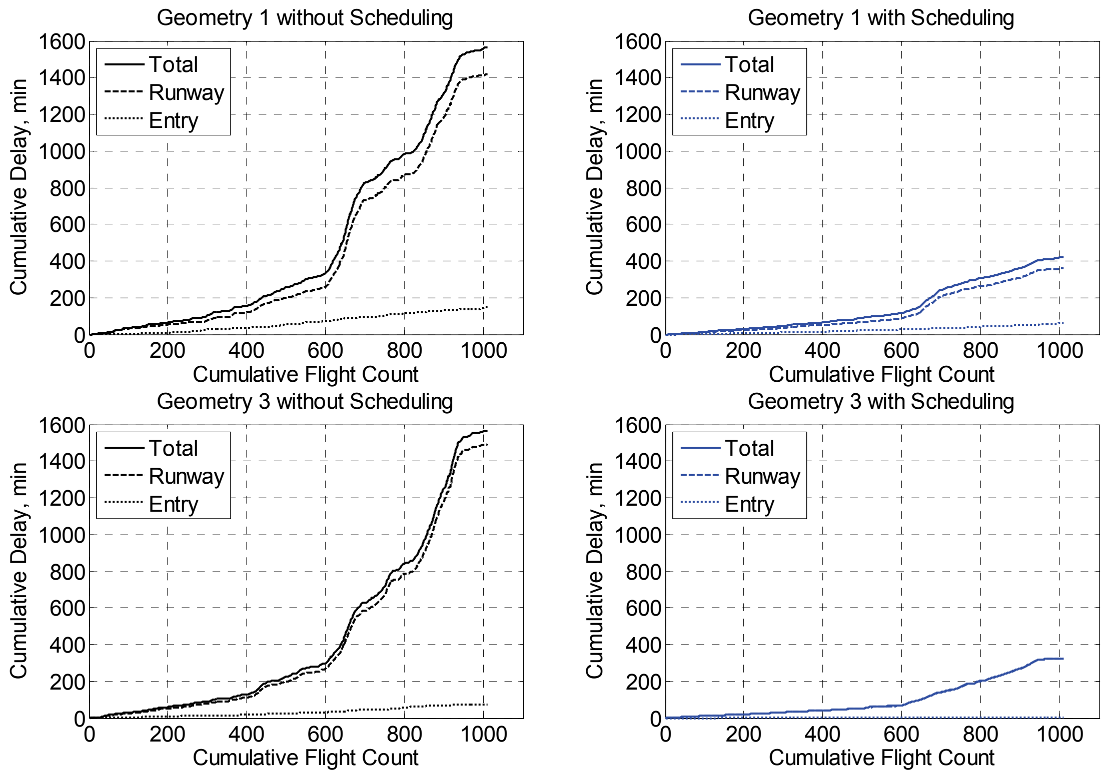


Figure 41. Cumulative delays versus cumulative throughput with and without scheduling.

The comparison of total delay per aircraft between geometry 1 and geometry 3 with and without scheduling is shown in Figure 42. As can be seen, on average without scheduling, a total delay of 1.55 min per aircraft was incurred in both geometries 1 and 3. With scheduling, the average total delay per aircraft was reduced to 0.42 min in geometry 1 and 0.32 min in geometry 3, corresponding to reductions of 73% and 79%, respectively. While without scheduling the average total delay per aircraft was roughly the same in both geometries, with scheduling the delay was 23% lower in geometry 3 than in geometry 1.

The comparison of total delay per aircraft between airport A and airport B with and without scheduling is shown in Figure 43. As can be seen, on average without scheduling, a total delay of 2.16 min per aircraft was incurred for flights destined to airport A, in both geometries 1 and 3. The average total delay per aircraft was 0.34 min for flights destined to airport B, in both geometries 1 and 3. The difference between airport A and airport B was mostly due to the difference in traffic demand at these two airports. While the traffic volume at airport B was about 50% of that at airport A, the average total delay per aircraft was 84% lower at airport B. This nonlinear relationship is typical of queueing systems. This observation suggests that, when airport runways are chock points, moving some operations from busy airports to a less-busy secondary airport may reduce metroplex system-wide delays because when demand is approaching capacity at busy airports, queueing delays tend to diverge.

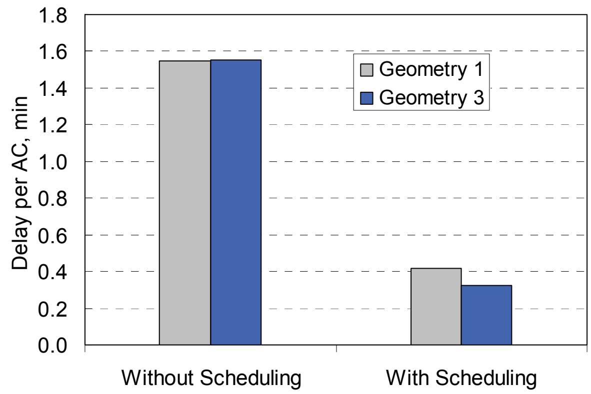


Figure 42. Comparison of total delay per aircraft between geometries, with and without scheduling.

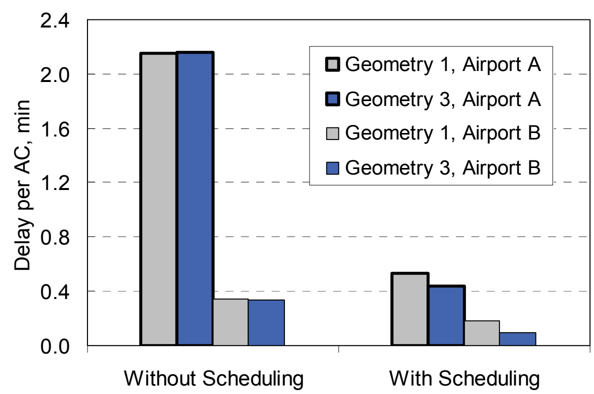


Figure 43. Comparison of total delay per aircraft between airports, with and without scheduling.

As shown in Figure 43, with scheduling, the average total delay per aircraft was reduced to 0.54 min for flights destined to airport A in geometry 1 and 0.44 min for flights destined to airport A in geometry 3, corresponding to reductions of 75% and 80%, respectively over the unscheduled case. For airport B, the average total delay per aircraft was reduced to 0.18 min in geometry 1 and 0.09 min in geometry 3, corresponding to reductions of 46% and 73%, respectively over the unscheduled case. Again, while without scheduling the average total delay per aircraft was roughly the same for flights destined to airports in both geometries, with scheduling, the average delay per aircraft was 18% lower for airport A in geometry 3 than for airport A in geometry 1, and almost 50% lower for airport B in geometry 3 than for airport B in geometry 1. With scheduling, geometry 3 contributed to further reductions in average per aircraft delays.

7.5.5 Impact of Temporal Control Accuracy

This analysis was conducted to study the effect of arrival–fix-crossing metering accuracy on delays. As shown in Table 21, the bias, i.e., the difference between the mean fix-crossing time and the nominal boundary crossing time is zero in both current systems and future four-dimensional trajectory (4-DT) operations. Thus, in this analysis, only different grouping values (defined as the variation in terms of two times standard deviation) were tested. A Generic Metroplex queueing simulation was conducted with the standard deviation (denoted as σ) ranging from 0 to 54 sec, with a 6-sec step. Note that this range is wider than the uncertainty assumption presented in Table 21. It was selected to better illustrate the trend of metroplex performance.

Figure 44 shows cumulative delay versus cumulative aircraft count for the entire day of traffic under three metering accuracy values: σ = 0, 24, and 54 sec. Arrivals without scheduling are shown for geometries 1 and 3 on the left and with scheduling on the right. It is seen in Figure 44 that in all cases, there was a trend of increase in delays as the metering accuracy decreases (larger σ values). However, in the cases of arrivals with scheduling, the trend was more consistent throughout the day. With scheduling, flights were planned to cross entry fixes at target times to reduce potential conflicts. Lower metering accuracy means less target time compliance, thus negating some of the scheduling benefits. By comparing results without scheduling on the left and results with scheduling on the right, it is seen that even for σ values comparable or larger than current operational performance (see Table 21), most of the scheduling benefits could still be retained.

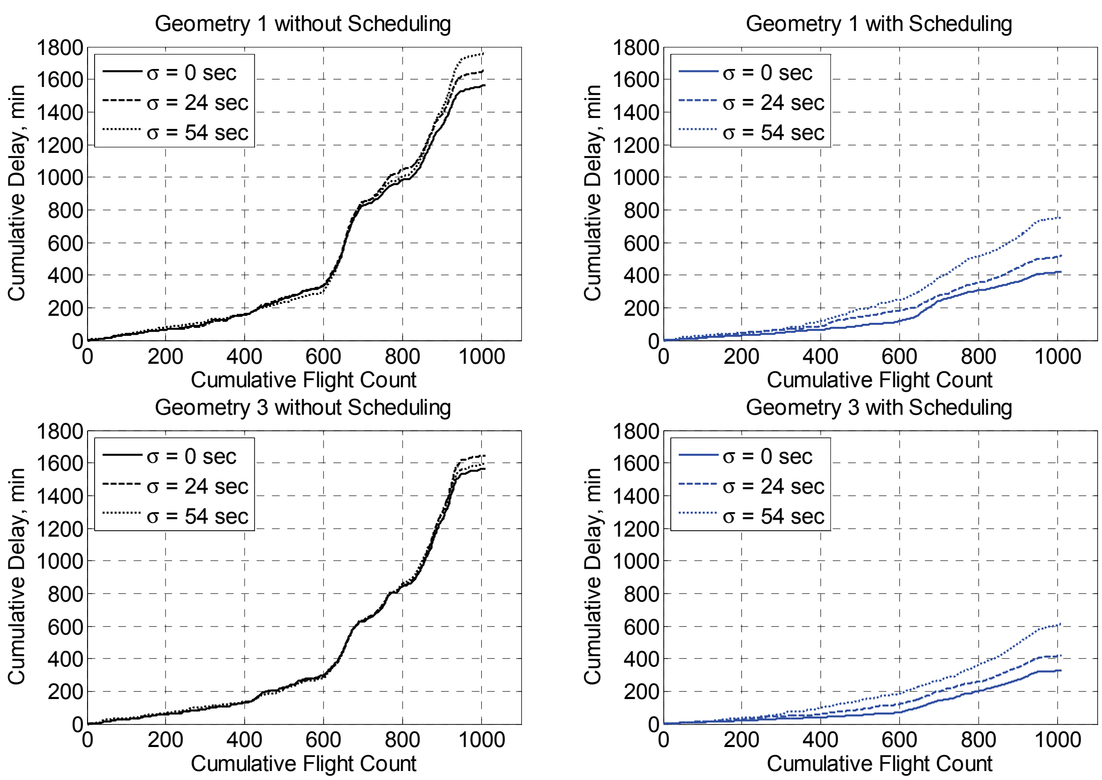


Figure 44. Cumulative total delays versus cumulative throughput with different metering accuracy.

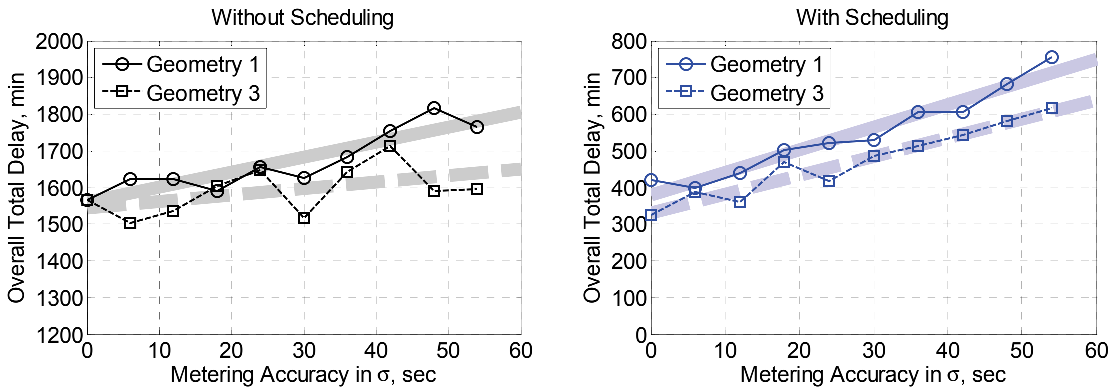


Figure 45. Overall total delays versus metering accuracy.

To further the understanding of the relationship between delays and metering accuracy, the overall total delays of the entire day are plotted against σ values in Figure 45. Results for arrivals without scheduling are on the left, and those with scheduling are on the right. In this figure, the shaded bands are linear regressions of data points. The vertical axes have different lower and upper limits but the same scale. Thus, the slope of the curves can be compared with each other.

As seen in Figure 45, in all cases the trend of increasing delays with increasing σ values was observed. Again, it is seen that the trend was more consistent throughout different σ values for arrivals with scheduling. The slopes for arrivals with scheduling were also slightly higher, meaning that the metering accuracy had a stronger impact on scheduling. It was observed that for the largest σ value tested (54 sec), nearly one-third of the 75% overall total delay reductions could be lost. Still, even in this worse case, the delays were reduced by 50% from the case without scheduling. It is also observed that, for any given metering accuracy, the delays were lower in geometry 3 (segregated traffic flows to different airports) than in geometry 1 (shared entry fixes).

7.5.6 Conclusions of the Generic Metroplex Queueing Simulation

With the developed linked-node queueing-process model, three simulation studies were conducted: sensitivity analysis of delay vs. arrival rate, the impact of arrival scheduling, and the impact of temporal control accuracy. For arrivals, the entry fixes at the boundary of the metroplex terminal area and the runways at metroplex airports are two sets of flow check points.

The arrival-rate sensitivity analysis revealed that when runways are the choke points (capacity limits), increasing the number of entry fixes to segregate traffic to different airports would not necessarily help reduce delays. In this case, the entry fixes serve as regulators to limit the number of flights to runway queues and thus limit terminal area delays. Without arrival scheduling, at high traffic volumes, the average delay per aircraft remained roughly the same for the Generic Metroplex geometry 1 (4 shared entry fixes), geometry 3 (8 fixes, segregated routes), and geometry 4 (16 fixes, segregated routes). Actually, delays incurred within the terminal area tended to be higher as the number of entry fixes increased and therefore higher fuel-burn costs would be incurred. It is expected that to realize the benefits of more direct routing and decoupled traffic flows from an increased number of entry fixes, some mechanism to regulate arrival traffic should be in place. It is also expected that for metroplexes with multiple large hub airports, entry fixes may become major choke points; consequently an increased number of entry fixes would improve system-wide throughput.

The simulation revealed that arrival scheduling greatly reduced both entry delays and runway delays. Under the given simulation conditions, total delays for the entire day were reduced by roughly 75%. Delays were similar for geometries 1 and 3 when no scheduling was applied; with scheduling the decoupling of traffic flows in geometry 3 provided additional delay reductions. The simulation also revealed that the delay reductions realized by scheduling were most significant at busy airports. On average delay per aircraft was reduced by roughly 1.5 min from over 2 min to the order of 0.5 min for airport A, the busy airport in the Generic Metroplex.

The temporal control accuracy, or metering accuracy, affected delays whether or not scheduling was applied. The impact is more evident when scheduling was applied. Because the lower metering accuracy reduced the compliance to target fix-crossing times, some delay reduction benefits would be negated. However, even with the worst possible metering accuracy, two-thirds of the delay reductions from the perfect metering still could be retained, suggesting that even without the temporal control accuracy that is expected for future 4-DT operations, scheduling would still result in revolutionary delay reductions.

7.6 Generic Metroplex Environmental-Impact Analysis

In this section, the environmental-impact analysis conducted for the four Airspace Geometries of the Generic Metroplex is described. This analysis was conducted as an attempt to evaluate the fuel-burn and emissions impact of the four Generic Metroplex geometries. The effects of scheduling and temporal control strategies were not considered for the sake of simplicity. The analysis utilized the NAS-wide Environmental Impact Model (NASEIM) [M09] to model fuel burn and emissions. The results for each geometry were compared to the baseline (geometry 1).

7.6.1 NASEIM Fuel-Burn Calculations

Fuel-burn values in NASEIM are derived from Eurocontrol's Base of Aircraft Data (BADA) [BADA09], which contains fuel-consumption rates for specific airframe and engine combinations at various altitudes and modes of flight (thrust settings). For portions of the flight below 3,000 ft above ground level (AGL), fuel burn is given by the Emissions and Dispersion Modeling System (EDMS) [EDMS]. The basic formula for calculating fuel burn is given by:

$$F_{a,i} = ne_a \times ff_{a,i} \times tm_{a,i}$$

where:

$F_{a,i}$ = the fuel burned by aircraft a, while in mode i

ne_a= the number of engines on aircraft a

$ff_{a,i}$= the fuel flow rate of aircraft *a*, while in mode *i*

$tm_{a,i}$ = the time aircraft *a* spends in mode *i*

Flight modes are defined as climb, cruise, and descent, and are related to the engine thrust settings. The BADA and EDMS data tables specify fuel-flow rates by altitude and flight mode. The tables specify fuel-burn rates for low, nominal, and high aircraft weights; NASEIM assumes nominal aircraft weight. Fuel-flow rates for intermediate altitudes are interpolated from the table values. Fuel burn is then calculated by multiplying the specified fuel flow rate by the time spent between each node in the flight trajectory. Summing the fuel burn for each trajectory segment gives the fuel burn for the entire flight.

7.6.2 NASEIM Emissions Calculations

Emissions calculations in NASEIM utilize the value of fuel burned in each of several operational phases to estimate the mass of pollutants generated. For each of several pollutants (CO, HC, NO_x, and SO_x), the mass is given by:

$$M_{i,total} = \Sigma_m (F_m * EI_{i,m})$$

where F_m is the fuel burned in mode *m* (kg) and $EI_{i,m}$ is the emission index for pollutant *i* in mode *m* (g/kg fuel).

Engine-specific International Civil Aviation Organization (ICAO)/EDMS taxi/idle fuel-flow values are used to derive the fuel burn during the taxi phase, and are combined with ICAO/EDMS taxi/idle emission factors to compute the pollutant totals emitted during surface movement.

The airborne aircraft trajectory is broken into several phases. Below 3000 feet AGL, engine-specific ICAO/EDMS fuel-flow rates and emissions indices are applied, with takeoff values used from takeoff to 1000 feet AGL, climb values between 1000 and 3000 feet on departure, and approach values between 3000 feet and touchdown. The mapping from aircraft type to engine type is made based on a review of the domestic commercial fleet and default engine assignments specified in the EDMS.

Above 3000 feet AGL, aircraft-specific BADA fuel-flow factors are used. Each distinct segment is classified as a climb, cruise, or descent segment. The mean altitude of the segment is used to determine the corresponding BADA fuel-flow rate for that segment type.

7.6.3 Generic Metroplex Inputs to NASEIM

The flightpaths and traffic demand set for each geometry used as inputs to NASEIM were described in section7.2.1. Fuel-burn and emissions calculations also require specification of aircraft types and times at each point along each track. Speeds along each path were taken as linearly interpolated between 350 knots at the arrival or departure fix and 150 knots at the runway threshold. The arrival or departure fix-crossing times for each track were defined in the traffic demand set, and the times at each point along each track were computed from these points using the interpolated speeds described previously. A single aircraft type was used for this study (similar to a Boeing 757-200).

7.6.4 Results for the Generic Metroplex Environmental Impact Study

Results are presented for each of the four Generic Metroplex geometries. Fuel-burn and emissions totals, as well as total distance traveled, are given for arrivals, departures, and all flights. The percentage change for each of these relative to the baseline (geometry 1) is also shown.

Table 30, 31, and 32 show that geometry 3 had slightly better environmental impact for arrivals using this demand set than geometry 1, whereas for departures the numbers are slightly worse. The total values for geometries 1 and 3 look very similar. Emissions and fuel consumption for geometries 2 and 4 were higher than for geometry 1 for both arrivals and departures, with the values for geometry 4 being significantly higher.

TABLE 30. ARRIVAL FUEL BURN AND EMISSIONS FOR GENERIC METROPLEX, BY AIRSPACE GEOMETRY

	Arrival CO (kg)	**Arrival HC (kg)**	**Arrival NOx (kg)**	**Arrival SOx (kg)**	**Arrival Fuel (kg)**	**Arrival Distance (km)**
Geometry 1	1370.5	77.3	6866.5	702.8	702817.3	91046.2
Geometry 2	1406.3	79.3	7045.8	721.2	721171.1	95061.3
Geometry 3	1357.6	76.6	6802.0	696.2	696217.0	89327.9
Geometry 4	1519.9	85.7	7615.0	779.4	779429.6	107648.6

TABLE 31. DEPARTURE FUEL BURN AND EMISSIONS FOR GENERIC METROPLEX, BY AIRSPACE GEOMETRY

	Departure CO (kg)	**Departure HC (kg)**	**Departure NOx (kg)**	**Departure SOx (kg)**	**Departure Fuel (kg)**	**Departure Distance (km)**
Geometry 1	2213.4	126.9	59504.4	2804.1	2804013.1	87290.4
Geometry 2	2311.7	132.4	60575.2	2874.2	2874245.1	89745.1
Geometry 3	2225.2	127.5	59652.2	2813.2	2813180.2	87640.6
Geometry 4	2960.0	169.1	66525.2	3305.3	3305337.6	105376.2

TABLE 32. TOTAL FUEL BURN AND EMISSIONS FOR GENERIC METROPLEX, BY AIRSPACE GEOMETRY

	Total CO (kg)	Total HC (kg)	Total NOx (kg)	Total SOx (kg)	Total Fuel (kg)	Total Distance (km)
Geometry 1	3583.9	204.2	66370.9	3506.8	3506830.4	178336.7
Geometry 2	3718.0	211.8	67621.1	3595.4	3595416.2	184806.4
Geometry 3	3582.8	204.1	66454.2	3509.4	3509397.3	176968.5
Geometry 4	4479.9	254.9	74140.2	4084.8	4084767.2	213024.8

TABLE 33. FUEL BURN AND EMISSIONS PERCENT CHANGE FROM BASELINE, ARRIVALS

Geometries	Arrival CO, %	Arrival HC, %	Arrival NOx, %	Arrival SOx, %	Arrival Fuel, %	Arrival Distance, %
2 vs. 1	2.61	2.61	2.61	2.61	2.61	4.41
3 vs. 1	-0.94	-0.94	-0.94	-0.94	-0.94	-1.89
4 vs. 1	10.9	10.9	10.9	10.9	10.9	18.23

TABLE 34. FUEL BURN AND EMISSIONS PERCENT CHANGE FROM BASELINE, DEPARTURES

Geometries	Departure CO, %	Departure HC, %	Departure NOx, %	Departure SOx, %	Departure Fuel, %	Departure Distance, %
2 vs. 1	4.44	4.39	1.80	2.50	2.50	2.81
3 vs. 1	0.53	0.52	0.25	0.33	0.33	0.40
4 vs. 1	33.7	33.3	11.8	17.9	17.9	20.7

TABLE 35. FUEL BURN AND EMISSIONS PERCENT CHANGE FROM BASELINE, TOTALS

Geometries	Total CO, %	Total HC, %	Total NOx, %	Total SOx, %	Total Fuel, %	Total Distance, %
2 vs. 1	3.74	3.72	1.88	2.53	2.53	3.63
3 vs. 1	-0.032	-0.030	0.13	0.073	0.073	-0.77
4 vs. 1	25.0	24.8	11.7	16.5	16.5	19.5

7.6.5 Conclusions for the Generic Metroplex Environmental Impact Study

From Table 33, Table 34, and Table 35 it can be seen that geometry 3 had slightly better environmental impact for arrivals using this demand set than geometry 1, whereas for departures the numbers were slightly worse. The total values for geometries 1 and 3 look very similar. Emissions and fuel consumption for geometries 2 and 4 were higher than for geometry 1 for both arrivals and departures, with the values for geometry 4 being significantly higher.

7.7 Major Findings and Future Work

7.7.1 Summary of Major Findings of Generic Metroplex Simulation Study

In the Generic Metroplex model, four metroplex airspace design geometries were proposed. These geometries range from geometry 1 with a standard four-corner-post configuration and direct routing from entry fixes to runways, to geometry 4 with 16 entry fixes, 16 exit fixes, and fully segregated routes for traffic flows for the two airports. The intersect flow analysis indicated that geometry 3, with dual fixes as compared with the standard four-corner-post and segregated traffic flows, had lowest traffic flow interactions. The fuel-burn and emissions analysis indicated that geometry 3 had slightly better environmental impact. Geometry 4 would allow most direct routing for arrival and departures but it would also require numerous flow intersections, thereby increasing traffic-flow complexity. The linked-node queueing simulation with different arrival rates also indicated that, for the initial Generic Metroplex model with only two airports, runways were choke points. The increased number of entry and exit fixes in geometry 4 did not provide additional benefits. However, it is expected that as the number of airports and traffic demand increase, airspace geometries with more entry and exit fixes may become necessary. As such, additional simulation and analysis were focused on geometries 1 and 4.

Both the scheduling analysis (see section 7.4) and the linked-node queueing simulation (see section 7.5) indicated that arrival traffic scheduling could greatly reduce the amount of delays incurred at the Generic Metroplex terminal-area boundary and the amount of delays incurred within the Generic Metroplex terminal area. The linked-node queueing simulation indicated a 73% and a 79% overall total delay reduction for the geometries 1 and 3, respectively. Regardless of scheduling, geometry 3 provided additional delay reductions over geometry 1.

The linked-node queueing simulation indicated that the temporal control accuracy affected delay reductions provided by scheduling. Because the lower metering accuracy would affect the compliance to target fix-crossing times recommended by the scheduling algorithm, some delay-reduction benefits would be lost. However, even with the worst possible metering accuracy, two-thirds of the delay reductions from the perfect metering still could be retained. This result suggests that even without the high temporal control accuracy that is expected for future 4-DT operations, scheduling would still bring in revolutionary delay reductions (see Figure 46). Advance in trajectory predictions and 4-DT operations would then provide incremental improvements.

7.7.2 Future Generic Metroplex Analysis

Because of the limited time and resources, the Generic Metroplex analysis and simulation focused on arrival operations. Departure operations were studied but in much less depth. It is thus recommended that a detailed analysis and simulation be extended to departure operations. One challenge in studying the departure operations is realistic modeling of the over-flight traffic and downstream en-route traffic because these are the constraints for departure scheduling. For best performance, the departure scheduling algorithm should be coupled with en-route sequencing and spacing; or at a minimum it should have access to real-time en-route traffic information.

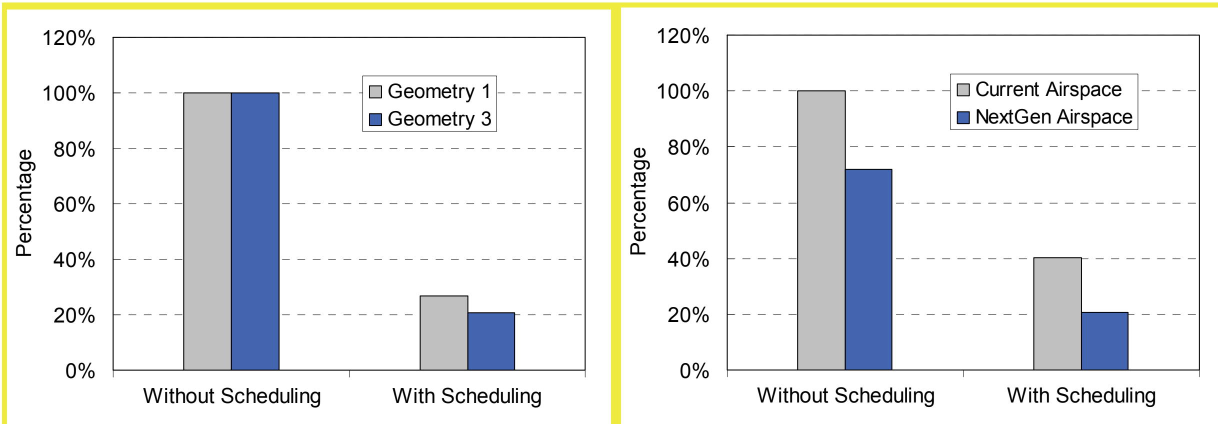


Figure 46. Comparison of total delay between airspace geometries with and without scheduling.

The initial Generic Metroplex model consisted of only two airports, each with a pair of parallel runways. This model represents a relatively simple metroplex, thus greatly simplifying the analysis and simulation. This simplification allowed the effects of NextGen concepts on system performance to be evaluated and the most promising concepts to be identified within the short study time frame, as demonstrated by the major findings presented in section 7.7.1. On the other hand, because of the simplifications, runway capacity was more of a constraint than entry fixes and exit fixes, whereas in the most complex metroplexes of the NAS, such as N90 and SCT, entry fixes and exit fixes frequently become major constraints. It is thus recommended that additional airports and runways be added to the Generic Metroplex analysis, with varying airport locations and runway orientations for future simulations studies to refine the concepts and identify concept technical challenges.

As the number of airports increases and the traffic flows become more complex, the size of the metroplex terminal area may also need to be adjusted from the current 40- to 50-nm radii to allow for better airspace geometry design concepts. Additionally, more flexible entry fix and exit fix setups need to be introduced. In the initial Generic Metroplex design, interactions between crossing routes were simplified; the route design method and the linked queueing model need to be extended to reflect those interactions.

One of the important factors that affect metroplex operations is airspace restrictions. As identified from the metroplex site-survey study, these restrictions include the effects of SUAs and terrain features. Because of limited resources available for the current project, SUA and terrain constraints were not considered in the initial Generic Metroplex model. These factors can be included in future Generic Metroplex analysis. SUAs and terrain features can be modeled parametrically to explore the impact of airspace restrictions on metroplex system performance. Various airspace designs and traffic coordination algorithms can be explored to identify best approaches to the problem.

For similar reasons, standard atmosphere and zero wind were assumed in the Generic Metroplex study. Severe weather was not considered either. These factors can be considered in future Generic Metroplex studies to test the robustness of the airspace design strategy and the scheduling algorithms. Problems associated with system response to severe weather can also be identified and explored.

8.0 N90 SIMMOD SIMULATION STUDY

8.1 Introduction and Background

The goal of the N90 simulation study was to verify in a real-world metroplex the Next-Generation Air Transportation System (NextGen) technologies that were down-selected as a result of analysis and the Generic Metroplex simulation study. As discussed in section 6.1, the two most important abstractions of NextGen technologies relevant to metroplex operations are spatially segregating terminal-area routes to and from multiple airports, and temporally coordinating arrivals and departures. N90, the most complex metroplex studied by the team, provides a suitable experiment platform. First, the effectiveness of the selected NextGen technologies can be tested in the most challenging environment. In addition, experiment results can provide recommendations to operational improvements in N90, to which 60% of the NAS-wide delays can be traced.

Members of the Georgia Institute of Technology (GaTech) team have been performing extensive modeling and simulation of the N90 airspace as part of the NASA Project NNH07ZEA001N-IAC1, entitled "Integration of Advanced Concepts and Vehicles into the Next Generation Air Transportation System (NextGen)". The focus of this research effort was to conduct a systems study that addresses the issues associated with deploying new/advanced vehicles by exploring the trade among procedures, vehicle characteristics, and overall NextGen performance. This work involved the analysis of advanced vehicles expected to be available for commercial use in the 2025 to 2040 time frame. The detailed modeling of current and NextGen procedures and technologies for the N90 Metroplex was directly applicable to achieving the objectives of the Metroplex Project, and the modeling used for the Advanced Vehicles project was leveraged to successfully meet these goals.

8.1.1 Simulation Tool

The simulation tool used for this effort was ATAC Corporation's Airport and Airspace Delay Simulation Model, SIMMOD. SIMMOD is a discrete-event simulation model that traces the movement of individual aircraft and simulated air-traffic-control (ATC) actions required to ensure aircraft operate within procedural rules. This tool computes capacity and aircraft delay-related metrics caused by a variety of inputs, including traffic demand and fleet mix, route structures (both in the airspace and on the airport surface), runway use configurations, separation rules and control procedures, aircraft performance characteristics, airspace sectorization, interactions among multiple airports, and weather conditions. SIMMOD uses a node-link structure to represent the airspace route structure and the surface system, including runways, taxiways, and gates.

Based upon a user-input scenario, SIMMOD tracks the movement of individual aircraft through an airport/airspace system, detects potential violations of separations and operating procedures, and simulates ATC actions required to resolve potential conflicts. The model properly captures the interactions within and between airspace and airport operations, including interactions among multiple neighboring airports.

8.1.2 Model Development

The current-day airspace route structure was developed using radar flight track and flight plan data extracted from the performance-data-analysis-and-reporting-system (PDARS). The selected day (19 March 2007) represents typical visual-meterological-conditions (VMC) flight operations in the N90 Metroplex. Four runway plan changes made during the day were included in the overall simulation model. However, because of the complexity of accounting for the dynamics of the plan changes in the temporal scheduling, only a single runway plan was utilized for the entire day.

The airports modeled in SIMMOD include the four primary N90 Metroplex airports: JFK, EWR, LGA, and TEB; and four secondary airports, including FRG, HPN, ISP, and SWF. When more than one arrival or departure runway was available, the distribution of runway operations was based upon the PDARS data. Figure 47 presents the arrival and departure runways for each of the modeled airports. In the figure, red arrows indicate runways used for departures and green arrows indicate runways used for arrivals.

The airspace boundary of the N90 SIMMOD model encompassed all of the airspace within the radar coverage of the N90 TRACON. The flightpaths of each airport-fix pair were grouped and a route, which is representative of a nominal flight trajectory, was defined. Routes for jet and turboprop aircraft were segregated and separate routes were built for each group. Special attention was paid to route convergence and divergence points in order to capture airspace interactions. Aircraft speeds by weight class along the trajectories were also noted so that an accurate representation of the four-dimensional (4-D) trajectory could be modeled. Figure 48 presents the arrival and departure route structure modeled in SIMMOD for the N90 current-day conditions (arrival: green, and departure: red).

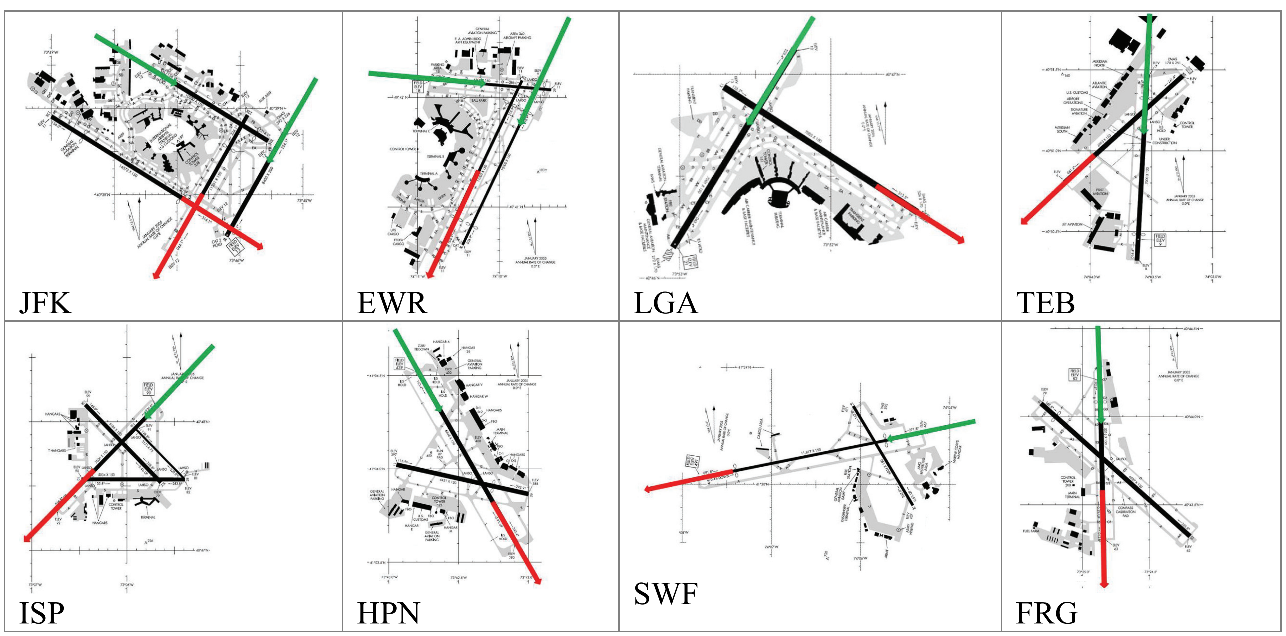


Figure 47. Runway plans of simulated airports.

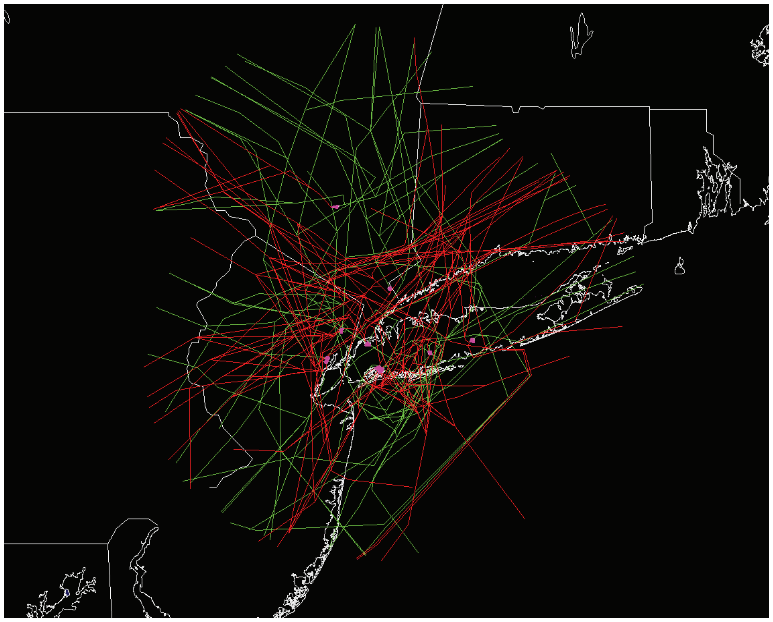


Figure 48. N90 current airspace route structure.

Modeled flight demand was based on the demand that occurred on the representative day. Only arriving and departing flights for the eight airports modeled were considered in the demand schedule. Figures 49 and 50 present the number of arriving and departing aircraft for each of the modeled airports.

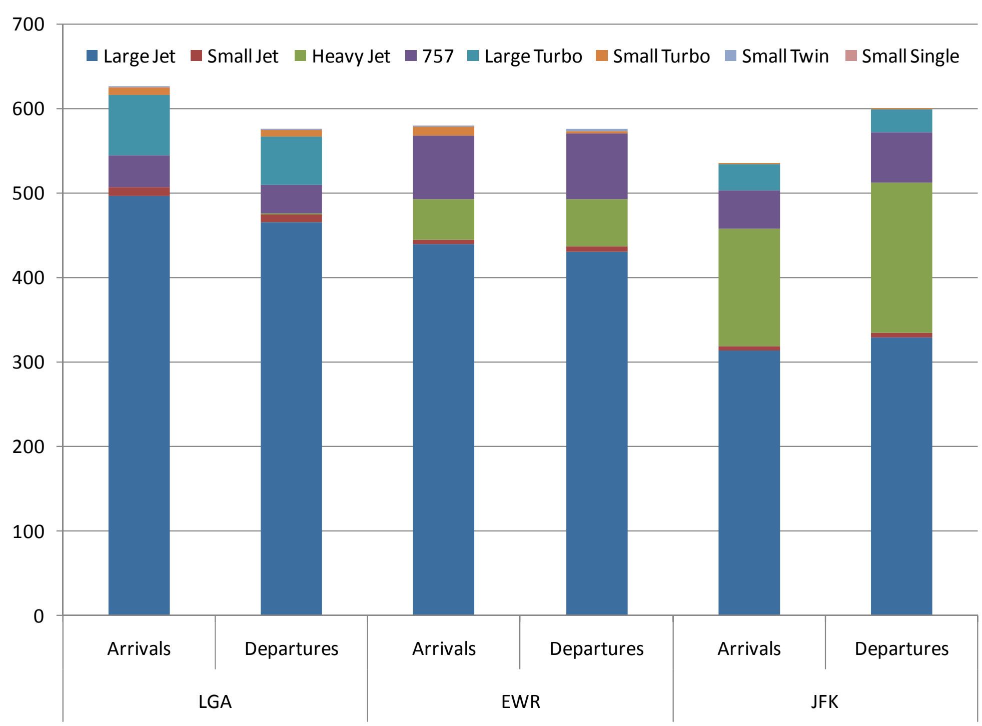


Figure 49. N90 hub-airport demand.

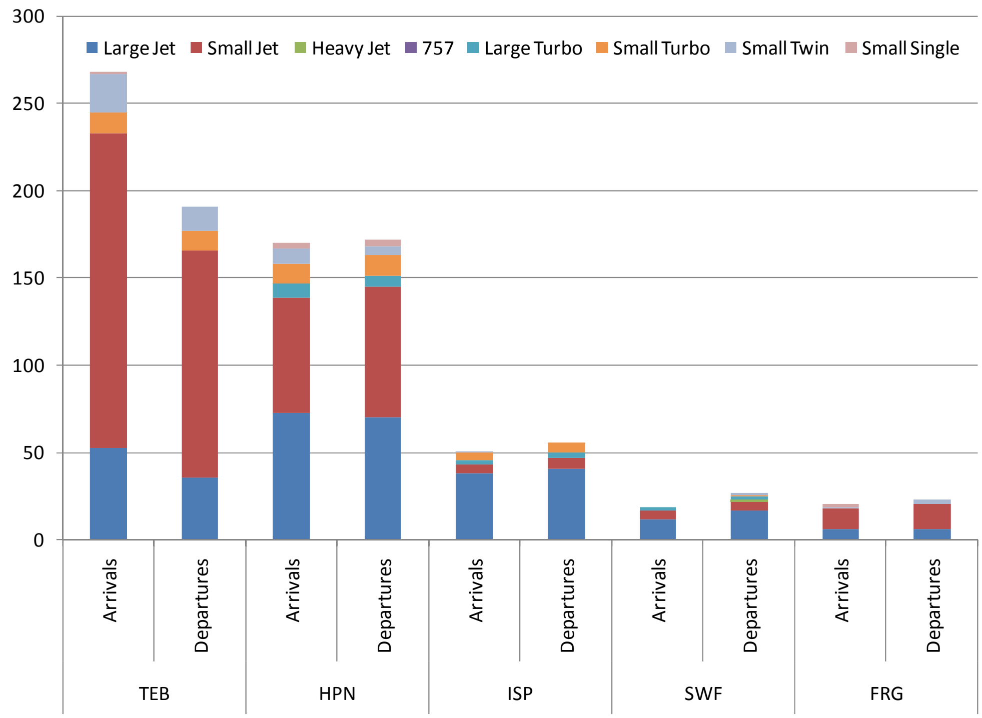


Figure 50. N90 satellite-airport demand.

Aircraft arriving to one of the eight airports were injected into the simulation based on the time they first appear in the radar data. For departures, radar flightpaths typically began when an aircraft was approximately 200 ft above ground level (AGL). To account for this reality, departure injection times were adjusted to account for the time it takes to taxi from the departure queue, the runway ground roll, and the flight time to 200 ft AGL. The impact of the surface movement was not required for this effort, so departures were injected into the simulation at the departure queue rather than at a gate.

Next the current-day airspace model was developed and its performance was calibrated against the PDARS data. The primary metrics used for calibration were runway throughput and arrival and departure transit times. Runway throughput was compared between the simulated results and what was observed in the radar data, as shown in Figure 51.

The transit times for each runway/departure or arrival route combination were also compared between the simulated results and what was observed in the radar data. The comparison of arrival transit times is shown in Figure 52. As a secondary comparison, transit times by aircraft weight class were made to ensure that these differences were accurately accounted for in the model.

To study the potential impacts of NextGen technologies and procedures, a second simulation model was developed. The SIMMOD NextGen airspace structure was constructed as a combination of the current-day airspace structure and the NextGen airspace designed by the Georgia Institute of Technology (GaTech). Figure 53 presents a schematic of the GaTech airspace design. The NextGen airspace provided the “inner” airspace of the model while the current-day routes were connected to the various entry and exit points of the inner airspace. Speed and altitude profiles were then adjusted to reflect a continuous-descent arrival (CDA) profile for arrivals and continuous ascent and acceleration for departures. The most important characteristic of the NextGen airspace is the fact that all routes are decoupled from each other. Procedures associated with each arrival or departure fix-runway combination do not interact with each other, significantly simplifying the airspace operations since operations at one airport do not affect the operations at another airport. One potential concern with the decoupled airspace is its conformance to existing noise constraints restrictions in N90. In the decoupled airspace design, the arrivals and departures assumed near optimal profiles, thus the noise footprint should be smaller. The purpose of the design was to test delay and throughput impact of the decoupled airspace concept. Although some of the arrival or departure routes might fly over noise-sensitive areas because of the simplified design, design improvements could be incorporated in the future to address the noise concern should an implementation be desired.

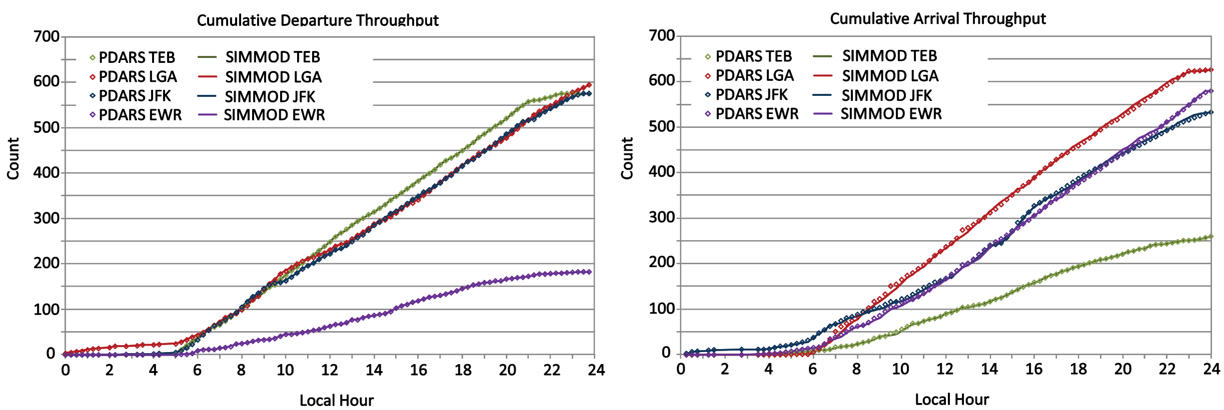


Figure 51. N90 SIMMOD model calibration – throughput.

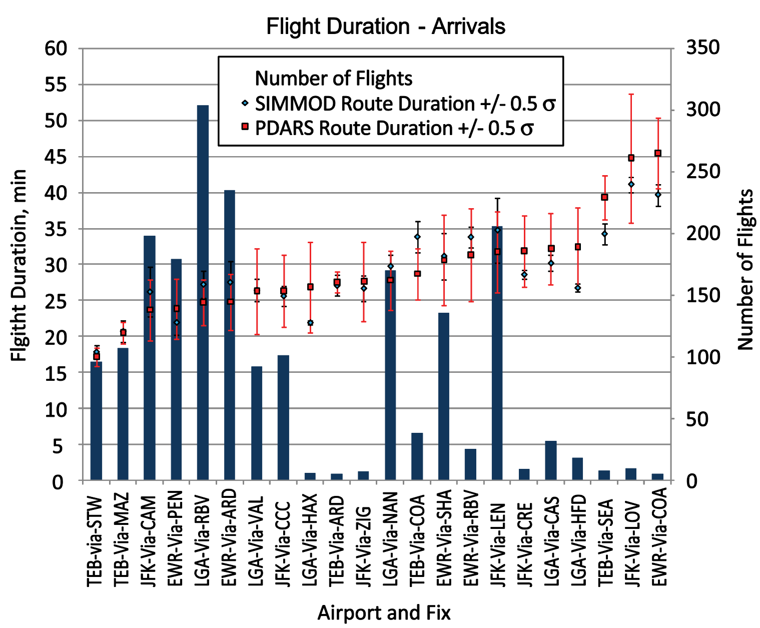


Figure 52. N90 SIMMOD model calibration – transit times.

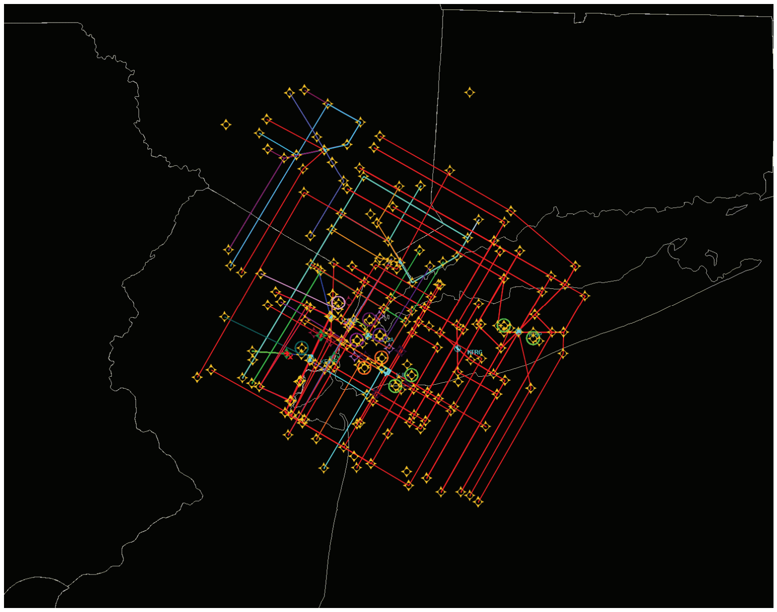


Figure 53. N90 NextGen decoupled route structure.

8.2 Simulation Setup

8.2.1 Selection of Major Control Variables

From the analysis in the previous sections and what is already available in the SIMMOD N90 models, the control variables were selected as follows:

Spatial Control Variables

Two spatial route structures were selected to present spatial control variables. The first one reflects current-day operations, and the second one was the proposed NextGen fully decoupled route structure. Both the strategic-level airspace structure and tactical-level separation standards were embedded into these two route structures.

Temporal Control Variables

Two levels of temporal control were selected. The first one reflects current-day N90 operations, and the second one was a proposed future proactive scheduling and temporal control. The scheduling and metering strategies and temporal control uncertainties were carefully integrated into two separate scheduling modules that were applied to the SIMMOD model inputs before those inputs were fed into the SIMMOD model for simulation.

Current-Day Scheduling and Metering

As described in section 8.1.2, the current-day scheduling and metering were developed from 24 hours of operations on a representative day, i.e., 19 March 2007. PDARS data were analyzed to obtain arrival and departure traffic properties such as inter-arrival times and traffic loading on each fix or runways.

Future Scheduling and Metering

The scheduling algorithm described in section 6.6 was used to emulate the best strategy given potential traffic, weather, and other information that may be available in the NextGen time frame. Metering accuracy was also improved to assume NextGen capability. Nominal schedule and sequencing was generated first, and then the algorithm was applied to adjust the schedule and sequencing of the aircraft at the arrival fixes. A tolerance of +/– 10 seconds was applied to the arrival times, and the simulation was run for five iterations to account for the expected variability of actual operations.

8.2.2 Selection of Other Experiment Variables

In addition to these two major control variables, the following variables had to be provided for the simulation:

Demand Levels

Based on previous discussions with NASA, current-day demand levels were selected for the current phase of the project because of time constraints. However, a wider range of demand level would provide an opportunity to explore the response of candidate solutions to system demand. The nominal demand selected for simulation is the 100% current-day demand derived from a representative day, i.e., from 19 March 2007, as described in section 8.1.2.

Weather Scenarios

Based on previous discussions with NASA, and given the complex nature of the weather, only a VMC scenario was modeled for the current phase of the project.

Runway Configurations

Because of the complexity of the runway configuration changes and based on discussions with NASA, it was decided to use constant runway configurations for an entire day. Comprehensive analysis of runway configuration changes requires an understanding of the behavior of the controller and of the specific NextGen technology dynamics. Given the time available, using a constant configuration was a reasonable approach and produced valid experimental results.

8.2.3 Test-Case Design

Figure 54 presents the test-case matrix used for the N90 experiment. In each test case, identical demand, weather, and runway configurations were used. Test cases were designed to explore the impacts of temporal control variables and spatial control variables separately and jointly. Four test cases were conducted, starting from current-day N90 operations to conceptual future operations.

Current-Day N90 Operations

This test was a straightforward experiment of the current-day N90 operations. Conditions included current-day demand, current terminal-area route structure, and current flow control and metering performance.

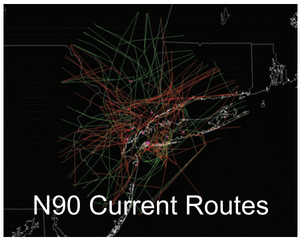
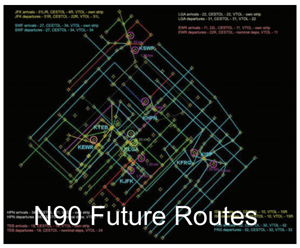
Route Structure	Test Case Design	
	**Current Operations** ▪ Current route structure ▪ Current day scheduling and metering	**Improve Temporal Control** ▪ Current route structure ▪ Future scheduling and metering
	**Improve Spatial Control** ▪ Future route structure ▪ Current day scheduling and metering	**Future Operations** ▪ Future route structure ▪ Future scheduling and metering

Figure 54. N90 SIMMOD simulation test-case design.

Simulation with Current Route Structure and Improved Temporal Control

This test was an experiment of the current-day N90 operations with improved metering. Conditions included current-day demand, current terminal-area route structure, improved flow control and metering performance, and traffic coordination between different airports.

Simulation with Decoupled Route Structure

This test was an experiment of the future decoupled route structure. Conditions included current-day demand and current flow control and metering performance.

Simulation with Future Route Structure and Improved Temporal Control

This test was an experiment of the future decoupled route structure. The current-day demand was imposed to the system, but the same improved flow control and metering performance and traffic coordination were applied.

8.3 Delay and Throughput

A primary metric to compare the impact of the spatial route decoupling and the temporal shift of arrival times at the arrival fix is the amount of air delay incurred by aircraft within the N90 terminal-radar-approach-control-facilities (TRACON) boundaries. Figure 55 presents the average arrival air delay per aircraft, in minutes, for the four test cases. Two significant findings are contained in these data. First, in almost all cases the decoupled airspace had significantly lower arrival air delay than the current airspace configuration. The second result is that the temporal shift at the arrival fix significantly reduced arrival air delay after aircraft were released at the arrival fix for both airspace configurations.

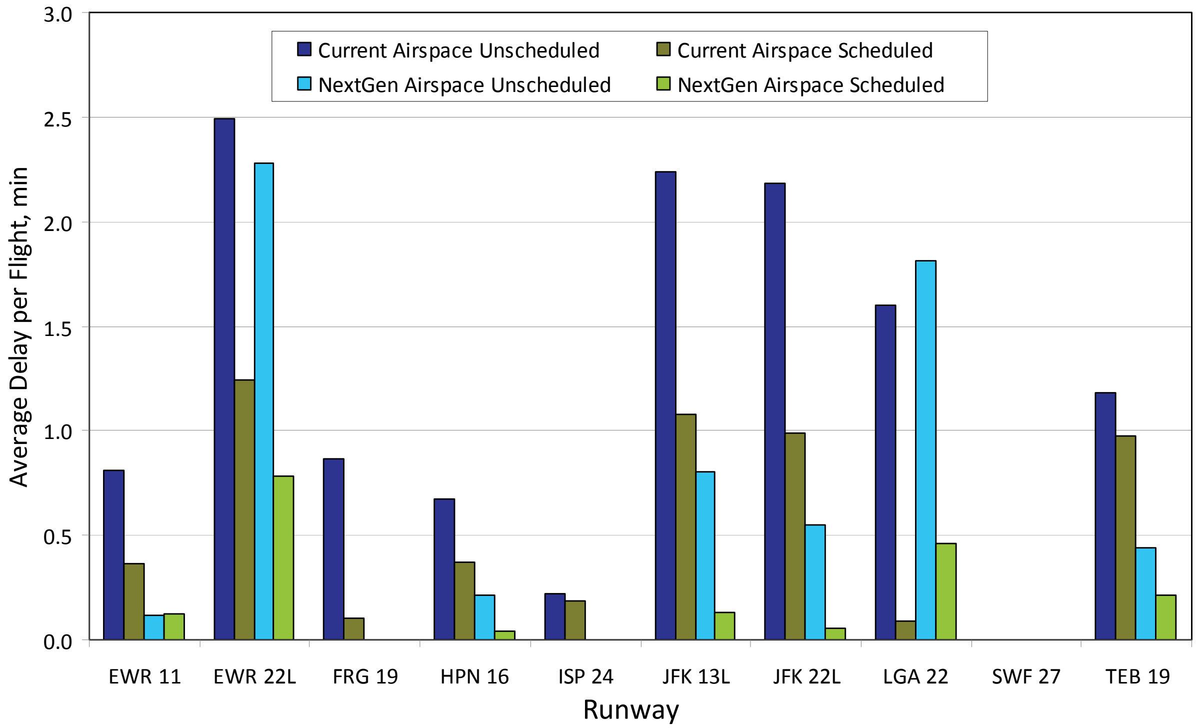


Figure 55. N90 average arrival air delay per flight.

Causes of Arrival Delay

In the current airspace, arrival air delay may be incurred for several reasons. The first is due to the arrival timing at the arrival fix. In the simulation, the aircraft were injected at the arrival fix, and any pair of aircraft injected so that insufficient spacing would cause the trailing aircraft to incur delay. This same effect can be observed at any merge point along their trajectory, since the trailing aircraft would have to absorb delay so that sufficient separation from the leading aircraft exists at all times. For heavily utilized routes, each merge point caused a ripple effect to all trailing aircraft. Within the simulation, this effect was somewhat mitigated by increasing the in-trail spacing upstream from the merge points so that the two streams of aircraft have greater spacing prior to entering the merge point and can merge with less delay. However, making this spacing too large would potentially penalize arrivals during periods of low demand or even when there were no merging conflicts. Sophisticated modeling capabilities required to make these types of air-traffic-control (ATC) decisions is available only in the advanced version of SIMMOD and was not available for this research.

Another potential source of delay results from faster aircraft trailing slower aircraft. The amount of delay incurred by the trailing aircraft is a direct function of the common path length between the two aircraft. Any type of procedure that segregates slow aircraft from fast aircraft will reduce delay.

In-trail wake vortex separation requirements between different aircraft weight categories could also result in increased delay. Optimal sequencing of heavy, large, and small aircraft categories would reduce arrival delay by minimizing the overall separation distances required between successive pairs of aircraft.

The Impact of Decoupled Airspace

In the decoupled airspace, these same factors are still present, with one exception. The decoupled airspace removes the dependency of arrival operations at one airport from the operations at another airport. In the decoupled airspace used for this research, each arrival runway was also decoupled from other arrival runways, decreasing the number of merge points and the number of aircraft that were required to merge.

The benefits of decoupling the airspace can be observed by the results presented in Figure 55 for JFK runways 13L and 22L. The aircraft arriving to these runways incurred 64% and 75% less delay, respectively, on average in the decoupled airspace compared to the current airspace. In addition, this figure shows that the decoupling of the airspace provided significantly more improvement than the temporal shifting of arrival fix times for JFK runways 13L and 22L. These effects were also present at all other modeled airports except LGA runway 22 and EWR runway 22L.

The potential noise impact of the decoupled route structure was not analyzed in this study to allow for evalution of the design concept in a short time frame. As mentioned earlier, the decoupled airspace would utilize near optimal arrival and departure profiles, and the noise footprint would be smaller than current-day operations. It is expected that some of the routes in decoupled airspace may fly over noise-sensitive areas, and thus may raise concerns about community noise impact. The issue, however, could be addressed by considering the noise constraints in refining the airspace design without losing much of the benefit of the overall concept.

The Impact of Temporal Improvement

Again, referring to Figure 55, the temporal shift of arrival times at the arrival fix provided additional and significant decreases in delay incurred within the N90 airspace. One thing to note about this reduction of delay is that it was actually a shifting of delay. Delay that was originally incurred within the N90 airspace boundary was moved into the en-route airspace by specifying arrival time at the fix. This specification allowed the arriving aircraft to travel through the terminal airspace closer to their nominal travel times, but required some procedure for the aircraft to arrive at their designated arrival-fix time. It is important to note that for the decoupled airspace, any delay reduction observed was a true reduction in overall flight time.

The impact of temporal shifting on delay reduction can be significant; however, shifting demand to reduce terminal airspace congestion could result in reduced arrival throughput. Two interesting cases within the N90 Metroplex illustrate how a reduction in arrival delay may or may not affect throughput. For a runway operating near or below capacity, the temporal shift reduces arrival delay by allowing two aircraft arriving at the arrival fix at about the same time to be deconflicted with minimal impact on aircraft further up the arrival stream. However, when arrival demand exceeds the runway capacity, the temporal shift will affect all aircraft upstream, requiring a similar temporal shift to be applied to all of them. The scheduling of the aircraft effectively serves as a way to meter the arrivals so that they do not exceed the runway capacity, resulting in a reduction in runway throughput. Figure 56 presents examples of this throughput reduction for the decoupled airspace when scheduling was applied. The charts present the cumulative difference in runway throughput (15-min time bins) between the scheduled and unscheduled cases for EWR runway 22L and LGA runway 22. For EWR runway 22L, the chart on the left shows that the cumulative runway throughput for the scheduled case never deviated more than two aircraft (in any given 15-min time bin) from the unscheduled case. However, for LGA runway 22, the scheduled arrival stream fell significantly behind during several periods in the day, and up to 17 aircraft at one point. In both of these cases, the scheduling of the arrival demand achieved a significant reduction in arrival delay. Part of the reason of the momentary throughput reduction was that the demand of LGA runway 22 was about 15% higher than that of EWR runway 22L. Referring to Figure 55, EWR runway 22L had a 65% decrease in arrival air delay within the N90 airspace and LGA runway 22 had a 75% decrease, a reduction of flight time with the N90 airspace. A close inspection revealed that that during the periods in which LGA runway 22 throughput was observed, the throughput (demand) was high and fluctuated significantly when the scheduling was not applied. When the scheduling was applied, the throughput was at the roughly the same level but with smaller fluctuations.

Comparison of Decoupled Airspace and Temporal Control

Figures 57 and 58 present the cumulative arrival air delay versus cumulative arrival throughput for the entire N90 Metroplex. The results in Figure 57 are comparisons between the current airspace and decoupled airspace. In this figure, the comparison for the unscheduled arrivals is shown on the left and the comparison for the scheduled arrivals is shown on the right. For both unscheduled and scheduled arrivals, the decoupled airspace provided significant benefit relative to the current airspace configuration. It can be seen that, in terms of absolute values, the decoupled airspace contributed greater reduction in arrival air delay when no scheduling was applied to arrivals than the case when scheduling was applied (1,128 minutes vs. 788 minutes). Percentagewise, the decoupled airspace reduced total arrival air delay by 50% from that in the current airspace when scheduling was applied versus 28% when no scheduling was applied.

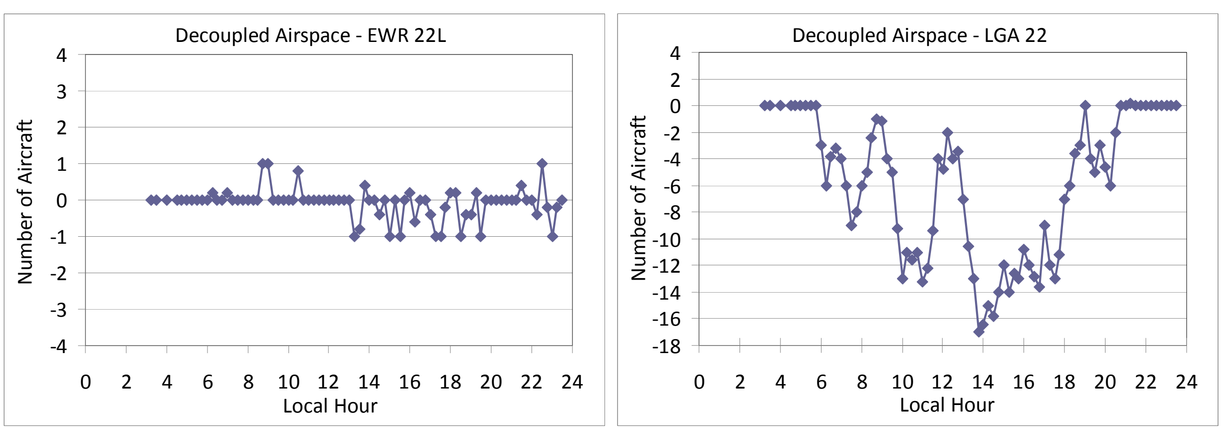
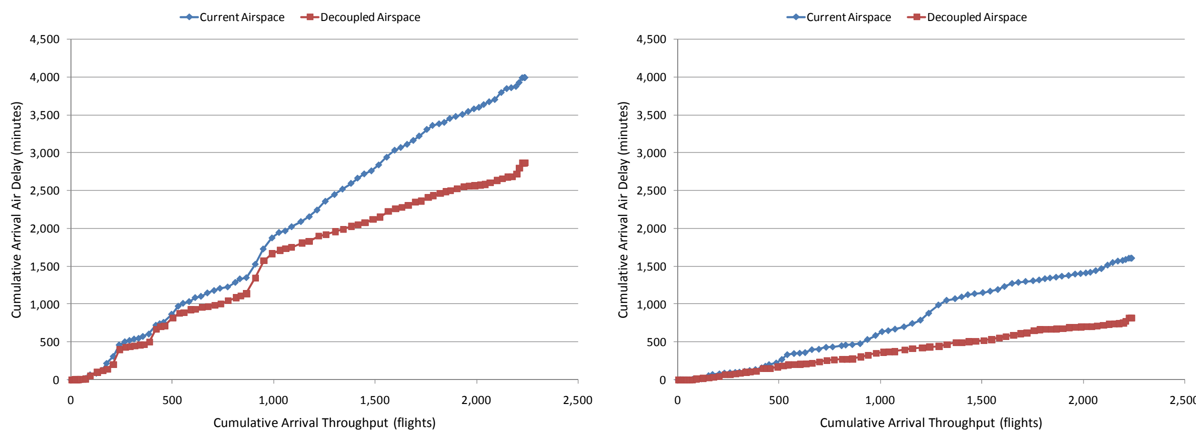


Figure 56. Cumulative throughput difference due to scheduling in NextGen airspace.

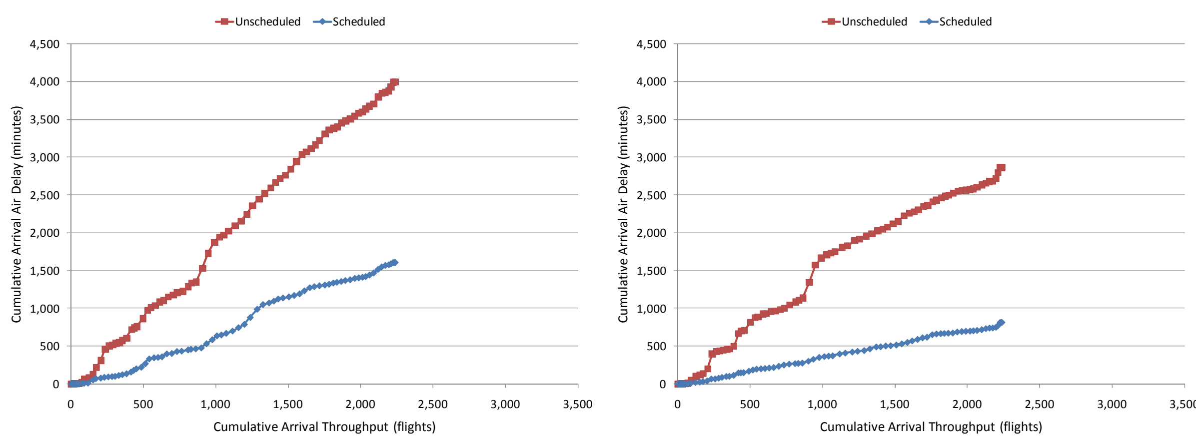
The total delay reduction from current airspace without scheduling to the decoupled airspace with scheduling was 79%—which happened to be the same number as in the Generic Metroplex study.

Figure 58 presents a similar comparison, showing the impact of scheduling for each type of airspace (current and decoupled). Incorporating arrival scheduling into the current airspace reduced total arrival air delay in the metroplex from 3,992 minutes to 1,608 minutes for a reduction of 60%. The benefit of scheduling the decoupled airspace was an overall reduction of 2,044 minutes, or 71%.



Unscheduled Scheduled

Figure 57. Cumulative delay versus cumulative throughput—impact of airspace design.



Current airspace Decoupled airspace

Figure 58. Cumulative delay versus cumulative throughput—impact of scheduling.

8.4 Fuel Burn and Emissions

Fuel burn and emissions were calculated to evaluate the energy and environmental impact of the spatial route decoupling and the temporal shift of arrival times at the arrival fix.

Fuel Burn

Figure 59 presents the arrival fuel burn for the four test cases, with total fuel burn per runway on the left and average fuel burn per flight on the right. As seen, in both current airspace and decoupled airspace, the scheduling saved fuel for arrival flights at most runways. However, mixed results were observed for the decoupling of the airspace. For JFK runway 22L and LGA runway 22, the decoupled airspace saved total fuel burn. For EWR runway 22L, FRG runway 19, and JFK runway 13L, the decoupled airspace actually slightly increased the total fuel burn. No significant total fuel-burn changes were observed for other runways. On a per-flight basis, similar results were observed for the NextGen airspace, mostly because in the decoupled airspace arrival routes were longer for almost all runways. A system-wide fuel burn reduction of 11% was still observed; it was due to reduced delays and improved arrival profiles (see Table 36). The differences in average fuel burn between runways were mixed effects of different aircraft types that landed at the runways and the runway-dependent operating efficiency.

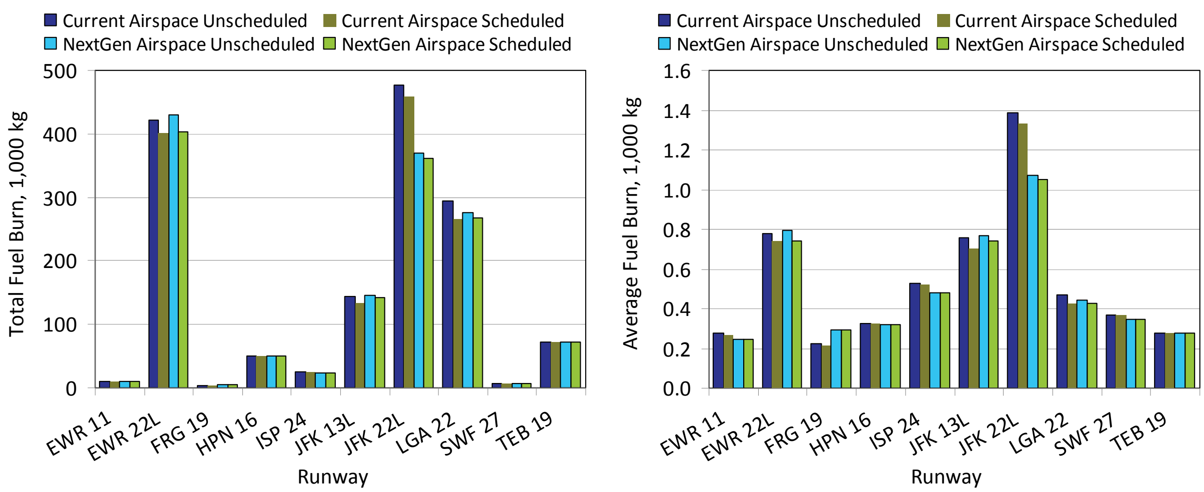


Figure 59. N90 arrival fuel burn for each runway.

TABLE 36. N90 ARRIVAL FUEL BURN

Airspace	Total Fuel Burn (kg)		Percentage	
	Unscheduled	***Scheduled***	***Unscheduled***	***Scheduled***
Current airspace	1503,431	1426,169	100%	95%
NextGen airspace	1389,031	1339,000	92%	89%

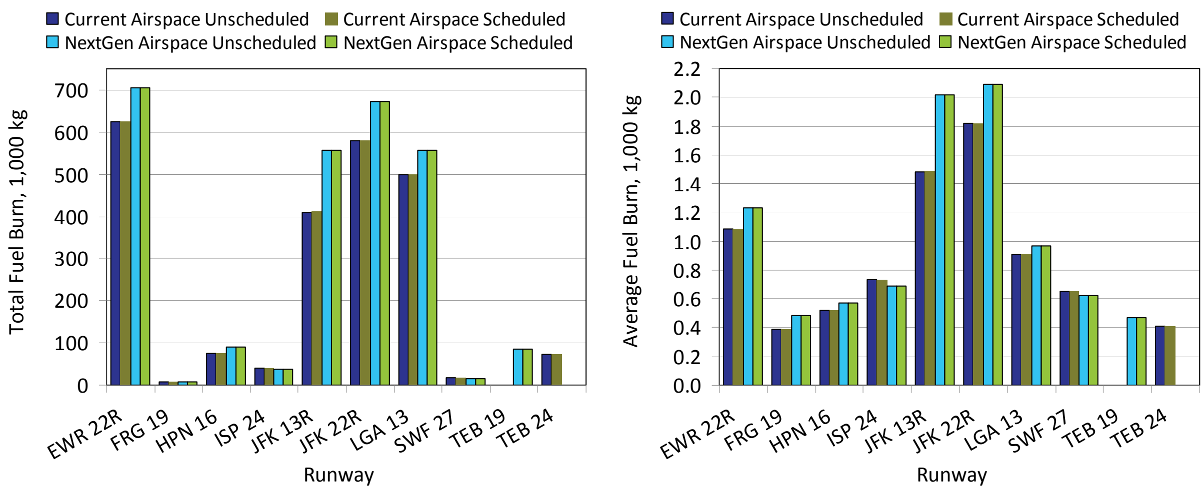


Figure 60. N90 departure fuel burn for each runway.

Figure 60 presents the departure fuel burn for the four test cases, with total fuel burn per runway on the left and average fuel burn per flight on the right. As seen, arrival scheduling did not significantly affect departure fuel burn. The decoupled airspace, on the other hand, actually increased fuel burn for aircraft departed at most runways. In the decoupled airspace, departure routes were longer for almost all runways. Compared with arrivals, the room for profile improvement was also limited. Thus, the use of improved departure profiles was not able to compensate for the effect of extended route length. The end result is increased fuel burn with the decoupled airspace.

Emissions

The amount of CO_2 emitted from aircraft engines is directly proportional to fuel burn. Each kilogram of jet fuel produces 3.155 kilogram of CO_2. The same observations in fuel burn directly apply to the CO_2 emission. The NO_x and particulate matter (PM) emitted from aircraft engines are correlated only to fuel burn, but also influenced by engine operating conditions. Figure 61 presents the average NO_x and PM per flight for arrivals to different runways. As can be seen, for arrivals to most runways, both the NextGen decoupled airspace and scheduling contributed to NO_x emission reductions because of the CDA profiles employed in the NextGen airspace and the reduced delays within the terminal area. Less reduction was observed in the PM emission. For some runways, such as EWR runway 22L and JFK runway 13L, an increase in the PM emission was observed for the NextGen airspace. However, consistent reductions in PM were observed with scheduling. The overall total emissions for arrivals are summarized in Table 37.

Figure 61 presents the average NO_x and PM per flight for departures from different runways. Similar to fuel-burn results, arrival scheduling significantly affected departure emissions. The NextGen decoupled airspace increased emissions for the major runways for similar reasons that caused fuel-burn increases.

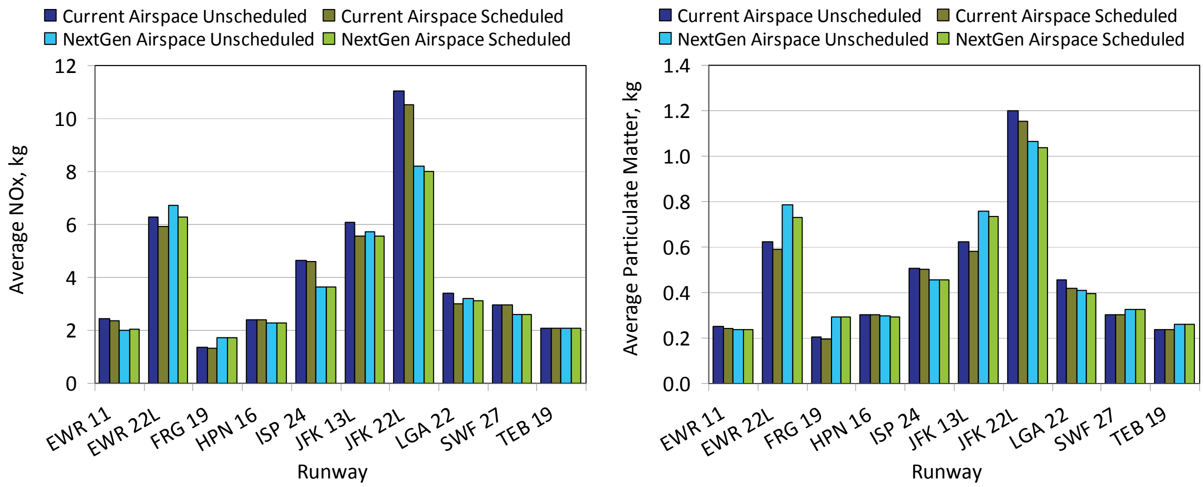


Figure 61. Average arrival NO_x and PM emissions for each runway.

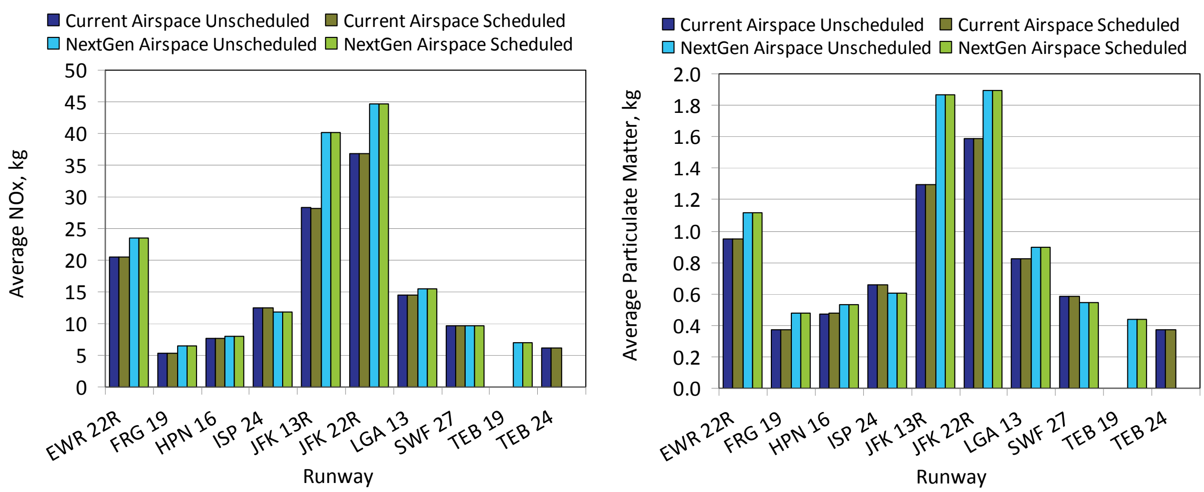


Figure 62. Average departure NO_x and PM emissions for each runway.

TABLE 37. N90 ARRIVAL EMISSIONS

Emission Species	Airspace	Total Emissions (kg)		Percentage	
		Unscheduled	***Scheduled***	***Unscheduled***	***Scheduled***
CO_2	Current airspace	4,743,324	4,499,564	100%	95%
	NextGen airspace	4,382,392	4,224,546	92%	89%
NO_x	Current airspace	11,794	11,069	100%	94%
	NextGen airspace	10,776	10,396	91%	88%
PM	Current airspace	1,305	1,238	100%	95%
	NextGen airspace	1,348	1,296	103%	99%

8.5 Summary of Major Findings

Based on the Generic Metroplex analysis and simulation study, four test cases were developed to test the performance of two concepts in N90. The first concept was a fully decoupled airspace route structure that enabled flights to and from different runways to operate independently. The second concept was an arrival scheduling algorithm that recommended entry–fix-crossing times adjustments so that operations within the N90 Metroplex terminal area can operate with much fewer conflicts.

The SIMMOD simulation revealed that, applied separately, both the NextGen fully decoupled airspace and the arrival scheduling significantly reduced arrival air delay incurred within the N90 terminal area; 28% and 60% system-wide reductions from current-day operations were realized, respectively. Combined, the decoupled airspace and scheduling reduced the system-wide arrival air delay from current-day operations by 79%. Consequently, fuel burn and emissions were also significantly reduced. The reductions from the NextGen decoupled airspace verified the hypothesis drawn from the Generic Metroplex linked queueing simulations. Results indicated that when entry fixes become major choke points, increasing the number of entry fixes and decoupled routes would improve system-wide performance. That said, scheduling showed a higher impact on system-wide delay reductions, similar to the results from the Generic Metroplex simulation.

In the SIMMOD simulation some issues were also identified. In the NextGen decoupled airspace, with the application of scheduling, the cumulative throughput for LGA runway 22 was below the throughput without scheduling during some busy periods, mainly because the scheduling algorithm intended to smooth out demand fluctuations at the entry fixes. In any case, this phenomenon warrants further study in the future. Another issue in the N90 NextGen decoupled airspace departure routes had longer ground tracks than that in the current airspace. Effort was taken to utilize improved departure profiles, but these improvements were limited and did not compensate for the impacts of longer ground tracks. Thus, the departure fuel burn was higher in the NextGen decoupled airspace than in the current airspace. Optimization could be employed to improve the NextGen decoupled airspace design to mitigate this effect.

9.0 DISCUSSION AND CONCLUSIONS

This section synthesizes the findings and issues identified through the current phase of the metroplex research. Observations are explained, results interpreted, and inferences conducted; implications of this research are discussed.

9.1 Major Conclusions

In this research the Georgia Institute of Technology (GaTech) Metroplex team systematically studied the parameters that determine the coupling and inefficiencies in metroplex operations; developed a framework to evaluate concepts and capabilities that manage the coupling of metroplex operations; and conducted the initial simulations to evaluate the impact of down-selected technological capabilities to identify the most promising concepts. Specifically:

1. The team conducted survey studies at four representative metroplexes in the National Airspace System (NAS): Atlanta (A80), Los Angeles (SCT), New York (N90), and Miami (MIA). The team developed comprehensive site-survey reports documenting major facilities, constraints, traffic demand, operational procedures, air-traffic-control (ATC) automation tools, and potential future developments at each site.
2. Based on the site-survey studies, through subject domain expert evaluation and qualitative analyses, the team identified and rank-ordered major metroplex issues, including: airspace entry fix and exit fix sharing; major volume-based traffic-flow management (TFM) restrictions; proximate-airport configuration conflicts; slow inter-airport surface connectivity; inefficient and high-workload airport configuration changes; inefficient inter-airport departure sequencing; flow constraints; inefficient “flushing” of airport flows; external special-use airspace (SUA)-caused flow dependencies; terrain-caused flow dependencies; severe limitations on instrument procedures due to proximate airport; and insufficient regional airport capacity.
3. The team conducted detailed analysis of airspace-related issues and categorized airspace dependencies into six types, including: sharing of fixes through metering; sharing of path segments through metering; sharing of volume of airspace through holding or stop of one flow; vertical flow segregation; lateral flow segregation; and downstream flow restrictions for multiple airports.
4. Through quantitative analyses, the team developed three sets of metrics to categorize existing metroplexes in the NAS and identify the potential need for future metroplexes because of regional traffic growth. A set of geographic-based metrics was developed to measure intrinsic dependencies within each metroplex. An arrival flow airspace volume-based metric was used as the “distance” measure for clustering airports into metroplexes and identifying potential future metroplexes in the NAS. A set of intersect flow metrics was developed to measure the complexity of traffic flow interactions within a metroplex terminal area. Among the four sites surveyed, the metrics identified N90 as the most complex metroplex, followed by SCT. It was also identified that N90 and SCT have many similarities. A80 and MIA could be categorized as moderately coupled metroplexes.

5. The team then developed a framework for evaluating the impact of NextGen and team-proposed future concepts and capabilities for managing metroplex operations. In this framework, measures handling interdependencies among metroplex traffic flows were abstracted as two distinct control strategies: temporal displacement, or spatial displacement from unimpeded ideal four-dimensional (4-D) arrival and departure trajectories.
6. Metroplex concepts were then presented by their temporal impact and spatial impact on metroplex operations. In the evaluation framework, the temporal control was represented by traffic-flow coordination or scheduling that provided target times, e.g., fix-crossing times and takeoff times; and traffic-flow metering or surface management to achieve the target times. The spatial control was represented by lateral and vertical separation standards; and airspace design geometries and segregated 3-D routes based on separation standards and aircraft performance limits. To evaluate the impact of temporal control concepts on metroplex performance, the team developed several prototype scheduling algorithms and models of metering accuracy. To evaluate the impact of spatial control concepts on metroplex performance, the team developed schematic prototype airspace geometries and 3-D aircraft routes that aimed to decouple metroplex traffic flows. The team conducted two studies to evaluate the impact of metroplex concepts: a parametric Generic Metroplex simulation study and a N90 simulation study.
7. The Generic Metroplex linked-node queueing simulation revealed that arrival delays incurred at the metroplex terminal-area boundary and within the terminal area were reduced by 73% from the standard four-corner post geometry 1 through employing scheduling algorithms to coordinate arrival traffic flows alone. Without scheduling, geometry 3 (with duplicate entry fixes to segregate traffic flows to different airports) did not achieve delay reductions. With scheduling, geometry 3 provided a 23% delay reduction from geometry 1. Additionally, geometry 3 achieved a combined 79% delay reduction from the case of geometry 1 without scheduling. Scheduling provided more significant delay reductions than the segregated route airspace geometry. The simulation also revealed that, with lower metering accuracy, the effectiveness of scheduling was impacted but most delay reductions from scheduling were retained even with the worst-case metering accuracy. This finding suggests that scheduling tools can be developed to achieve revolutionary delay reductions, even with current-day metering accuracy. Future four-dimensional trajectory (4-DT) operations would then provide further enhancements to the traffic scheduling and coordination.
8. The New York Airport and Airspace Delay Simulation Model (SIMMOD) simulation revealed that, applied separately, the NextGen fully decoupled airspace and the arrival scheduling reduced system-wide arrival air delay incurred within the N90 terminal area by 28% and 60%, respectively, from current-day operations. Similar to the Generic Metroplex simulation study, scheduling provided more significant delay reductions than the fully decoupled airspace design. Combined together, the decoupled airspace and the scheduling reduced the system-wide arrival air delay from the level of current-day operations by 79%. Consequently, fuel burn and emissions were also significantly reduced.

Based on the extensive study of metroplex operations, their inefficiencies, and potential metroplex solutions, the GaTech team developed numerous research recommendations. These research recommendations include suggested next steps beyond the work that has been performed to date in this project as well as a summary of implications for NextGen and beyond that are summarized in the next two sections.

9.2 Next Steps and Beyond for Metroplex Research

As documented in this report and summarized in the previous section, a significant range of metroplex issues and inefficiencies have been identified, a range of potential metroplex concepts have been analyzed, and significant potential benefits of metroplex concepts have been quantified, both in a set of representative Generic Metroplex configurations and for N90. The definition of these potential metroplex concepts and quantification of the potential benefits constitute the beginning of a broader set of metroplex research and development tasks and benefits-assessment tasks. NASA plans to fully validate these tasks and improved metroplex concepts and requirements before transitioning the research to the Federal Aviation Administration (FAA). In general these broader future metroplex research tasks can be categorized as the development of refined concept modeling and prototype metroplex decision support tools, and further investigation into the analysis of metroplex concept impacts.

9.2.1 Refine Concept Modeling and Develop Metroplex Decision Support Tools

As described in section 6.2, many potential metroplex concepts have been identified as metroplex-specific Joint Planning and Development Office (JPDO) Operational Improvements as well as other metroplex concepts that the GaTech team has identified as having potential to reduce metroplex inefficiencies. Moving forward, it is suggested that NASA take numerous additional steps to refine, develop, and test new metroplex concepts. Ultimately, the successful development and testing of such metroplex concepts should lead to additional new metroplex concepts, technologies, and procedures that could be transitioned to the FAA through existing, e.g., integrated arrival-departure surface research transition teams (RTTs) or future, e.g., metroplex-specific RTTs. The recommend steps include:

1. Select one or more desired metroplex concepts from the concepts discussed in section 6.2. Ideally, these concepts should be ones that address the major metroplex issues identified from site surveys and either showed up as a high-priority issue in section 5.1; or addressed the major inefficiencies quantified in Generic Metroplex (section 7) or N90 (section 8) analyses; or were less dependent on technologies that require extensive long-term research so that they can benefit metroplex operations in the near term.
2. Expand and refine the concept description from section 6.2 and appendix A into a full-blown metroplex concept-specific concept of operations. Details would include the concept goals; expected concept benefits; stakeholders; system requirements; roles and responsibilities of the relevant operational personnel; functional, technical, and operational system architecture; and user-interface requirements. Additionally, it should describe how the future operation would work (and ideally the baseline "no-metroplex-concept" system as well), through a series of "cognitive walk-through" nominal and off-nominal operational scenarios including nominal and off-nominal scenarios.

3. Adapt and enhance the metroplex scheduling algorithms from sections 6.6 and 7.4 and other related metroplex concept assessment assumptions from section 6 to build fast-time, concept-specific algorithms to significant levels of fidelity for conducting performance-based impact assessments. These assessments should emulate the full scope of the expected planning horizon (e.g., including en-route, terminal, and surface planning elements) and account for expected system uncertainties (e.g., gate pushback uncertainties, runway takeoff time-compliance emulations, and arrival fix-crossing time uncertainties) such as those described in sections 6.4 and 6.5.
4. Develop proof-of-concept mockups of the user interfaces for the different metroplex automation and communication input and output devices, elicit operational subject-matter expert review, and perform human-in-the-loop studies. This development should be done for all of the major operational positions that will be significantly impacted by the new metroplex concept.
5. Leverage the proof-of-concept mockups and feedback and human-in-the-loop experiment results for the development of real-time operational software that provides the metroplex advisories with appropriate user interfaces and integration with emulations of real-world input data, e.g., Airport Surface Detection Equipment, Model X (ASDE-X) data, traffic flow management system (TFMS), integrated-terminal-weather-system (ITWS) weather data, and en-route-automation-modernization (ERAM) flight plans. Then, test this operational software in a real-time simulated environment such as NASA's Future Flight Central (FFC).
6. Adapt the software to work in real-world operational environments such as provided at NASA's North Texas Research Station, testing the efficacy of this system with qualified operational personnel in either live-use or shadow mode. In general, the choice of the right operational environment depends on the magnitude and frequency of the inefficiencies within the proposed metroplex that are mitigated by the concept. Therefore, if analysis of the concept does not suggest significant benefits can be achieved within a metroplex such as Dallas/Ft. Worth, it may make more sense to choose a location such as New York or Los for a focused operational test.

9.2.2 Extend Metroplex Concept Impact Analyses

In addition to developing the metroplex decision support tools, it is suggested that NASA extend the metroplex concept impact analyses presented in sections5, 7, and 8 in a direction that supports the goals of understanding more broadly and/or deeper the impact of metroplex concepts described in section 6.2. These suggested future impact analyses include analyzing the sensitivity to a range of metroplex problem exogenous variables; extending the analysis to other metroplexes; studying different metroplex airspace designs, algorithms, and concepts for planning and control operations; analyzing different airport demand allocation schemes; quantifying the metroplex inefficiency impact on flights from secondary airports; and extending the range of impact metrics quantified. Numerous broader-scope and higher-fidelity impact analyses that are suggested follow:

1. Extend previous analyses to conduct a broader scope of high-fidelity, simulation-based evaluations. The team proposes to extend the Generic Metroplex analysis described in section 7 by performing a sensitivity study of metroplex performance to key metroplex

exogenous variables, refined airspace geometries, and scheduling approaches. The team proposes to extend the N90 airspace analysis described in section 8 by considering additional scheduling approaches, considering airspace geometries developed with site-specific constraints, and extending analysis to other metroplexes. In performing the latter, the team will leverage the metroplex extended dependency analysis in section 5.3 and clustering analysis described in section 5.4 as the source for identifying the future metroplexes. Lastly, the team proposes extending both the Generic Metroplex and N90 analyses to assess different metroplex designs, algorithms, and concepts for planning and control operations for the related metroplex tools discussed in section 6.2.

2. The GaTech team has identified a multitude of metroplex system exogenous variables and inputs, including traffic demand, metroplex geometry, weather, and Traffic Management Initiatives. Traffic variables that could be explored include the metroplex airport daily traffic volumes and the relative ratios of traffic across the metroplex airports, traffic time-over-the-day profiles, traffic directional distributions, and airport demand-to-capacity ratios mentioned in section 7.2.2. Metroplex geometric variables include the number of metroplex airports; their relative proximities and runway orientations and their capacities; the number of arrival and departure fixes and their availability schedules; the shapes, volumes, and availabilities of metroplex airspace regions; and the design of arrival and departure procedures to and from the metroplex airports. Metroplex weather variables include impacted portions of metroplex airspace, weather probabilities, and resulting metroplex resources availabilities. Traffic Management Initiative impacts include miles-in-trail or minutes-in-trail restrictions, expected departure clearance times, coded departure routes (CDRs), and other major restrictions [SS09a]. The values and ranges of each exogenous parameter may be obtained by analyzing current-day metroplexes and their operations and anticipated future metroplexes identified in section 5.4 through analysis of the extensive amount of ASDE-X, Automated Radar Terminal Systems (ARTS), host, and Enhanced Traffic Management System (ETMS) operational data along with other airport, airspace, and weather data available to the team.

3. Conduct a metroplex performance sensitivity analysis to characterize the impacts of the full range of exogenous variables on metroplex operations and to identify the variables with the greatest impact on metroplex performance. This analysis would help pinpoint the most effective approaches for improving the metroplex operations individually and collectively. The study would likely leverage the Generic Metroplex assessment process, which abstracts the metroplex to these fundamental variables. Findings from the Generic Metroplex studies could isolate variables for closer analysis in high-fidelity, simulation-based studies of N90 and other metroplexes.

4. Formulate and refine various metroplex-scheduling algorithms and conduct further performance sensitivity analyses via fast-time simulations. As described in section 5.2, many metroplex operational complexities and constraints hindering performance result from the sharing of common fix, route, and/or airspace resources among metroplex airports. Referring to section 6.1, scheduling is the only way to temporally coordinate the traffic among airports vying for use of shared metroplex resources where spatial control cannot be exercised. With respect to traffic-flow scheduling algorithms, the GaTech team has developed and evaluated multi-airport traffic-flow scheduling algorithms for this study, as discussed in sections 6.6 and 7.4. The team has investigated alternative

optimization approaches and members have developed other metroplex traffic scheduling algorithms [SS09a]. The study would extend the analysis to consider algorithms pertaining to metroplex-wide airport configuration scheduling, airspace resource scheduling, and trajectory management. Thus, the sensitivity of metroplex performance to both spatial and temporal spacing techniques would be studied as well as combinations thereof. For instance, an example is the metroplex concept that would include the dynamic process of providing procedural spatial separation only when the delays inherent in the temporal separation reach a critical threshold. The study would leverage the Generic Metroplex assessment process to evaluate different scheduling and spacing approaches and their sensitivities to exogenous variables (especially traffic and weather) and operational uncertainties (such as those identified in sections 6.4 and 6.5), and the most promising methods could be evaluated in high-fidelity, simulation-based studies of N90 and other metroplexes. Special cases such as metroplex terminal with en-route Traffic Management Advisor (TMA) scheduling interactions, inter-metroplex interactions (e.g., N90-PHL), and secondary airport traffic-flow interactions (e.g., LVK interactions with major San Francisco Bay Area flows) could be studied.

5. Formulate and evaluate demand allocation approaches and algorithms for metroplex-wide strategic and tactical flight allocation to individual airports as per metroplex concepts proposed in section 6.2.1 and appendix A. The study would explore the benefits gained from such approaches and the sensitivities of various approaches on airport inter-connectivity times, different demand scenarios (traffic volumes, fleet mixes, tail connectivity, other), metroplex resources availabilities, and Airline Operation Center business models. The study would leverage the Generic Metroplex assessment process, and the most promising methods could be evaluated in high-fidelity, simulation-based studies of N90 and other metroplexes.

6. Of particular interest to evaluating both metroplex-wide inefficiencies and metroplex-wide scheduling tools, the team proposes to quantify the delay incurred by departure flights from smaller secondary airports in the current call-for-release paradigm in order to establish a baseline delay performance at smaller, secondary metroplex airports lacking major infrastructure or staffing. Even though overall traffic levels at these secondary airports may be significantly lower, the lower priority given to this traffic, the greater number of airports that fit into this category, and the lack of readily available operational data on such operations make this topic an interesting one for additional research. An open research question that remains is whether the total metroplex system delay is greater at the higher-traffic but favored primary airports, or at the lower-traffic and not-favored secondary airports. For such flights, airfield measurements of estimated desired takeoff time and actual takeoff time obtained through site visits, observations, and radio communication monitoring would be used to estimate delay incurred by each flight. Site visits to several secondary airports within one or more metroplexes would likely provide sufficient data for this analysis.

For each analysis simulation output data will be analyzed to assess performance metrics, including throughput, delay, fuel burn, noise and emissions, and controller taskload. For these studies, the effort will leverage the vast warehouses of ASDE-X, ARTS, host, and ETMS data available, as well as the existing tools and experience necessary to analyze these data. Data analyses will be applied towards metroplex model formulation and calibration, verification and validation of models and simulation analysis results, and establishing a baseline performance analysis for performance improvement comparison.

Candidate tools for the aforementioned analyses are the Generic Metroplex assessment process and associated tools developed by the GaTech team for the current study as discussed in section 7, the SIMMOD-based N90 assessment process employed in this study and discussed in section 8, or other simulation tools capable of representing metroplex terminal areas. These tools include high-fidelity simulations of airport surface operations, such as NASA's Airspace Concept Evalution System (ACES), Airspace Traffic Generator (MACS), Test of Reaction and Adaptation Capabilities (TRAC), Surface Management System-Airspace Traffic Generator (SMS-ATG), or Sensis' AvTerminal simulation. The chosen tools should provide high-fidelity modeling of metroplex terminal airspace, explicit instantiation of scheduling algorithms, and real-time adjustment of metroplex exogenous geometric and traffic variables.

9.3 Implications to NextGen and Beyond

The research results of the GaTech team summarized in section 9.1 and the NASA metroplex research work suggested in section 9.2 are critical to improving current and future NAS metroplex operational efficiency. As traffic demand increases in the future, more regions in the NAS are expected to become metroplexes. Thus, as these metroplexes grow, so will the expected levels of metroplex-induced air traffic delays due to the multiple metroplex issues and inefficiencies that have been studied in the current research. Thus, it is important for NASA to take additional metroplex research steps such as those suggested in the previous section to move metroplex concepts out from a low technology readiness level (TRL), concept exploration phase that has been the basis of this work, to further along the TRL scale towards future operational implementation and deployment. This process will help ensure that the NAS will be prepared to minimize the expected significant growth in future metroplex delays.

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APPENDIX A SUMMARY OF OPERATIONAL CONCEPTS BRAINSTORM

During the project, based on specific knowledge gained during the site visits (especially the New York Metroplex visits), the Georgia Institute of Technology (GaTech) team brainstormed other concepts to alleviate the metroplex inefficiences. This appendix lists these concepts in brief.

Dynamic "TDMA" Concept

Time-division multiple access, or TDMA, involves the time-domain multiplexing of multiple signals for transmission along a single communication channel. Each signal is granted access to the channel for a sequence of time slots, and the time slots are dynamically assigned to each signal based on the traffic demand of each signal. Special mechanisms are in place to coordinate the timing of transmission to compensate for travel delays so that the packets arrive just in time to fully utilize the time slot. Dynamic allocation of time slots (rather than distributed based on prescribed scheme) enables all time slots to be fully used to accommodate varying demand among different users. In its application to the metroplex problem, the concept concerns the time allocation of shared resources among the multiple airports comprising the metroplex. It could be used to control airspace access. In turn, direct-to routing utilizing required-navigation-performance (RNP) routes could yield short routes cutting through currently segregated airspace, thereby making routes shorter. Automatic Dependent Surveillance – Broadcast (ADS-B) could be used to communicate route and time-allocation information to individual flights. The concept is similar to the Route Availability Planning Tool (RAPT) or expedite departure path (EDP), i.e., generating a schedule of resource availability to metroplex airports. A key concept of TDMA is the advance of transmission times to fit the packet in the allocated time slot. The same concept can be applied to the scheduling of flights to shared resources using both delay and advance to achieve the desired schedule, whereas in current operations delay is often used as the sole means.

Departure Flow Management Concept

The Departure Flow Manager (DFM) is a strategic decision support tool currently under development by the Federal Aviation Administration (FAA) and partner companies that automates the coordination of departures from multiple airports over shared and congested National Airspace System (NAS) resources. The metroplex concept is to extend the DFM to perform scheduling not just for time-period traffic-rate specification, but to ensure the tool incorporates all applicable restrictions (i.e., not just TFM restrictions, but local mile-in-trail (MIT) restrictions for merging, etc.), to schedule flights to reach allocated time slots at fixes and/or other shared resources, to incorporate continuous-climb departures into its planning, and to perform concurrent management of arrival and departures.

Integer Concept

The Integer Concept concerns efficient airspace or runway use by ensuring inter-flight spacing, particularly when merging, is no more than the minimum absolutely necessary; i.e., the spacing between two successive flights should be no more than one minimum spacing plus a minimum spacing buffer. This concept also requires separations minima or spacing targets to be presented in finer granularity than what is used in the current system. In current operations, separation minima and MIT restrictions are rounded up to at least integer nautical miles, i.e., 3-, 4-, 5-, or

6-nm separation minima or 5-nm increments for MIT. At very busy airports, a minimum 2.5 nm (noninteger) has been used between aircraft established on final approach to improve throughput and significantly reduce delay when the leading aircraft has a large or lighter weight class and the trailing aircraft has a large or heavier weight class. Greater throughput and delay reductions could be achieved when spacing required by metroplex traffic-flow scheduling is given in fraction numbers, e.g., 8.7 nm instead of 10 nm, but may be very difficult for the controller to quickly "eyeball" whether or not enough spacing exists in the traffic stream, particularly during heavy traffic periods. The Integer Concept is to implement the necessary metering and delivery control to create gaps just big enough in the arrival stream (e.g., a gap of 2.05 times minimum spacing rather than 2.5 times minimum spacing). Aircraft RTA capabilities make this implementation easier.

Mega-Airport Network

The Mega-Airport Network concept concerns allocation of flights among metroplex airports by aircraft type or other criteria determined to maximize metroplex throughput and efficiency. In turn, passengers are ferried between metroplex airports to meet connecting flights using vertical/short takeoff and landing (V/STOL) aircraft or other high-speed ground transportation options. This concept or some version of it may represent the George Mason University (GMU) Metroplex concept.

Metroplex V/STOL TransCon/International Connection Network

The Metroplex V/STOL TransCon/International Connection Network is similar to the Mega-Airport Network. In this concept, international flights are segregated from metroplex traffic and isolated to an off-line airport (e.g., 100 miles away). The concept uses four-dimensional trajectory (4-DT) V/STOL aircraft or a high-speed train to take international passengers to the off-line airport. A concourse for passengers to check in would be provided at piers; e.g., for the N90 Metroplex, piers in downtown New York (similar to Hong Kong). The concept could be applied to multiple terminal radar approach control facilities (TRACONs) and would relieve traffic on the East Coast since international flights can disrupt otherwise stable operations at metroplex airports (e.g., JFK).

"Perfect" Airport

The "Perfect" Airport concept concerns paving the entire surface surrounding each metroplex airport, i.e., eliminating individual runways; dynamically determining runways according to prevailing wind, weather, and traffic conditions; and distributing runway assignment and procedures information to individual aircraft in real time.

Airport Arrival-Departure-Surface Planning

The Airport Arrival-Departure-Surface Planning concept involves affecting metroplex arrivals and departures in coordination with surface operations. It involves using precise runway assignments for arrivals and departures (whereas currently the pilot requests a runway), and could involve crossing aircraft in the air as part of the dynamic runway assignment (whereas currently aircraft are not crossed in the airspace).

Dynamic Weather Reconfiguration Planning

Dynamic Weather Reconfiguration Planning concerns the dynamic allocation and assignment of fixes, routes, and runways to accommodate local metroplex weather patterns. Currently, if a pilot does not accept a route, the route is closed, and it is very difficult to open it again. The concept involves flexible routing and having a large number of configurations with transition plans between each. The concept uses datalink to support dynamic aircraft changes and calls for common situational awareness between pilot and controller.

Improved Airport Configuration Management and Coordination

The concept of Improved Airport Configuration Management and Coordination involves the closer coordination and planning across metroplex airports (e.g., PHL flights are coordinated with N90). Currently the tower operationally requests an airport configuration change and the TRACON approves/disapproves the request. The concept calls for surface surveillance and information sharing across all airports and arrival, departure, and configuration management planning tools. Currently only SFO has a formal runway use program in the Bay Area (flights can take off in a 15-kt tailwind instead of a 5-kt tailwind).

Improved Airport Use Strategic Planning

Improved Airport Use Strategic Planning calls for better strategic origin-destination planning (e.g., international flights out of PHL, airport revenue sharing) as metroplex airports currently compete with one another for traffic and are not incentivized to allocate traffic or aircraft types among themselves to maximize their performance. For instance, closing LGA would allow the same amount of traffic through JFK and EWR as is currently operating at JFK, EWR, and LGA concurrently. Doing so would allow JFK to have greater capacity without interference from LGA operations in part due to human and current airport limitations.

Dynamic SUA Configuration Management

The Dynamic SUA Configuration Management concept calls for the FAA to electronically reserve airspace by request (e.g., based on airspace and time that they need) as significant volumes of special-use airspace (SUA) remaining idle for extended periods of time could be used to offload flights from congested routes and airspaces. However, complications do arise when SUA is being used for commercial traffic and suddenly comes under military use. The concept calls for dynamic sharing of airspace as a function of usage, weather, and opening smaller portions of airspace (altitudes or airspace) if the airspace is not being used (e.g., China Lake). For example, in Los Angeles, the Hector-Daggett corridor has one route currently, but with RNP could double the number of corridors. Also, SUA east of ZDC airspace is not being used. Virginia Capes Operating Area (VACAPES) sometimes opens up airspace to offload traffic; otherwise all east-coast northbound traffic is routed over JFK. Currently the Military Airspace Management System (MAMS) is used as a tool for SUA management.

Multi-Airport Arrival and Departure Bank Coordination

The Multi-Airport Arrival and Departure Bank Coordination concept calls for the dynamic coordination across multiple metroplex airports in order to flush arrival and departure queues/banks. In N90 this coordination is done by the TRACON Traffic Management Unit (TMU) in a very ad-hoc manner. The concept is similar to what is currently done to coordinate traffic flows around road work on a highway system: two people with traffic signs at either end of the flow constraint coordinate to flush cars through the constraint.

Terminal Advanced Airspace Concept

The Terminal Advanced Airspace Concept calls for automating all the airport planning and air traffic control (ATC) to perform strategic and tactical 4-DT management. The concept uses datalink to have terminal ATC communicate 4-DT clearances to participating aircraft. Aircraft are outfitted with appropriate automation to implement the 4-DT clearances.

Environmentally Driven Airport Assignment

The Environmentally Driven Airport Assignment concept calls for allocating aircraft to different metroplex airports based on their environmental characteristics. This allocation would permit isolating noisier or more emissions-prone aircraft to airports where they have less impact. Aircraft types that should aggregate at different airports for noise and emission considerations would need to be determined, but in general the concept calls for heavier, noise-emitting aircraft to operate out of airports further away from populations and for airport assignment to be driven by environmental performance.

Secondary Airport Traffic Flow Access Control

Secondary airport traffic-flow access control calls for automation to schedule and execute the release of departures from smaller metroplex airports having less staff and infrastructure in order to fit departures in to metroplex traffic streams. Currently many smaller metroplex airports must call the TRACON or the appropriate metroplex airport tower to release their departures, and during busy traffic periods such flights may be unduly delayed because of the difficulty in identifying available slots in overhead streams coupled with the time required to perform such coordination.

APPENDIX B SUMMARY OF FURTHER READING MATERIALS

This appendix provides abstracts and summaries of additional detailed specific reports that support this final report. It gives the reader a chance to browse through the subjects before examining those detailed reports.

B.1 METROPLEX LITERATURE REVIEW REPORT

Citation:

Ren, L.; Saraf, A.; Thompson, T.; Mullick, L.; Stefanidis, K.; Schleicher, D.R.; Lewis., T.; Arora, N.; Wong, L.; Crisp, D.L.; and Clarke, J.-P.: Metroplex Operations and the Metroplex Problem: A Literature Review. NASA Metroplex NRA Project Report, Contract No. NNX07AP63A, unpublished, July 1, 2009.

Abstract:

This report documents a thorough literature review of previous studies relevant to metroplex operations. The goal of the literature review was to first develop an overview of the metroplex phenomenon, and then identify typical metroplexes in the National Airspace System (NAS) that warrant further study. The state of the art in managing today's metroplex operations and previously studied concepts and methods that may be applied to improve the performance of metroplex operations are also reviewed. The intent was to identify areas that need more rigorous study and to identify candidate capabilities to be evaluated for future metroplex operations. The literature was selected and reviewed for its value to the current research on metroplex operations. The nature of the literature includes websites of related agencies, past research publications, simulation programs, and other items. The traditional use of the term "metroplex" is discussed along with the Joint Planning and Development Office (JPDO) definition of metroplex as a group of highly interdependent airports. The previous studies on interdependencies and interactions between metroplex airports are examined. The state of the art in managing these interdependencies is reviewed subsequently, followed by concepts and capabilities proposed in the literature that can be applied to improving the performance of metroplex operations. The report contains appendices detailing individual literature review notes. In each literature review note, the reviewer identifies the objectives of the literature, challenges and methods to achieve the goals, and the results or effects of implementation. The reviewer also provides a critique and states the relevance of the literature to the metroplex research.

B.2 METROPLEX SITE-SURVEY STUDY

This section briefly introduces materials presented.

B.2.1 A80 Site-Survey Report

Citation:

Ren, L.; Saraf, A.; Thompson, T.; Mullick, L.; Stefanidis, K.; Schleicher, D.R.; Lewis., T.; Arora, N.; Wong, L.; Crisp, D.L.; and Clarke, J.-P.: Metroplex Operations and the Metroplex Problem: A Literature Review. NASA Metroplex NRA Project Report, Contract No. NNX07AP63A, unpublished, July 1, 2009.

Abstract:

The Atlanta Metroplex includes the busiest airport in the world—Hartsfield-Jackson Atlanta International Airport (ATL) with an average of over 2700 daily operations in 2007. Operations in this metroplex are dominated by the traffic to and from ATL. Although corridors exist above ATL airport to allow departure traffic from smaller airports to direct to their destination [[to direct to their destination? Does that make sense? Do you mean: to go directly to their destination?]], traffic to and from other smaller satellite airports is normally routed around the ATL traffic pattern. Atlanta thus represents a unique type of metroplex operations. It was therefore selected by the Georgia Institute of Technology (GaTech) team as a candidate site for detailed survey study. Also, Atlanta Metroplex was selected as the first site to be surveyed because of the existing close collaboration between the GaTech team, the Atlanta Large Terminal Radar Approach Control facility (Atlanta TRACON, or A80) and the Atlanta Air Route Traffic Control Center (Atlanta ARTCC, or ZTL). A80 and ZTL support the operations of the entire Atlanta Metroplex. The A80 report documents in great detail key findings from the three major sources: analysis of documented materials relevant to A80 operations, analysis of traffic-flow patterns, and A80 briefing materials and notes taken by the team members during the site visit. An overview of A80 is presented to provide background information such as the geographic location, organizational support structure, layout and dimensions of the TRACON airspace, major players in A80 operations, and system-wide operational statistics. Major airports supported by A80, such as ATL and numerous relatively busy secondary airports, are described with details such as their geographic location, runway layout, traffic demand, major operators based at each airport, and major constraints. A80 airspace and operational procedures are discussed with examples of detailed current-day ATL and secondary traffic-flow analysis. The environmental constraints, which constitute an important aspect of operations, are also presented. A80 future developments, such as the Atlanta Class B airspace redesign, the implementation of continuous-descent arrivals, a second commercial airport, and connection between ATL and suburban or exurban areas are also discussed. For the sake of simplicity and enhancement of information flow, certain artifacts of this site survey are listed as appendices, including the questionnaire developed by the GaTech team for the A80 site visit, the site-visit notes, a detailed summary of constraints and coordination as defined in the A80-ZTL letters of agreement, and a summary of observations of traffic flow into and out of ATL. Illustrations are used extensively throughout the report to help readers understand the subjects.

B.2.2 SCT Site-Survey Report

Citation:

Schleicher, D.; Lewis, T.; Gutterud, R.; Wong, L.; Clarke J.-P.; Crisp, D.L.; Thompson, T.; and Sliney, B.: Characterization of and Concepts for Metroplex Operations: NY Site Report. NASA Metroplex NRA Project Report, Contract No. NNX07AP63A, unpublished, Mar. 23, 2009.

Abstract:

The SCT site-survey report discusses the key SCT findings organized as follows. The second section summarizes the major SCT findings, followed by a third section consisting of a higher-

level summary of SCT statistics and information. Then the major SCT airports are discussed in detail, followed by a detailed discussion of the SCT airspace. A sixth section covers major ongoing SCT airspace design changes. A seventh section covers findings associated with the potential for future decision support tools to improve SCT operations, followed by adocumentation of additional outstanding issues that were left unanswered from our analysis and that merit additional investigation. A following section covers important references. The major body of the document is followed by multiple appendices. A first appendix covers the site-visit questionnaire that was created in preparation for the site visit. Then, a second appendix provides the summary notes from the site visit. A third appendix provides the detailed person-by-person site-survey notes that were taken during the SCT site visit. A fourth appendix summarizes findings based on an analysis of the SCT standard operating procedures (SOPs) and letters of sgreement (LOAs).

B.2.3 New York Site-Survey Report

Citation:

Timar, S.; Lewis, T.; Gutterud, R.; Ren, L.; Crisp, D.L.; Saraf, A.; Sliney, B.; Levy, B.; Rappaport, D.; Stefanidis, K.; Clarke J.-P.; Thompson, T.; and Schleicher, D.: Characterization of and Concepts for Metroplex Operations: NY Site Report. NASA Metroplex NRA Project Report, Contract No. NNX07AP63A, unpublished, Mar. 23, 2009.

Abstract:

The New York site-survey report summarizes the key findings from the Georgia Tech team's visit to and associated analysis of the New York Metroplex. The site visit was conducted during the week of May 26, 2008, and included visits to the following facilities: the New York Center (ZNY), New York TRACON (N90), JFK International Airport (JFK), Newark Liberty International Airport (EWR), LaGuardia Airport (LGA), and Teterboro Airport (TEB).

The report summarizes the key New York Metroplex findings and provides an overview of the New York area airspace and facilities. It discusses the New York Metroplex airports in detail, first summarizing their current and forecasted operations volumes, and then providing detailed descriptions of the New York Metroplex main and satellite airports configurations, individual operational characteristics, interactions, and a quantification of the interdependencies among the airports. The report provides an extensive characterization of the N90 airspace necessary for understanding the complexities and limitations of current-day New York Metroplex operations and identifying opportunities for—and challenges in—improving operational efficiency. The report then discusses the main New York Metroplex airports traffic flows and their interactions, the N90 coordination of shared resource use (e.g., departure fixes, airspace) among the main airports, decision support tools N90 uses to manage traffic, a characterization of the typical traffic-flow management (TFM) restrictions N90 encounters, and key complications to efficient current-day operations. It continues with an overview of the N90 SOPs and LOAs governing current-day operations, and then discusses the constraints to current and future N90 operations, including terrain, environmental considerations (water quality, air quality, and noise), special-use airspace (SUA), and weather. It is followed by discussions of the Center airspaces N90 interfaces with in managing traffic flows to and from the New York Metroplex airports, and the requirements each places on N90 operations. Other topics discussed include the current and future arrival and departure procedures and airspace design changes to N90 and ZNY that will impact New York Metroplex operations; future plans for expanded use of current decision support tools used and use of new decision support tools by N90, ZNY, and/or airport tower for managing metroplex operations; and outstanding issues for future New York Metroplex intelligence gathering and research. The report also includes three appendices: the questions formulated for the New York site visit, the site-visit notes captured by the Georgia Tech team members, and a detailed summary and analysis of the standard operating procedures governing New York Metroplex air-traffic-control (ATC) facilities interactions.

B.2.4 MIA Site-Survey Report

Citation:

Schleicher, D.R.; Ren, L.; Gutterud, R.; Timar, S.; Crisp, D.L.; Lewis, T.; Clarke J.-P.; and Saraf, A.: Characterization of and Concepts for Metroplex Operations: Miami Site Survey Report. NASA Metroplex NRA Project Report, Contract No. NNX07AP63A, unpublished, May 5, 2009.

Abstract:

The Miami Metroplex has two Operational Evolution Partnership (OEP) airports, i.e., Miami International (MIA) and Fort Lauderdale-Hollywood International (FLL), within 18 nm of each other, along with numerous satellite airports. Operations in the Miami Metroplex are supported by the Miami Terminal Radar Approach Control Facilities (MIA TRACON), and the Air Route Traffic Control Center (Miami ARTCC, also known as the “Miami Center”, or ZMA). The MIA TRACON is a combined TRACON and Air Traffic Control Tower (ATCT or Tower) facility; hence the facility performs both functions. The Miami Metroplex represents the case in which two busy major airports of comparable configuration and traffic volume are located close to each other. It is thus a very good site to examine real-world interdependencies and interactions among multiple airports in close proximity with each other.

The site survey started with collecting and assimilating documents relevant to the current operations in the Miami Metroplex, including operational statistics at the airports, published and standard operational procedures (SOP), and letters of sgreement (LOAs) between facilities. Also, information about the environmental aspects of the Miami Metroplex airports were collected and environmental analyses were performed for both the current status and future scenarios.

The next step was to examine traffic-flow patterns of current operations in Miami TRACON to identify flow interactions among airports in the area. This assessment was done mainly by examining archived radar tracks utilizing the performance data analysis and reporting system (PDARS) developed by ATAC Corporation. This work also helped to prepare the team for an efficient site visit at MIA.

For additional preparation, a questionnaire was developed by the team and submitted to NASA project management and MIA TRACON prior to the site visit. This questionnaire also guided the team during the site visit. On November 14, 2008, the Metroplex Project Team visited the MIA

TRACON/Tower located at the airport. The site visit was mainly an interview session of the MIA TRACON/Tower staff. After the interview session, the team toured the MIA Tower Cab and the MIA TRACON control room located below the Tower.

The goal of this site-survey report is to summarize key findings from the three efforts, i.e., the analysis of documented materials and data relevant to Miami operations, analysis of traffic-flow patterns, and the actual site visit.

The MIA Site Visit Report discusses the MIA TRACON findings as follows. Following the introduction, the major MIA TRACON findings are summarized, followed by a higher-level summary of MIA TRACON statistics and characteristics. Then the major MIA TRACON airports are discussed in detail, followed by a detailed discussion of the MIA TRACON airspace. A sixth section covers major ongoing MIA TRACON airspace design changes, and a seventh section covers findings associated with the potential for future decision support tools to improve MIA TRACON operations. Then additional outstanding issues that were left unanswered from our analysis and that merit additional investigation are documented. Important references are then listed. The major body of the document is followed by appendices that cover the site-visit questionnaire prepared before the site visit and summarize findings based on an analysis of the MIA TRACON/Tower SOP and LOAs with interacting facilities.

B.2.5 Contrast and Comparison of Metroplex Operations

Citation:

Ren, Liling; Clarke, John-Paul B.; Schleicher, David; Timar, Sebastian; Crisp, Donald; Gutterud, Richard; Lewis, Taryn; and Thompson, Terence: Contrast and Comparison of Metroplex Operations – An Air Traffic Management Study of Atlanta, Los Angeles, New York, and Miami. AIAA 2009-7134, 9th AIAA Aviation Technology, Integration, and Operations Conference (ATIO), Hilton Head, S.C., Sept. 21–23, 2009.

Abstract:

A metroplex is a group of two or more airports within a metropolitan area whose arrival and departure operations are highly interdependent; thus the solution for the airspace structure around and the traffic flows to and from constituent airports must be solved cooperatively as a system. Existing metroplexes in the National Airspace System have gone through different development paths and possess different characteristics, in large part because of differences in natural, social, environmental, and political considerations. Consequently, strategic and tactic air-traffic-control measures tend to be specific to a given metroplex and therefore not easily abstracted. However, to develop concepts for metroplex operations to meet future traffic demand in the 2025 time frame, it is necessary to develop a deeper understanding of the constraints on metroplex operations that limit system capacity, and to develop a model of metroplex operations. To this end, a study of the state of the art in air traffic management of metroplex operations was conducted at four metroplexes, Atlanta, Los Angeles, New York, and Miami, each representing unique characteristics. The results from the survey of each site, covering airport configuration dependencies, airspace delegation, traffic-flow interaction, weather, and environmental constraints, were compared to identify the most critical issues in today's metroplex operations.

Next-Generation Air Transportation System (NextGen) concepts were analyzed against metroplex issues to identify their potential impact on metroplex operations. This study provides bases for developing novel NextGen metroplex design and operating concepts. The process and the results from the contrast and comparison of metroplex at the aforementioned four metroplex sites are documented in this paper.

B.3 METROPLEX CHARACTERIZATION STUDY

B.3.1 Metroplex Operational Issues and Examples

Citation:

Schleicher, David; Saraf, Aditya; Lewis, Taryn Butler; Gutterud, Richard; and Georgia Tech team: NASA Project NNX07AP63A, Characterization of and Concepts for Metroplex Operations: Metroplex Issues Map. Aug. 28, 2009.

Abstract:

This document describes the identified metroplex issues and the associated prioritization approach. An overview and summary of the findings is presented, followed by a description of the identified metroplex issues, with detailed examples. Then the prioritization approach is described, followed by a presentation of the result of the prioritization of the metroplex issues. Then the metroplex issues are grouped into a set of metroplex interdependency categories and these categories are prioritized according to the severity of the adverse impact on metroplex operations. Finally, the relationship between the prioritized metroplex issues and the planned parametric metroplex quantitative system assessments is discussed. Essential reference materials are provided at the end of the document.

B.3.2 Metroplex Clustering Analysis

Citation: McClain, Evan; Clarke, John-Paul; Huang, Alex; and Schleicher, David: Traffic Volume Intersection Metric for Metroplex Clustering Analysis. AIAA-2009-6069, AIAA Guidance, Navigation, and Control Conference, Chicago, Ill., Aug. 10–13, 2009.

Abstract:

A metric was developed to determine the strength of the pairwise interaction between two airports. This metric is based on both the air traffic and the displacement of that traffic off of a notional “optimal” approach. A clustering algorithm was implemented using this metric as a “distance” to determine the groups of airports with strong interactions. Such a group is viewed as a metroplex.

B.3.3 Metroplex Intersect Flow Metrics

Citation:

Cross, Carolyn M.; Thompson, Terence R.; White, Tyler H.; DiFelici, John; and Lewis, Taryn: Metrics for Aircraft Flow Interaction Complexity. AIAA 2009-7217, 9th AIAA Aviation Technology, Integration, and Operations Conference (ATIO), Hilton Head, S.C., Sept. 21–23, 2009.

Abstract:

In this paper, two metrics for quantifying the complexity of metroplex airspaces are introduced. Complexity of the airspace surrounding two or more closely spaced airports will increase with the amount of overlap between their aircraft flows. An aircraft flow is defined to be an aggregation of flights following a perceptible pattern. Flights are grouped into flows by the proximity of their tracks in space and time. In order to quantify the interaction of flows, the notion of an aircraft flow envelope was developed, and it was used to define two metrics for flow interactions: flow envelope intersections and flight pairs. The Flow Envelope Intersections Metric is simply the sum of all pairwise intersection volumes of distinct flow envelopes in the metroplex. The Flight-Pairs Metric utilizes the idea of flow envelopes, but creates a conceptually more realistic metric describing interactions of flights rather than volumes of airspace. The difference is that instead of computing the volume of airspace in the intersection of two convex polyhedra, the expected number of "flight pairs" contained in that intersection is calculated. The idea of flight pairs is to count the expected number of flights from Flow1 and Flow2 that come into close proximity. The IntersectFlows Metrics for airspace complexity comparisons were implemented both in the context of existing metroplexes (using historical track data), and in the Generic Metroplex Study.

B.4 METROPLEX SIMULATION STUDY

B.4.1 Metroplex Demand Generation for Simulation Analysis

Citation:

Timar, S.; and Schleicher, D.: Generic Airspace Demand Generation. NASA Metroplex NRA Project Report, Contract No. NNX07AP63A, unpublished, Aug. 26, 2009.

Abstract:

Generic Airspace Demand Generation is a process for creating a traffic demand set (set of scheduled arrivals and departures) to a generic airport to support simulation-based evaluation of a hypothetical terminal airspace configuration. The hypothetical airspace comprises "m" generic airports within a specified terminal airspace boundary. Each generic airport has hourly arrival and departure capacities. Specified quantities of arrival and departure fixes lie along the terminal airspace boundary with the en-route airspace at particular locations. Peripheral to the terminal airspace are "n" source/sink airports distributed at a uniform angular interval and a specified radius. The traffic demand set generated for each generic airport derives from a historical Enhanced Traffic Management System (ETMS) schedule of instrument-flight-rules (IFR) traffic for a single day in the NAS, and reflects the current-day or forecasted traffic demand to a particular NAS airport. The traffic volume in the generated generic airport demand set reflects a specified airport demand-to-capacity ratio and its capacity. Each generic airport flight in the demand set is assigned to an arrival fix or a departure fix on the terminal airspace boundary and to a source/sink airport peripheral to the hypothetical terminal airspace. Arrival flights have estimated times of arrival to their assigned fix and the generic airport, and departure flights have estimated takeoff times and times of arrival to their assigned fix and sink airport. Times of arrival reflect the transit distances inherent in the hypothetical airspace geometry and per the fix assignment rules, estimated nominal transit speeds or times by domain, and stochastic

perturbations of distance and speed or time quantities. The output of the generic airspace demand-generation process is a schedule of generic airport arrivals and departures. Each scheduled flight has an assigned arrival or departure fix and source/sink airport, a scheduled gate departure time, and estimated takeoff, fix crossing, landing, and gate arrival times.