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Investigation, Modeling, and Analysis of Integrated Metroplex Arrival and Departure Coordination Concepts

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1 Introduction

The consensus amongst government, industry, and academic stakeholders is that there will be a significant increase in air traffic demand within the National Airspace System (NAS) by the time the Next Generation Air Transportation System (NextGen) is operational [AF09, BC06]. Much of the projected demand growth will be in the form of traffic to and from major metropolitan areas, as history has shown that they are the nucleus for both population and economic growth. Thus, even if additional airports are built to accommodate the increased traffic, the airspace above major metropolitan areas will be far more crowded than they are today, and the interactions between traffic flows will be more frequent and more consequential.

1.1 Metroplex Definition

A metroplex is defined by the Joint Planning and Development Office (JPDO) as a metropolitan area with high traffic demand that is served by two or more airports with arrival and departure operations that are highly interdependent [JPDO07]. The projected traffic growth will therefore increase the coupling of operations in the metroplexes that already exist, and potentially create new metroplexes. In fact, the FAA predicts 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.

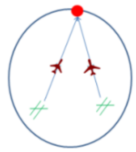
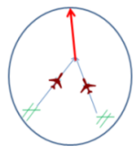
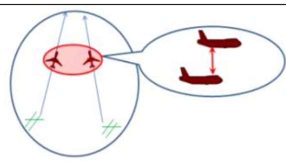
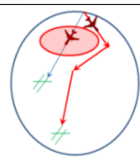
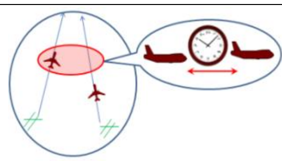
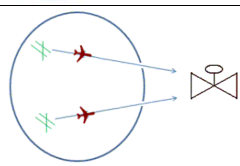
Table 1. OEP15 Airports Anticipated as Metroplexes

Airport		LAS	JFK	FLL	EWR	SAN	ORD	LAX	CLT	ATL	BOS	SFO	DTW	LGA	DFW
3X demand to 2015 capacity ratio		3.94	3.03	2.9	2.58	2.36	2.27	2.02	1.75	1.71	1.58	1.57	1.37	1.27	1.07
FACT-2 Report problem metro by year	2007	-	√	-	√	-	-	-	-	-	-	-	√	-	
	2015	√	√	-	√	-	√	√	√	√	-	-	√	-	
	2025	√	√	√	√	√	√	√	√	√	-	-	√	-	

1.2 Metroplex Interdependencies

In our prior work, we identified six types of interdependencies between traffic flows in a metroplex based on observations from metroplex site visits and traffic flow data analysis [RE09]. These interdependencies were found to result from the sharing of common fixes, paths or airspace volumes within the metroplex (i.e. metroplex resources) by different traffic flows, or the sharing of common downstream traffic flow restrictions. The six different types of interdependencies are listed and defined in the table below.

Table 2: Major Metroplex Interdependencies

#	Diagram	Definition
1		Arrivals/Departures to/from two or more proximate airports using the *same points in the airspace* – Arrival/Departure fixes
2		Arrivals/Departures to/from two or more proximate airports using *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 with *vertical separation*
4		Arrivals/Departures to/from two or more proximate airports intend to use the *same volume of airspace* but with *lateral separation*
5		Arrivals/Departures to/from two or more proximate airports intend to use the *same volume of airspace* but with *temporal separation*
6		*Downstream restrictions*, applied across multiple airports in the metroplex

The aforementioned interdependencies may be managed in one of two ways. Either, the traffic flows are physically separated, by lengthening the paths of some or all flights, such that different traffic flows will traverse different volumes of airspace; or the traffic flows are coordinated, by regulating the entry time and speed profile of the flights that are transiting the metroplex, such that the constituent traffic flows remain conflict-free [RE09]. The former is referred to as spatial control while the latter is referred to as temporal control. Examples of temporal control include holding and speed control.

1.3 Research Focus

Prior analysis of the N90 (New York) metroplex showed convincingly that, while scheduling (temporal control) and airspace redesign to separate traffic flows (spatial control) are synergistic, if one had to chose between the two then scheduling is far more effective from the viewpoint of reducing delays. This is shown very convincingly in Figure 1 below, which depicts the average delay per flight for the four different combinations of airspace re-design and scheduling. As is readily seen, there are significant reductions in delay whenever scheduling is utilized, and the reduction in delay when both airspace redesign and scheduling are utilized is slightly greater than the individual reduction when both are utilized separately, i.e. they are synergistic.

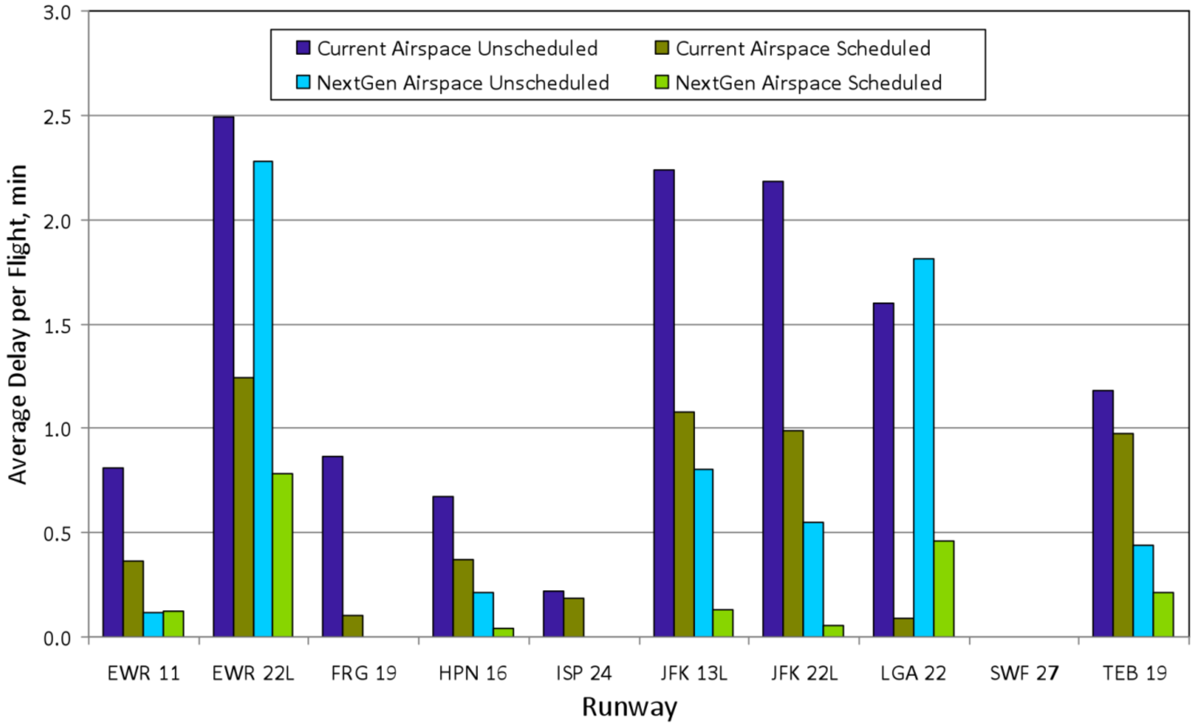


Figure 1: Benefits of Spatial versus Temporal Control in N90 (taken from [RE09])

Given these results, our team decided to focus on the development of a scheduling algorithm for metroplex operations. The name given to the tool that this algorithm would inhabit is the Multiplexer.

1.4 Structure of Report

The report is structured as follows. In the following section, Section 2, we list all the pertinent abbreviations and acronyms used throughout the document. In Section 3, we describe the "Multiplexer" algorithm that has been developed. In Section 4, we describe the emulation of TMA that was developed to represent the current state of practice in terminal area scheduling, along with a brief validation of its fidelity. In Section 5, we present the sets of geometries that were used to evaluate the performance of the algorithms. The first set of geometries includes fourteen (14) generic geometries that span the metroplex geometries observed in the NAS. The second set of geometries includes the two N90 (New York) geometries (current and future geometries) that were developed in our prior work. In Section 6, we present the analysis framework followed in Section 7 by the details of the evaluation test-bed. Results are presented in Section 8 followed by a summary of our findings in Section 9. In the last substantive section of the report, Section 10, we provide our vision for how the Multiplexer might be deployed by way of a concept of operations.

2 Abbreviations/Acronyms

ACARS	Aircraft Communications Addressing and Reporting System
ADSB	Automatic Dependent Surveillance - Broadcast
AF	Arrival Fix
ANSP	Air Navigation Service Provider
AOC	Airline Operations Center
ARTCC	Air Route Traffic Control Center
ARTS	Automated Radar Terminal System
ASDE-X	Airport Surface Detection Equipment - Model X
ATA	Actual Time of Arrival
ATCT	Air Traffic Control Tower
BADA	Eurocontrol Base of Aircraft Data
CAS	Calibrated Air Speed
CNS	Communications Navigation and Surveillance
CTAS	Center TRACON Automation System
DP	Dynamic Planner
DPs	Departure Procedures
DST	Decision Support Tool
ERAM	En Route Automation Modernization
ETA	Estimated Time of Arrival
ETMS	Enhanced Traffic Management System
FAF	Final Approach Fix
FCFS	First Come First Serve
IFR	Instrument Flight Rules
NAS	National Airspace System
Nm	Nautical mile
PBN	Performance Based Navigation
RNAV	Required Navigation
RNP	Required Navigation Performance
RTCA	Radio Technical Commission for Aeronautics
RUC	Rapid Update Cycle
SID	Standard Instrument Departure
STA	Scheduled Time of Arrival
STAR	Standard Terminal Arrival
TAF	Terminal Area Forecast
TAS	True Air Speed
TDMA	Time Division Multiple Access
TFMS	Traffic Flow Management System
TMA	Traffic Management Advisor
TMC	Traffic Management Coordinators
TRACON	Terminal Radar Control
TS	Traffic Synthesis
VFR	Visual Flight Rules

3 Multiplexer Algorithm

Application of a scheduling algorithm that does not fully account for the interactions between traffic flows can result in a rapid buildup of delay that gets pushed back into the en route airspace. Thus, if a scheduling algorithm is to be used in dense operations, we must first make sure that any savings in time or fuel that are gained within the metroplex are not negated by the added cost of the delay that is pushed back into the NAS as a whole (by way of en route delays).

3.1 Objective

The multiplexer algorithm is formulated as a mixed integer linear program for the scheduling of aircraft arrivals and departures. This schedule format is in terms of arrival and departure fix crossing times which allows for future changes in the objective to be minimized (fuel burn, etc.) with minimal changes to the scheduling program.

The current primary objective of the set of programs that have been developed is to minimize the change between the estimated times of arrival and departures with the computed times within the metroplex. The arrival changes are between the reported ETA to an arrival fix and the computed arrival time at the fix while the departure changes are changes to the estimated time to the departure fix and the computed time to the fix. This objective can be written as:

$$\min \sum_{i \in \text{Arrivals}} |\text{eta}_i - \text{sta}_i| + \sum_{j \in \text{Departures}} |\text{etd}_j - \text{std}_j|$$

Where eta_i or etd_i is the estimated time of the i^{th} aircraft (which is given as an input to the program) and sta_i or std_i is the scheduled time of the i^{th} aircraft (which is computed by the program). Elsewhere in this formulation this sta constraint will be referred to simply as t.

The goal for this set of optimization programs is to minimize the difference in the expected estimated time of each aircraft and the scheduled time producing an RTA such that the delays inside the metroplex could be reduced while not drastically increasing the delay absorbed en route. Since the optimization problem is set to minimize a sum of absolute values, there will be some cases where an aircraft is required to increase speed to meet a more optimal scheduled time. To prevent an unreasonable speed change, a constraint was added to each program such that no aircraft could be asked to push forward it's estimated time by more than 1.2 minutes. This parameter is entirely configurable, but was chosen to represent the time change resulting from a 10 knot speed increase over a 500 Nm distance.

3.2 Algorithm 1: Staged Optimization for Arrival Fix and Runway Operations

This first optimization program is a simple linear programming approach that is very fast but does not account for swapping and can only push back to account for violated constraints in the metroplex. This optimization program is two staged where the problem is separated into two sub problems and solved sequentially. This algorithm was developed in a previous metroplex project, but is included here for direct comparison.

The first problem in the series was to schedule the runway separations. Each runway was treated as a separate problem. The aircraft order was determined by the ETA to the runway with the following constraints:

$$t_{i+1} - t_i \geq sep_{i,i+1}^{runway,k} - transit_j + transit_i$$

Where t is the time at the runway and the separation is extracted from a table lookup based on aircraft weight class and arrival or departure status. This method relies on the sequence of aircraft being sorted and can only push the STA back from the ETA. It cannot swap aircraft. The output for this algorithm was saved in the variable t^{runway}.

The second stage problems relied on the first stage problems to provide an intermediate schedule time. This schedule time was then used to build an earliest constraint. The constraint followed a similar format as the previous one, with the additional constraint that the scheduled time at the entry fix could not be prior to the required time generated by the runway constraints:

$$t_{i+1} - t_i \geq sep_{i,i+1}^{entry,k}$$
$$t_i \geq t_i^{runway} - 1.2$$
$$t_i \geq eta_i$$

Since the scheduled times resulting from this simple algorithm can only be greater than or equal to the ETA, the objective can be simplified to:

$$\min \sum t_i$$

This formulation does not adequately account for the interaction between aircraft that share an arrival fix but go to different runways, but provides a simple and fast method for estimating delay values.

3.3 Algorithm 2: Joint Optimization for Airspace Fixes and Runway Operations

To more closely model the interactions between the metroplexes and provide scheduling solutions that do not push excessive delay into the en route flight regime, a more complete optimization program was developed.

3.3.1 Constraints Used to Model Metroplex Airspace

While our objective serves to provide the search direction for our optimization program, we must provide optimization constraints that accurately model the airspace constraints encountered by controllers to ensure that the algorithm generated STAs do not further complicate the problem. Optimization constraints are needed to prevent the trivial solution where an unchanged STA and ETA would be considered optimal. To accomplish this, both a runway constraint and a fix constraint were added as resource constraints.

3.3.2 Airspace Fix Constraints

The airspace fix constraints were built as follows:

Let A be the set of aircraft that use the specific airspace fix in question. Then AxA constraints were generated from the following equation:

$$t_j - t_i - Mx_{i,j} \geq sep_j - M, \qquad \forall\, i,j \in A \times A, \qquad i \neq j$$

Where t_i is the scheduled time of arrival for the i^{th} aircraft.

The variable sep_j is the required time separation (5 Nm divided by the speed of the trailing aircraft j). The variable x is a binary decision variable used to determine the leading and trailing aircraft pair. The value of x is one if aircraft i follows aircraft j and is 0 otherwise. The variable M is a sufficiently large variable that is used to ensure that the binary constraint is enforced. This is called the big M method and is a very common tool for modeling complex optimization programs. For this problem where we are optimizing a full day of traffic, a value of 3600 minutes was used.

This is a powerful method for generating constraints due to the ability of the program to allow for swapping the order of aircraft at each fix if swapping will lower the overall objective. The only limitation to this optimization method is that the number of constraints grows quadratically with the number of aircraft that use each individual resource. The worst case scenario for problem size considerations will occur when the majority of the traffic uses the same fix.

3.3.3 Runway Constraints

The runway constraints are generated in a similar manner. The primary differences are that the separation value is computed using a lookup table and that the scheduled times have to be modified by adding transit times. This constraint shown in the following equation:

$$t_j - t_i - Mx_{i,j}^{runway,k} \geq sep_{i,j}^{runway} - M - transit_j + transit_i$$

Where the transit times are factored into the equation and the separation is extracted from a table based on aircraft weight class and arrival or departure status. It should be noted here that for this algorithm to work with departures, the transit time should be negative and added to the resulting t to provide the proper departure time.

This formulation shares the same strengths and weaknesses as the airspace fix formulation. It allows for swapping when more optimal but at the cost of growing quadratically the number of constraints.

3.3.4 Solution Methodology

The solution methodology evolved with the project due to increasing problem sizes and runtime constraints. The first solution algorithm was to simply build the entire problem for the whole metroplex and solve. This extends the algorithm defined as Algorithm 1 by including swapping via the binary decision variables. However, the solution times were greatly increasing as the number of aircraft increased, and due to the binary variables, the solution times were large. While this problem could be solved given sufficient memory and computational resources, to increase efficiency, several math programming techniques were used.

To solve our mixed integer linear programming scheduling problem, a rolling horizon solution was used in conjunction with a Bender's decomposition scheme. This separated the scheduling into one hour pieces of the schedule to be solved sequentially. This rolling horizon solution method is commonly used and allows for a continuous solution case where every hour the next hour's schedule is optimized. If the hour is found to be too long or short, it can easily be adjusted to accommodate. The Bender's decomposition breaks the single large problem required to schedule a full hour of dense operations into separate sub-problems and master problems similar to the staged optimization procedure. The more difficult runway problems become sub-problems to the entry fix master problem. It takes the two sets of mixed integer constraints and turns them into problems, but instead of solving them sequentially, it solves them both iteratively, passing constraints up from the sub problems to the master problem until the solution converges.

3.3.5 Solution Algorithm

To solve the problem using the defined methodology, the algorithm sequence was as follows:

- Solve the master problems (entry fix problems) using CPLEX to generate an initial set of STAs (called *t* in the constraint equations).
- Take STA values and generate sub-problems (runway constraint problems) to solve for the feasibility of each runway schedule. Solve using CPLEX.
- If a sub-problem is infeasible, the dual problem will be unbounded. Use the unbounded ray to generate a constraint for the entry fix STAs following the standard Bender's scheme. Add this constraint to the master problem.
- Resolve the master problem with the updated constraints using CPLEX and rebuild the sub-problems to recheck for feasibility of each runway schedule.
- If every runway schedule is feasible, the algorithm has converged. Otherwise, iterate until converged.

4 TMA Algorithm

The baseline scheduling capability assumed in the previous Metroplex NRA was a first-in-first-out scheduling algorithm. Today, there are time-based arrival scheduling utilities such as the Traffic Management Advisor (TMA) in place in most ARTCCs. In addition, controllers also use a mental model of arrival fix sequences, TRACON traversal times, and the resulting landing times to enforce efficient and conflict-free arrival fix crossing and runway landing sequences. Additionally, there are departure sequencing and scheduling aids such as the Departure Sequencing Program (DSP), which is used in the New York TRACON for managing departure sequences over shared departure fixes. As a result, a FIFO scheduler is not a fair depiction of the arrival scheduling process in current-day terminal operations. Our Metroplex NRA team plans to develop a TMA-emulation arrival scheduling algorithm to better represent current day baseline scheduling capabilities against which the team's Integrated Metroplex Scheduling Concept will be compared.

4.1 Background

In the current air traffic system, the TMA is a decision support tool (DST) that assists the center Traffic Management Coordinators (TMCs) and controllers with planning and time-based scheduling of arrival traffic. TMA is a part of a suite of DSTs called the Center TRACON Automation System (CTAS). TMA is currently installed and functional at all 20 Air Route Traffic Control Centers (ARTCCs). TMA's time-based scheduling engine, called the Dynamic Planner (DP), is perhaps closest to the current state-of-the-art in multi-airport time-based scheduling controller aids. TMA's DP can handle up to five different airports within a TRACON and treats them as separate entities from a scheduling perspective. Runways at different airports are additionally treated independent of each other. Section 3 of this document discusses the development of a proxy model of TMA's DP scheduling capability and its application as a baseline for the assessment of a NextGen scheduling capability as applied to a set of generic metroplex geometries that cover the entire span of arrival geometry-types found in the National Airspace System (NAS), as well as its application to the scheduling simulation for a New York metroplex model. A validation study was conducted using Sensis' in-house CTAS simulation capability to assess how closely it emulates the real TMA schedules.

4.2 Technical Approach and Algorithm Description

Our technical approach was two-pronged. First, we leveraged existing literature which outlined the workings of TMA [EDG93, DE95] and the details of TMA's DP component [W00]. Second, we met with the principal developer of TMA – Mr. Harry Swenson of NASA Ames – to gain additional assistance in understanding the intricacies of the DP scheduling methodology. Based on the literature search and discussions with Mr. Swenson, we were able to develop a good understanding of TMA's scheduling process, and use it to develop the emulation. We outline the DP scheduling process in the following section.

4.3 TMA Scheduling Capability (Dynamic Planner) Description

The DP assists the Traffic Management Coordinators (TMCs) and controllers with planning and scheduling of arrival traffic that is within 35 to 200 nm of the destination airport. The DP computes schedules that conform to constraints that are manually input by TMCs and reflect the operational and environmental conditions of the airports and airspace. The Center TRACON Automation System's (CTAs') Trajectory Synthesizer predicts the Estimated Times of Arrival (ETAs) at an outer meter arc, the meter fix, the final approach fix (FAF), and the runway threshold. These scheduling points are collectively called Reference Points. Figure 1 shows typical arrival geometry at an airport having a four corner-post TRACON configuration. The DP uses these generated ETAs to compute de-conflicted STAs at the meter fix, and the runway threshold.

CTAS first predicts the ETAs to the runway and to the meter fix for all incoming aircraft within the center. These ETA estimates are based on the assumption that the aircraft will follow a nominal approach trajectory with no interference from other air traffic. TMA then creates STAs for the aircraft at the meter fix, retaining the first come, first served (FCFS) order of arrival, but delaying some aircraft to maintain the mandatory separations between successive arrivals at the meter fix. The TMC may alter the meter fix sequence by entering specific sequencing constraints and the DP will reschedule to conform to the input sequence constraints. The DP through a process called Runway Allocator also attempts to assign arrival aircraft to runways so as to reduce the overall delay. STAs at the meter fix and nominal fix-to-runway travel times are then used to generate ETAs at the runway. Runway STAs are then computed by deconflicting the runway ETAs in an optimized order using an Order of Consideration algorithm, to satisfy constraints for wake-vortex separation, acceptance rate, and runway occupancy. If the delay assigned to a specific aircraft is greater than the capacity of the TRACON, then the excess delay is fed back to the center. ETAs to the meter fix are updated accordingly and the scheduling process is repeated [W00].

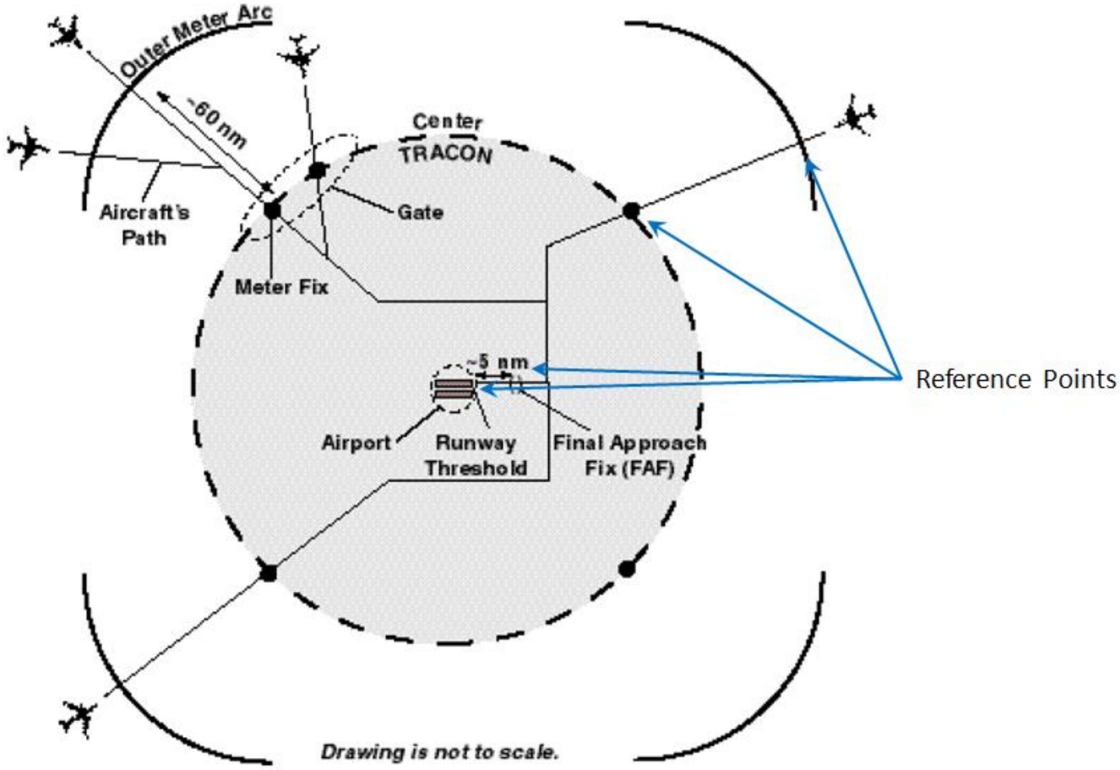


Figure 2: Typical Arrival Geometry with TMA Reference Points (taken from [W00])

4.4 Stream Class Concept and Order of Consideration Algorithm

Once the runway ETAs are computed from the meter fix STAs, the DP then uses a modified sequence – conserving scheduling strategy to compute runway STAs. The aircraft enter the scheduling process based upon an Order of Consideration. To compute the Order of Consideration, aircraft with similar scheduling characteristics (engine type, destination airport and runway, and assigned arrival fix) are first grouped together into classes called stream-classes. For example, all aircraft crossing the same arrival fix and inbound to the same airport form one stream-class; all turbo-props crossing the same arrival fix and inbound to the same airport form another stream-class; all aircraft crossing the same arrival fix and inbound to another airport form another stream-class; all aircraft crossing another arrival fix form still another stream-class, and so on. Figure 2 shows a notional example of stream class classification.

AC_ID	Assigned/Planned Arrival Fix	Assigned/Planned Runway	Engine-type
AA991	XYZ	22 L	Jet
LJ200	XYZ	11	Turboprop
UA001	ABC	22 L	Jet
SW002	XYZ	22 L	Jet
...	...	...	...

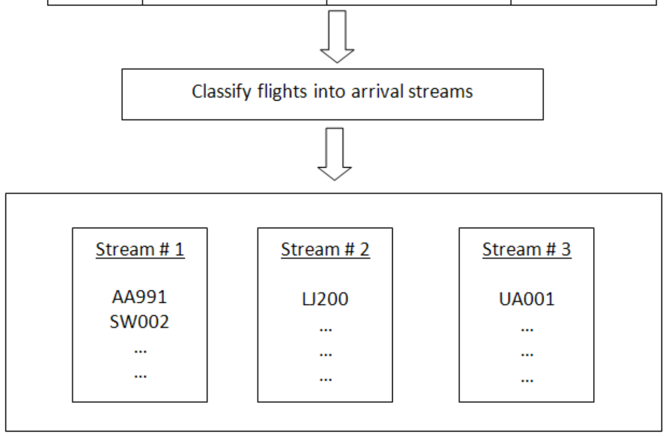


Figure 3: Classification of Flights into Arrival Stream-Classes

The Order of Consideration algorithm ensures that aircraft within a single stream-class are sequenced to the runway in the same order as the order in which they are predicted to cross the arrival fix. However, aircraft belonging to different stream-classes may be re-sequenced with respect to each other between the arrival fix and the runway. That is, if an aircraft A belonging to stream class # 1 has its Estimated Arrival-fix Crossing Time later than that of aircraft B belonging to stream class # 2, but its Estimated Runway Landing Time is earlier than that of aircraft B, then aircraft A will be sequenced ahead of B to the runway. The order in which aircraft are selected for finalizing their runway and FAF scheduled time of arrivals (STAs) is determined by the following Order of Consideration algorithm.

The algorithm begins by determining the flight with the earliest meter fix STA within each stream class. Among these meter-fix-leaders-within-each-stream-class flights, the flight with the earliest runway ETA is selected as the next flight in the Order of Consideration. This flight has its runway and FAF STA computed by spacing it with respect to any previous landing on the runway and any necessary delay is absorbed in the TRACON if it is within the TRACON absorption limit. Excess delay, if any, is fed back to its meter-fix STA. This algorithm is repeated until all the flights have been scheduled to the runway. Please see [W00] for an example of Order of Consideration computation.

4.5 TMA Scheduling Capability Emulation Description

The TMA Emulator mimics the scheduling process outlined in the previous section. Since the purpose is to develop a TMA-like scheduler for multi-airport systems, the emulator expands the stream class concept as follows – all flights inbound to the same airport and using the same arrival fix that have similar operational characteristics (i.e., the same engine type) are placed in the same stream class. The scheduling and order of consideration algorithms are also slightly adapted to apply to multi-airport systems and comprised of the following steps:

1. Start with estimated ETAs at the meter fix and de-conflict in the FCFS order. This gives the initial meter fix STAs.
2. Select the flight with the earliest meter fix STA from each stream class.
3. Among these flights, ”n” flights each having the earliest runway ETAs at the ”n” metroplex airports are chosen as the next flights in the order of consideration.
4. If any two or more of these”n” flights are crossing the same arrival fix, then only one flight (= the leader at the arrival fix) is selected to be next in the order of consideration.
5. Runway and FAF STAs are computed for the selected flights. Any delay required to achieve the minimum required spacing for the preceding flight that is over or above the Allowed Mean Delay Threshold is fed back to the meter fix STA.
    - If delay is required to be fed back to the meter-fix, then all flights in the same stream class are vectored or held, if required, to maintain minimum separation at the arrival fix.
    - Reordering of the initial arrival fix crossing order, if required.
    - Spacing satisfied for all flights crossing the arrival fix.
6. Meter-fix and runway STAs for the selected flights are finalized.
7. The scheduled flights are removed from the processing list.
8. This process is repeated until all flights have been scheduled to the runway.

4.6 Validation Approach

Our approach for validating the TMA emulation is simulation based. A traffic demand set consisting of arrival traffic to the Denver International Airport (DEN) is processed through the Sensis in-house CTAS simulation. The TMA scheduling process working within CTAS acts on the same traffic demand set, predicting aircraft trajectories, de-conflicting crossing times at the scheduling points, and providing the final TMA schedules for each flight in the input traffic demand set. The same traffic demand set is processed through the TMA scheduling emulator and the scheduling emulation final schedules are obtained. The two schedules are compared to determine if the fix crossing sequences and crossing times match.

4.7 Validation Results

The scenario used for initial validation was a simple one arrival-fix to one runway scheduling case for aircraft crossing the SAYGE arrival-fix to DEN runway 10. The purpose of this validation was to check if the sequence and timing of arrival-fix crossing produced by the TMA emulation was in agreement with what the scheduling algorithm within CTAS produced. As shown in Table 3 and Table 4, the TMA emulation produced the exact same sequence for arrival-fix crossings and the exact arrival-fix crossing times for most flights. As seen from Table 3, CTAS sometimes assigns a STA to a flight that is earlier than its ETA contrary to the algorithm specifications and sometimes delays flights more than required to satisfy the minimum separation requirement (imposed as 7 nautical miles at the arrival-fix in the validation scenario).

Table 3: Result of CTAS simulations for the validation scenario

Flight ID	ACType	Weight Class	Engine Type	Arrival Fix	Arrival Runway	ArrFix ETA	ArrFix STA	**ArrFix Spacing**
COA1423	B744	L	J	SAYGE	10	18:41:55	18:41:43	
COA1427	B744	L	J	SAYGE	10	18:41:59	18:42:59	**0:01:16**
COA1432	B744	L	J	SAYGE	10	18:42:03	18:44:15	**0:01:16**
COA1435	B744	L	J	SAYGE	10	18:42:05	18:45:31	**0:01:16**
COA1439	B744	L	J	SAYGE	10	18:42:09	18:46:47	**0:01:16**
COA1441	B744	L	J	SAYGE	10	18:42:10	18:48:15	**0:01:28**
COA1440	B744	L	J	SAYGE	10	18:42:11	18:49:31	**0:01:16**
COA1448	B744	L	J	SAYGE	10	18:42:17	18:50:35	**0:01:04**
COA1422	B752	L	J	SAYGE	10	18:43:04	18:51:53	**0:01:18**
COA1429	B752	L	J	SAYGE	10	18:43:04	18:53:17	**0:01:24**
COA1428	B752	L	J	SAYGE	10	18:43:07	18:54:33	**0:01:16**
COA1431	B752	L	J	SAYGE	10	18:43:09	18:55:49	**0:01:16**
COA1438	B752	L	J	SAYGE	10	18:43:09	18:57:07	**0:01:18**
COA1424	B738	L	J	SAYGE	10	18:43:10	18:58:23	**0:01:16**
COA1421	B738	L	J	SAYGE	10	18:43:11	18:59:39	**0:01:16**
COA1426	A319	L	J	SAYGE	10	18:43:12	19:00:53	**0:01:14**
COA1442	B752	L	J	SAYGE	10	18:43:14	19:02:09	**0:01:16**
COA1425	A320	L	J	SAYGE	10	18:43:16	19:03:25	**0:01:16**
COA1433	B738	L	J	SAYGE	10	18:43:16	19:04:41	**0:01:16**
COA1434	B738	L	J	SAYGE	10	18:43:17	19:05:57	**0:01:16**
COA1444	B752	L	J	SAYGE	10	18:43:17	19:07:13	**0:01:16**
COA1430	A320	L	J	SAYGE	10	18:43:18	19:08:29	**0:01:16**
COA1437	B738	L	J	SAYGE	10	18:43:20	19:09:45	**0:01:16**
COA1449	B752	L	J	SAYGE	10	18:43:20	19:11:03	**0:01:18**
COA1436	A320	L	J	SAYGE	10	18:43:21	19:12:19	**0:01:16**
COA1443	B738	L	J	SAYGE	10	18:43:22	19:13:35	**0:01:16**
COA1447	B738	L	J	SAYGE	10	18:43:26	19:14:47	**0:01:12**
COA1445	A320	L	J	SAYGE	10	18:43:28	19:16:07	**0:01:20**
COA1446	A320	L	J	SAYGE	10	18:43:29	19:17:23	**0:01:16**
COA1451	B738	L	J	SAYGE	10	18:43:29	19:18:37	**0:01:14**
COA1450	A320	L	J	SAYGE	10	18:43:32	19:19:53	**0:01:16**

The TMA emulation also adheres to delaying past the ETA, and also spaces the flights at the arrival-fix by the minimum amount required (7 nm in-trail separation requirements which equates to approximately a 76 second separation crossing the arrival fix). As shown in the tables, the TMA emulation produced excellent results when compared to the CTAS scheduling algorithm.

Table 4: Results of TMA emulation scheduling simulation (compare arrival sequence, Arrival Fix STAs and Arrival Fix spacing against the data in Table 3)

Flight ID	ACType	Weight Class	Engine Type	Arrival Fix	Arrival Runway	ArrFix ETA	ArrFix STA	**ArrFix Spacing**
COA1423	B744	L	J	SAYGE	10	18:41:55	18:41:55	
COA1427	B744	L	J	SAYGE	10	18:41:59	18:43:11	**0:01:16**
COA1432	B744	L	J	SAYGE	10	18:42:03	18:44:27	**0:01:16**
COA1435	B744	L	J	SAYGE	10	18:42:05	18:45:44	**0:01:17**
COA1439	B744	L	J	SAYGE	10	18:42:09	18:47:00	**0:01:16**
COA1441	B744	L	J	SAYGE	10	18:42:10	18:48:16	**0:01:16**
COA1440	B744	L	J	SAYGE	10	18:42:11	18:49:33	**0:01:17**
COA1448	B744	L	J	SAYGE	10	18:42:17	18:50:49	**0:01:16**
COA1422	B752	L	J	SAYGE	10	18:43:04	18:52:05	**0:01:16**
COA1429	B752	L	J	SAYGE	10	18:43:04	18:53:22	**0:01:17**
COA1428	B752	L	J	SAYGE	10	18:43:07	18:54:38	**0:01:16**
COA1431	B752	L	J	SAYGE	10	18:43:09	18:55:55	**0:01:17**
COA1438	B752	L	J	SAYGE	10	18:43:09	18:57:11	**0:01:16**
COA1424	B738	L	J	SAYGE	10	18:43:10	18:58:27	**0:01:16**
COA1421	B738	L	J	SAYGE	10	18:43:11	18:59:44	**0:01:17**
COA1426	A319	L	J	SAYGE	10	18:43:12	19:01:00	**0:01:16**
COA1442	B752	L	J	SAYGE	10	18:43:14	19:02:16	**0:01:16**
COA1425	A320	L	J	SAYGE	10	18:43:16	19:03:33	**0:01:17**
COA1433	B738	L	J	SAYGE	10	18:43:16	19:04:49	**0:01:16**
COA1434	B738	L	J	SAYGE	10	18:43:17	19:06:05	**0:01:16**
COA1444	B752	L	J	SAYGE	10	18:43:17	19:07:22	**0:01:17**
COA1430	A320	L	J	SAYGE	10	18:43:18	19:08:38	**0:01:16**
COA1437	B738	L	J	SAYGE	10	18:43:20	19:09:55	**0:01:17**
COA1449	B752	L	J	SAYGE	10	18:43:20	19:11:11	**0:01:16**
COA1436	A320	L	J	SAYGE	10	18:43:21	19:12:27	**0:01:16**
COA1443	B738	L	J	SAYGE	10	18:43:22	19:13:44	**0:01:17**
COA1447	B738	L	J	SAYGE	10	18:43:26	19:15:00	**0:01:16**
COA1445	A320	L	J	SAYGE	10	18:43:28	19:16:16	**0:01:16**
COA1446	A320	L	J	SAYGE	10	18:43:29	19:17:33	**0:01:17**
COA1451	B738	L	J	SAYGE	10	18:43:29	19:18:49	**0:01:16**
COA1450	A320	L	J	SAYGE	10	18:43:32	19:20:05	**0:01:16**

The team is currently continuing with more rigorous tests and the results will be presented in a paper at the AIAA Aviation Technology Integration and Operations Conference in September 2011.

5 Metroplex Geometries

5.1 Generic Geometries

Fourteen (14) Generic Metroplexes were developed based on two (2) arrival-departure-fix geometries from our previous work and seven (7) runway geometries that were determined in this effort to span the runway geometries of the NAS. The set of runway geometries was developed by analyzing the runway geometries of current metroplexes, with the caveats that there are only two airports within each metroplex, with one arrival and one departure runway each. For the sake of both brevity and clarity, the details of this analysis have been reserved for Appendix A.

An important thing to note and to remember about these generic geometries is that in the cases where there are dual arrival fixes at each corner post, there are only merge points – one at each arrival fix and one near each runway; and in the cases where there is a single arrival fix at each corner post, there is a combined merge and crossing point at each arrival fix and a merge point near each runway. The Multiplexer explicitly consider these merges and crossing, thus we expect that it will be able to determine the optimum schedule for each generic geometry, i.e. the schedule that produces the minimum total delay. The same is mostly true for TMA, however, because of some of the feature described in the previous section, it will likely not determine the best schedule from an overall delay perspective.

The resulting lateral paths (i.e. the arrival/departure routes) for the complete set of 14 Generic Metroplex Airspace Geometries were constructed by combing the aforementioned runway geometries with either a single or a double corner-post-fix geometry (Geometries 1 and 3 from our previous Metroplex project). The lateral paths for the complete set of generic geometries are shown below in Figure 4 and Figure 5.

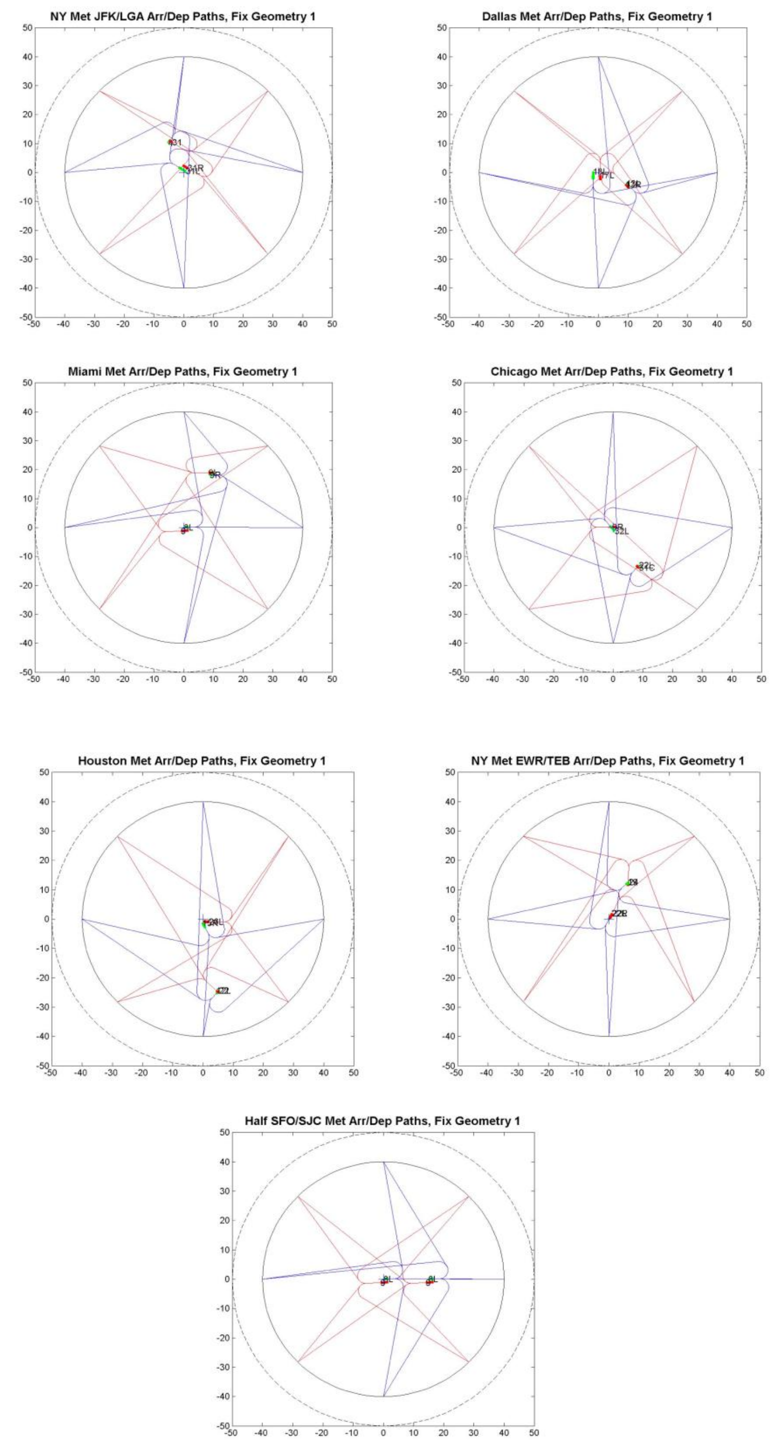


Figure 4: Lateral Paths for Generic Metroplexes with Single-Corner-Posts

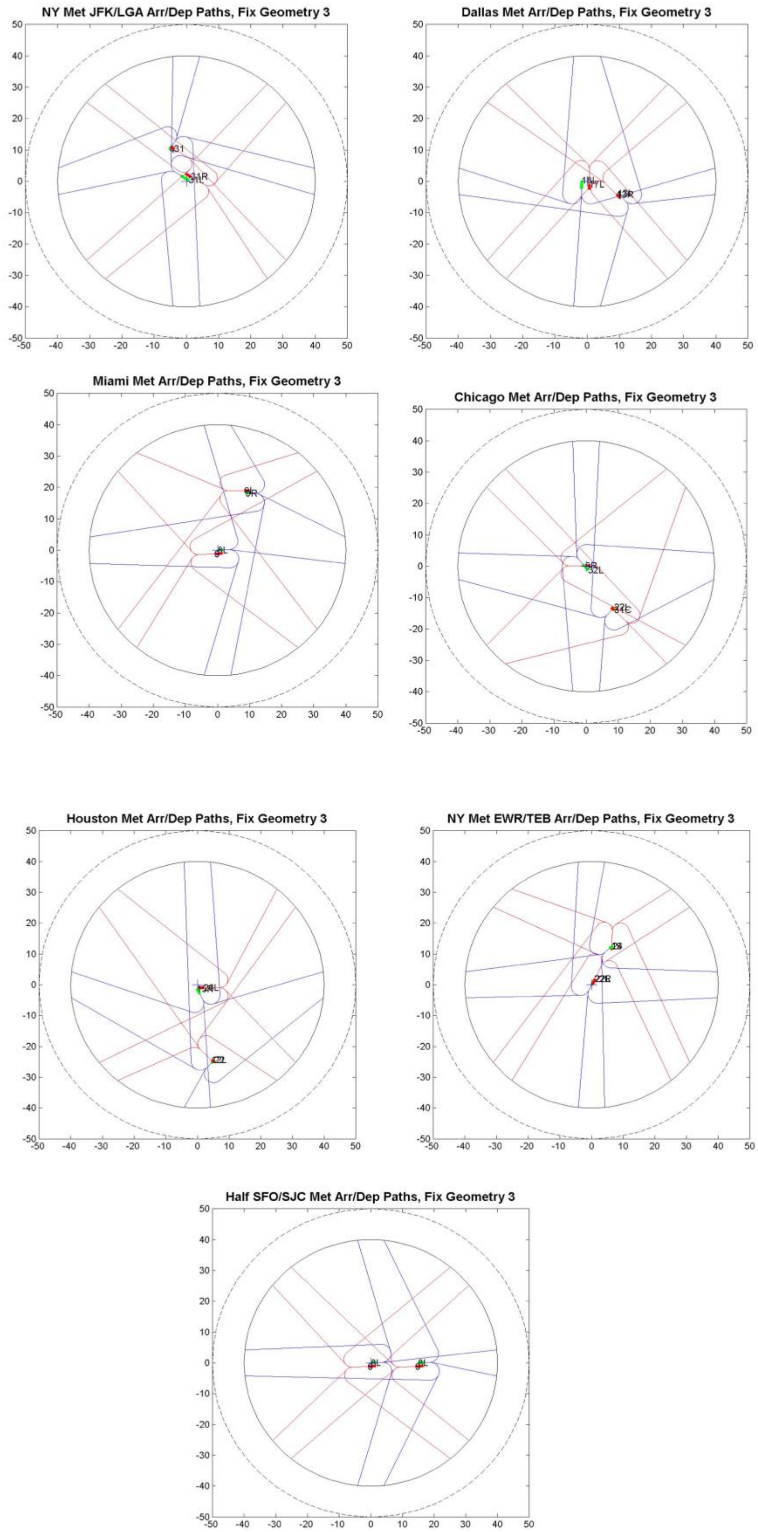


Figure 5: Lateral Paths for Generic Metroplexes with Double-Corner-Posts

The lateral paths served as the baseline lateral routes for each metroplex geometry. The vertical trajectory from each arrival and departure fix were extended to or from the respective runways along these lateral routes. The arrival vertical profiles were developed using TASAT, the Tool for Analysis of Separation and Throughput, and the departure profiles were developed from high fidelity operational and performance data. The airspace environment applied in TASAT was for nominal wind speed and direction, with a range of respective landing weights and ambient temperature. The vertical trajectory generated by TASAT was a Continuous Descent Arrival (CDA) profile terminating at a point of intercept with the respective runway ILS glideslope with intercept requirements, and standard IFR approach criteria [Ref 1]. Since the use of a CDA profile has been shown to minimize fuel burn along with noise and emissions by eliminating level flight segments, the nominal arrival profiles are inherently optimized.

Since the arrival and departures were developed with a range of aircraft types/categories (small, large, B757, and Heavy) over a representative range of landing/takeoff weights, wind, and temperature, a range of vertical and lateral profiles were produced for each path in the metroplex. The highest and lowest altitude profiles, along with the maximum lateral path width for each route was taken to be the arrival/departure path maximum and minimum thresholds.

These arrival and departure procedures were then input into the FAA's Terminal Area Route Generation Evaluation and Traffic Simulation (TARGETS) tool. TARGETS further checks for the flyability of each arrival and departure path with built-in criteria with respect to altitude and speed changes, and turn radius constraints. In order to satisfy these flyability criteria, the following restrictions were imposed on the CDA profiles developed by TASAT:

- During descent, the aircraft will maintain a flight path angle between 2.5 and 3.5 degrees.
- Until the aircraft reaches 10,000 ft, a descent speed of 300 knots will be maintained.
- A deceleration to result in a speed of 240 knots by 10,000 ft.
- A flight distance of 1 Nm is required for each 10 knot speed change.
- A flight distance of 1 Nm is required for each 318 feet of altitude change.
- When an arrival has a downwind leg, the speed restrictions are 210 knots for the turn onto the base-leg and 180 knots for the turn onto the final approach.
- The final approach fix is located 5 miles from runway threshold, at which point the aircraft is to intercept the ILS glideslope.

After development and meeting the flyability criteria in TARGETS, the baseline arrival and departure profiles were applied to all metroplex geometries. Figure A depicts the Miami metroplex Geometry 1 case study.

Figure 6: Aerial view of Miami Geometry 1 metroplex. On the right is an enlarged view of a typical conflict zone in this metroplex, where the upper threshold of the red arrival path intersects the lower threshold of the blue departure path.

As seen in Figure 6, there are several points/areas where the arrival and departure paths intersect. The next step in the metroplex design process was to deconflict these intersections in an optimized manner. A typical conflict region is annotated in Figure B, where only the vertical trajectory is shown for an arrival and departure threshold.

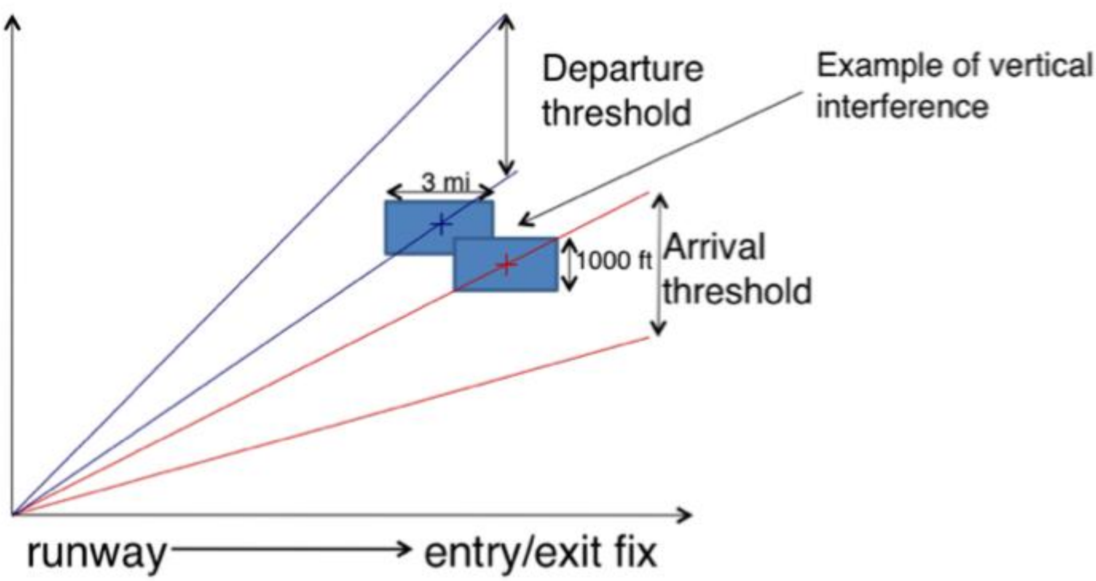


Figure 7: Example of an area of vertical interference.

In Figure 7, for discussion purposes, let the point of intersection between these arrival and departure paths be at the points denoted with the cross, '+', where the lower threshold of the departure trajectory intersects with the upper threshold of the arrival trajectory. Per ATC standard separation guidelines, a vertical separation of 1000 feet and a lateral separation of 3 Nm is required between aircraft. In order to maintain this separation on all paths and completely deconflict the flow of traffic in the metroplex, cylinders with a diameter of 3 miles and height of 1000 feet is imposed on the upper and lower bounds of all trajectories. If any adjacent cylinders insect, this region is treated as a conflict zone and deconfliction of the traffic is required. In Figure B, the two blue intersecting squares can be viewed as cross sections of the described cylinders, centered at the cross '+' notations. As evident in this scenario, where these cylinders are 'just' in contact with each other is where the minimum separation requirements are met.

At each of these conflict zones, there are two deconfliction strategies to be considered. In Figure 8, the lower (arrival) trajectory was leveled off in order to maintain the required vertical separation. As can be seen, the descent gradient of the arrival is kept constant to facilitate determining location for the level-off, so that the edges of the two cylinders just 'touch' each other on the surface. This process guarantees the required separation is observed, while optimizing the location of the level-off. The alternative strategy would be to laterally move the arrival trajectory to avoid the conflict when feasible, given the geometry of the adjacent routes in the metroplex. Movement of the arrival trajectory, when possible, is considered more fuel efficient than movement of the departure trajectory due to the difference in the engine power settings involved.

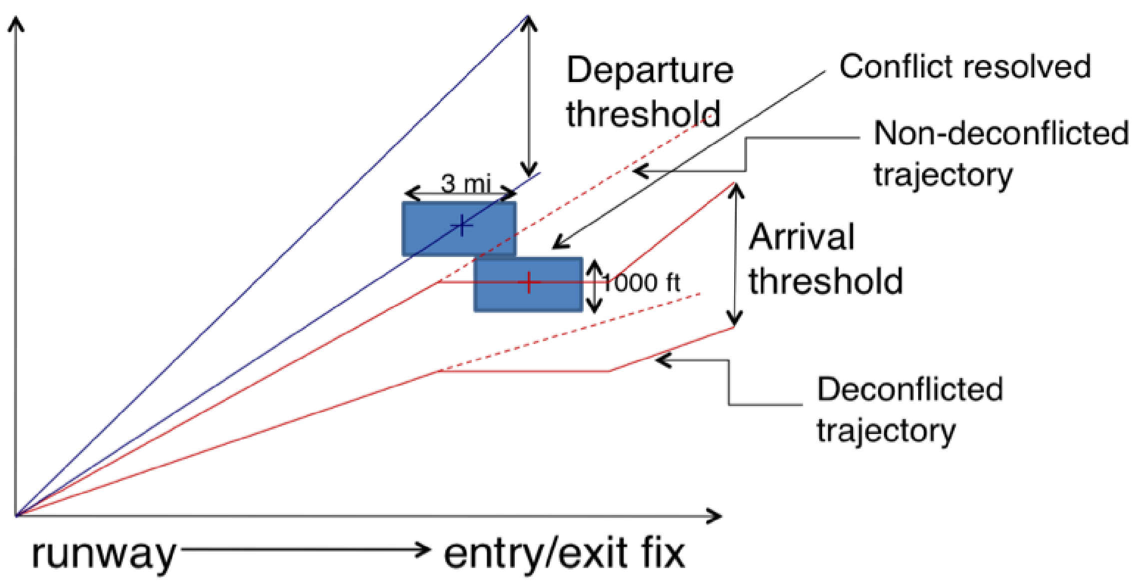


Figure 8: Example of a vertical deconfliction by level-offs.

To optimize the deconflicted routes (where both methods of deconfliction were feasible), the altered arrival paths were input into TASAT to produce fuel burn results for comparison. The altered route with lower fuel burn results was chosen as the new deconflicted path. In addition, the new paths were again input into TARGETS to ensure the flyability criteria were met.

The transit times obtained from a fully deconflicted metroplex traffic flow were fed into both the TMA and Multiplexer algorithms as baseline transit times. The arrival transit times input in these algorithms are given in Table 5 below.

.

Table 5: Metroplex Transit Times

	Route	Geometry 1 Heavy Aircraft	Geometry 1 Large Aircraft	Geometry 1 Small Aircraft	Geometry 3 Heavy Aircraft	Geometry 3 Large Aircraft	Geometry 3 Small Aircraft
MIA-FLL metroplex	MIA_NE	12.91	13.00	13.29	13.02	13.11	13.40
	MIA_SE	12.91	13.00	13.28	12.65	12.74	13.02
	MIA_SW	9.78	9.90	10.12	9.94	10.05	10.28
	MIA_NW	9.80	9.92	10.14	9.67	9.80	10.01
	FLL_NE	9.07	9.16	9.36	8.63	8.72	8.91
	FLL_SE	14.48	14.57	14.89	13.94	14.04	14.35
	FLL_SW	14.04	14.16	14.47	14.17	14.29	14.60
	FLL_NW	9.20	9.33	9.54	11.91	12.04	12.31
SFO-SJC metroplex	SFO_NE	12.70	12.79	13.07	12.62	12.71	12.99
	SFO_SE	12.84	12.93	13.21	12.60	12.69	12.97
	SFO_SW	9.97	9.85	10.06	9.74	9.87	10.09
	SFO_NW	9.97	9.85	10.06	9.73	9.85	10.07
	SJC_NE	9.64	9.53	9.74	9.43	9.52	9.73
	SJC_SE	9.64	9.74	9.95	9.57	9.66	9.87
	SJC_SW	13.19	13.06	13.35	12.87	12.99	13.28
	SJC_NW	13.21	13.08	13.36	12.90	13.02	13.31
ORD-MDW metroplex	ORD_NE	12.44	12.53	12.81	12.21	12.30	12.57
	ORD_SE	12.51	12.61	12.88	12.92	13.00	13.29
	ORD_SW	10.02	10.15	10.37	9.87	9.99	10.22
	ORD_NW	9.85	9.97	10.19	9.71	9.83	10.05
	MDW_NE	12.79	12.90	13.18	12.52	12.62	12.90
	MDW_SE	6.57	6.70	6.85	6.46	6.60	6.74
	MDW_SW	11.99	12.09	12.36	10.92	11.02	11.27
	MDW_NW	16.32	16.41	16.77	16.55	16.64	17.00
IAH-HOU metroplex	IAH_NE	9.66	9.78	10.00	9.76	9.89	10.10
	IAH_SE	10.18	10.30	10.52	10.09	10.21	10.43
	IAH_SW	12.73	12.73	13.10	12.87	12.96	13.24
	IAH_NW	12.31	12.40	12.68	12.10	12.20	12.47
	HOU_NE	13.59	13.70	14.01	13.62	13.70	14.00
	HOU_SE	9.97	10.05	10.27	9.64	9.72	9.93
	HOU_SW	8.88	8.99	9.19	8.56	8.67	8.86
	HOU_NW	13.55	13.69	13.99	13.35	13.49	13.78
DFW-DAL metroplex	DFW_NE	9.81	9.93	10.14	9.70	9.82	10.03
	DFW_SE	12.41	12.50	12.78	12.40	12.49	12.76
	DFW_SW	12.43	12.53	12.80	12.55	12.65	12.93
	DFW_NW	10.07	10.19	10.42	9.95	10.08	10.30
	DAL_NE	9.94	10.06	10.29	9.97	10.07	10.29

	DAL_SE	11.58	11.66	11.91	11.58	11.66	11.92
	DAL_SW	11.92	12.03	12.30	11.90	12.01	12.28
	DAL_NW	11.23	11.37	11.63	11.27	11.40	11.66
TEB-EWR metroplex	TEB_NE	7.32	7.45	7.61	7.20	7.33	7.49
	TEB_SE	12.88	12.97	13.26	12.67	12.77	13.05
	TEB_SW	15.42	15.51	15.85	15.28	15.37	15.71
	TEB_NW	10.82	10.93	11.17	10.52	10.64	10.87
	EWR_NE	9.35	9.49	9.69	9.39	9.52	9.73
	EWR_SE	11.43	11.53	11.79	11.54	11.64	11.90
	EWR_SW	13.40	13.48	13.78	13.56	13.64	13.94
	EWR_NW	10.95	11.05	11.30	11.12	11.22	11.47
JFK-LGA metroplex	JFK_NE	11.04	11.15	11.39	10.87	10.98	11.22
	JFK_SE	9.35	9.49	9.70	9.37	9.51	9.72
	JFK_SW	11.58	11.68	11.94	11.14	11.25	11.50
	JFK_NW	13.69	13.77	14.07	13.97	14.08	14.40
	LGA_NE	9.91	10.02	10.24	9.98	10.08	10.31
	LGA_SE	11.12	11.26	11.51	11.03	11.17	11.42
	LGA_SW	11.97	12.08	12.34	11.97	12.08	12.35
	LGA_NW	13.94	13.96	14.27	11.81	11.89	12.15

5.2 New York Geometries

Our intent in modeling the New York airspace was to explore the issues associated with and the impact of having multiple intermediate crossing and merge points within the metroplex, as opposed to the case for the generic metroplexes where (in the cases where there are dual arrival fixes at each corner post) there are only merge points, one at each arrival fix and one near each runway; or (in the cases where there is a single arrival fix at each corner post) there is a combined merge and crossing point at each arrival fix and a merge point near each runway. Because neither TMA nor the Multiplexer explicitly consider these intermediate constraints, we expected that there might be additional delays introduced simply because of the effects of un-modeled interactions between traffic flows.

Arrival and departure paths and vertical profiles were developed for all of the airspace within the radar coverage of N90 TRACON. The flight paths 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 4D trajectory could be modeled. The resulting arrival and departure route structure is shown in Figure 9 as modeled in SIMMOD for current day conditions (arrival in green and departure in red).

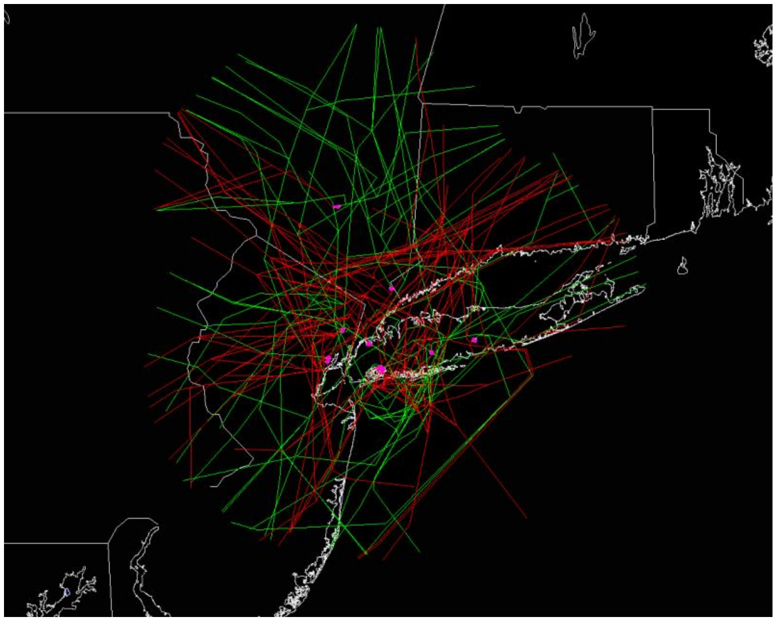


Figure 9: Current N90 Geometry

A second simulation model was developed to facilitate the study of the potential impacts of NextGen technologies and procedures, and more relevant for this study, to allow us to further illustrate the relative benefits of scheduling versus airspace redesign. The NextGen Geometry was constructed by combining the outer portion of the Current Geometry with an "inner" airspace geometry developed at Georgia Tech that is depicted in Figure 10. This inner airspace was basically connected to the outer airspace at the various entry and exit points of the inner airspace. Speed and altitude profiles were then adjusted to reflect a 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. This significantly simplifies 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 concept. Although some of the arrival or departure routes might fly over noise sensitive areas due to the simplified design, design improvements could be incorporated in the future to address the noise concern should an implementation be desired.

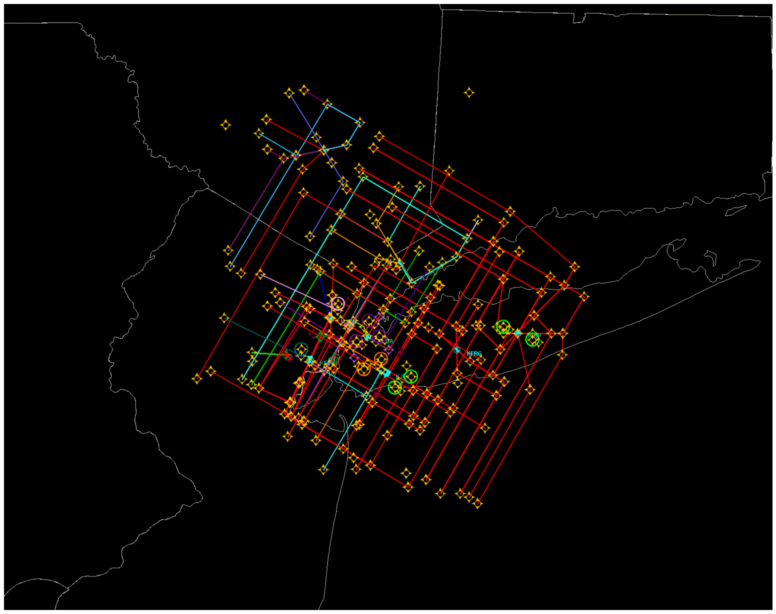


Figure 10: Inner Portion of NextGen N90 Geometry

6 Analysis Framework and Methodology

An overview of the framework and the methodology used to evaluate the metroplex scheduling algorithms is provided below.

6.1 Analysis Architecture

The analysis architecture is comprised of traffic demand, airspace model, traffic scheduling, traffic simulation, and simulation data post-processing elements. The architectures and components particular to the generic metroplex and N90 assessments are discussed below.

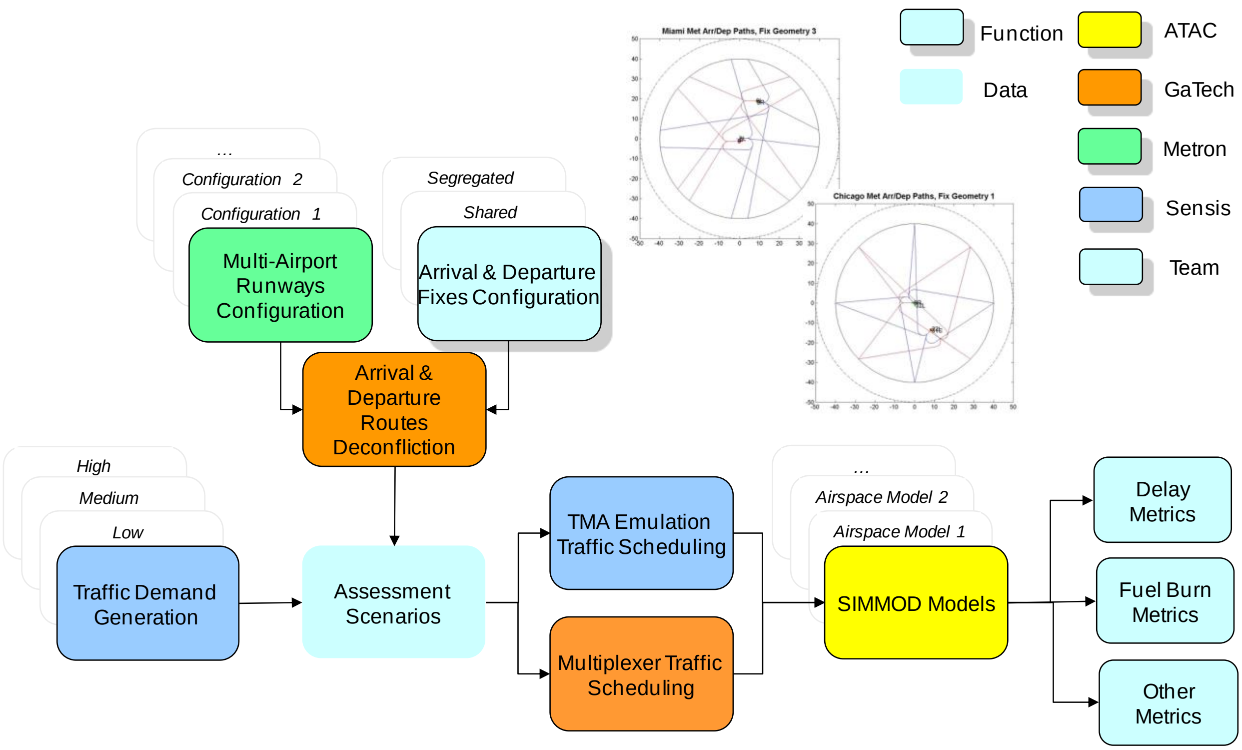


Figure 11. Generic Metroplex Evaluation Architecture.

The figure above depicts the evaluation system architecture to assess the impact of metroplex-wide flight scheduling for the range of geometries evaluated. The system is comprised of the following components: Traffic Demand Generation, Assessment Scenarios, Traffic Scheduling, SIMMOD models, and Delay, Fuel Burn, and Other Metrics. The Traffic Demand Generation component produced schedules of arrival and departure traffic to each generic metroplex airport. For this study, traffic demand scenarios were generated to represent low, medium and high metroplex traffic demand conditions. The Assessment Scenarios component creates the simulation scenarios used to evaluate the metroplex traffic scheduling algorithms. Each scenario was comprised of particular Multi-Airport Runway Configurations and Arrival and Departure Fix Configuration. This study specified 7 different runways configurations among the two generic metroplex airports, each representative of a distinct real-world configuration. This study also specified two different arrival and departure fix configurations: fixes shared between the metroplex airports and separate fixes for each metroplex airport. The combinations of multi-airport runway configurations and arrival and departure fix configurations yielded the 14 different generic assessment scenarios. For each assessment scenario, arrival and departure routes were designed to connect each metroplex airport runway with its associated arrival or departure fix, and the routes were adjusted laterally and vertically to ensure they were spatially deconflicted with one another between the fixes and the runways. For each assessment scenario, the nominal transit times were estimated for each arrival and departure route. These transit times were input to both the Traffic Scheduling and SIMMOD models. Traffic Scheduling computed STAs to the arrival and departure fixes and the runway thresholds for all generic metroplex flights. This study evaluated two scheduling algorithms: a TMA Emulation Traffic Scheduling algorithm and a Multiplexer Traffic scheduling algorithm. The TMA Emulation Traffic Scheduling algorithm modeled the scheduling algorithms and approach of the existing Traffic Management Advisor (TMA) terminal traffic scheduling system and served as the baseline traffic scheduler. The Multiplexer Traffic Scheduling algorithm implemented a linear programming-based optimization formulation to metroplex-wide traffic scheduling.

Traffic Scheduling was conducted off-line, prior to simulation, for each traffic demand scenario, and each generic metroplex geometry assessment scenario. In turn, the resulting set of scheduled metroplex flights for each demand scenario and assessment scenario was input to the appropriate SIMMOD Model of the generic metroplex airspace. The generic metroplex arrival and departure traffic movement was simulated using the SIMMOD software, using the appropriate airspace model per the assessment scenario, with the arrival STAs to the arrival fix and departure flight STAs to the runway thresholds as the SIMMOD injection times, i.e., the entry time of the flights into the traffic simulation. The SIMMOD queuing-based traffic flow model, simulated traffic flow associated with the specified assessment scenario and produced nominal route transit times, airport capacities, and inter-flight longitudinal spacing requirements to generate flight Actual Times of Arrival (ATAs) to the fixes and runways. The STAs, ATAs and other simulation data were analyzed to compute Delay, Fuel Burn and Other Metrics to assess metroplex scheduling system performance and effectiveness.

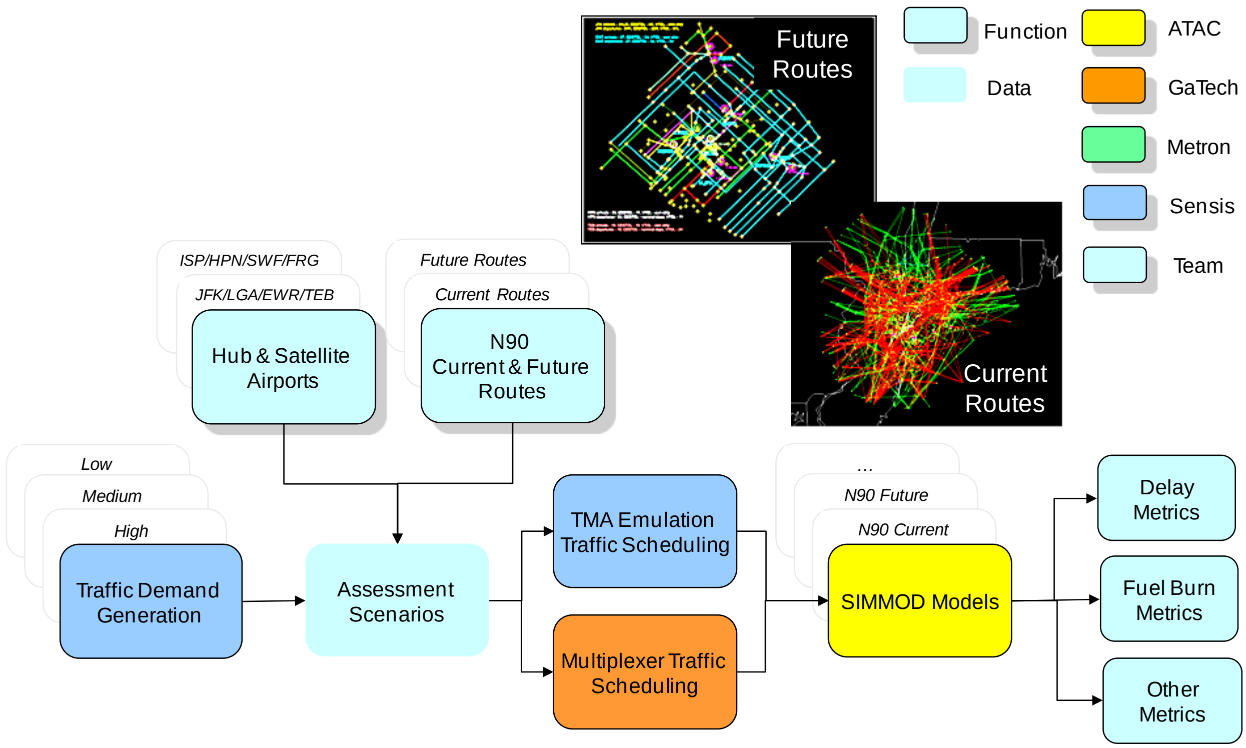


Figure 12. N90 metroplex evaluation architecture.

The evaluation architecture for the N90 metroplex simulations, depicted in the figure above, is very similar to that for the generic metroplexes. In this case, the Traffic Demand Generation specified traffic demand scenarios for the particular N90 metroplex airports to be evaluated. For this study, there were two Assessment Scenarios for the N90 metroplex: Current Routes and Future Routes. Each scenario, in the N90 metroplex model, modeled hub airports John F. Kennedy (JFK), LaGuardia (LGA), Newark (EWR) and Teterboro (TEB), and included key satellite airports Long Island MacArthur (ISP), Westchester County (HPN), Newburg Stewart (SWF), and Republic (FRG). The Current Routes scenario modeled the existing arrival and departure route structure to those airports, and the Future Routes scenario modeled a hypothetical arrival and departure route structure for those airports, that would be enabled by the enhanced aircraft navigation performances anticipated in the future NextGen national airspace system. Traffic Scheduling was conducted for each N90 airspace model, for each demand scenario. As in the generic metroplex studies, Traffic Scheduling comprised two alternative scheduling algorithms: TMA Emulation and Multiplexer. For each demand scenario, for each airspace, for each traffic scheduling algorithm, SIMMOD Models of the appropriate airspace simulated traffic flow. The resulting simulation data were analyzed in a post-processing step to evaluate the impact of scheduling on metroplex flight delays, fuel burn and other metrics.

6.2 Assumptions

The Georgia Tech Metroplex research team utilized certain common assumptions across the baseline and optimized scheduling scenarios to enable a reasonable comparative assessment of the two scheduling capabilities. These assumptions included:

(i) The required minimum separation criteria that the scheduling algorithms should adhere to (both at the runway threshold and at the TRACON boundary fix).

(ii) The nominal traversal times from TRACON entry to runway touchdown for different aircraft depending upon their engine types.

(iii) TRACON boundary fix usage (e.g., use of multiple altitude segregated streams passing over a common arrival-fix).

6.2.1 Required Minimum Separation Criteria

We assumed that the minimum required separation at the TRACON boundary fix (arrival fix) would be five nautical miles. Assumptions about the aircraft ground speeds while crossing the TRACON boundary fix are necessary for converting this distance-based separation criterion into a time separation for use in the Time-based scheduling algorithms. Our assumptions for arrival-fix crossing ground speeds are shown in Table 6. As shown in the table, when converting the distance-based separation criterion into a time separation, the minimum arrival-fix crossing speed between leading and trailing aircraft was used for the conversion. The resulting time separations for the different aircraft pairs are shown in Table 7.

Table 6: Arrival-fix Crossing Speed Assumptions

	Arrival-fix Crossing Speeds in Knots			
		Leader		
Trailer		H	L	S
	H	290	265	205
	L	265	265	205
	S	205	205	205

Table 7: Arrival-fix Crossing Time Separation Assumptions

	Required Time Separation in Seconds			
		Leader		
Trailer		H	L	S
	H	62.06897	67.92453	87.80488
	L	67.92453	67.92453	87.80488
	S	87.80488	87.80488	87.80488

The runway minimum required separation criteria were assumed to be dependent on the weight classes of the leading and trailing aircraft, as shown in Table 8. The runway landing speed assumptions are shown in Table 9. These values were used to convert the distance-separations into time separations. The resulting time separation criteria are shown in Table 10.

Table 8: Runway Minimum Required Distance Separation Criteria

	Required Distance Separation in NM			
		Leading		
Trailing		H	L	S
	H	4	3	3
	L	5	3	3
	S	5	3	3

Table 9: Runway Landing Speed Assumptions

	Runway Minimum Landing Speeds in Knots			
		Leading Aircraft		
Trailing Aircraft		H	L	S
	H	140	136.82	102.7
	L	136.82	136.82	102.7
	S	102.7	102.7	102.7

Table 10: Runway Landing Time Separation Criteria

	Required Time Separation in Seconds			
		Leading		
Trailing		H	L	S
	H	102.86	78.94	105.16
	L	131.56	78.94	105.16
	S	175.27	105.16	105.16

6.2.2 TRACON Traversal Time Assumptions

As explained in Section 5.1, we assessed the performance of the scheduling algorithms across a range of generic metroplex airspace geometries. The main difference across these geometries was the traversal times from the TRACON boundary to the runway. The Miami-Fort Lauderdale (MIA-FLL) runway layout geometry and its computed traversal times were used as the baseline nominal TRACON traversal times. For other geometries the additional times to fly were added to the traversal times for this geometry depending upon individual airspace definitions.

Table 11 and 12 show the baseline nominal traversal times for the MIA-FLL geometry with shared TRACON boundary fixes and de-coupled TRACON boundary fixes, respectively. As also explained in Section 5.1, the TRACON boundary fixes are equally spaced across the circular TRACON boundary and are named according to their angular difference from the North direction (e.g., arrival fix 45 refers to the North East TRACON boundary fix).

Table 11: TRACON Traversal Time Assumptions for the MIA-FLL runway layout (shared TRACON boundary fixes geometry) [all times are in minutes]

Arrival Route	Arrival Fix	Heavy	Large	Small
MIA_NE	45	9.153338	9.244566	9.448409
MIA_SE	135	9.969181	10.0583	10.28008
MIA_SW	225	9.781688	9.902703	10.12106
MIA_NW	315	9.796798	9.918178	10.13687
FLL_NE	45	9.073949	9.159798	9.361771
FLL_SE	135	14.29612	14.40966	14.72739
FLL_SW	225	14.03946	14.16068	14.47293
FLL_NW	315	9.201487	9.334798	9.54063

Table 12: TRACON Traversal Time Assumptions for the MIA-FLL runway layout (de-coupled TRACON boundary fixes geometry) [all times are in minutes]

Arrival Route	Arrival Fix	Heavy	Large	Small
MIA_NE	40	10.43861	10.52782	10.75995
MIA_SE	130	9.98983	10.10759	10.33046
MIA_SW	230	9.937076	10.0548	10.27651
MIA_NW	320	9.672392	9.796102	10.01211
FLL_NE	50	8.634465	8.721307	8.913612
FLL_SE	140	11.51284	11.60844	11.8644
FLL_SW	220	10.71176	10.83295	11.07181
FLL_NW	310	11.90714	12.04012	12.30561

6.3 Metrics

The primary metric for all the team's assessments was arrival delay. Delay was categorized by TRACON delay (i.e., delay to be absorbed inside the TRACON) and en route delay (i.e., delay to be absorbed before reaching the TRACON boundary). All delays were computed with respect to the initial arrival-fix (AF) and runway estimated times of arrival (ETAs).

7 Experimental Testbed

7.1 Simulation Platforms

7.1.1 Simple Queuing Model

We used the same network queuing model we used in our previous metroplex study, the only difference being the greater number of geometries that will be simulated. As you may recall, this simulation environment a set of queues that are used to model the delays that accrue when aircraft must wait for constrained resources. Because it is a queuing network, it is easily configured and thus very flexible.

7.1.2 SIMMOD and SIMMOD PRO!

The majority of our simulation evaluations were conducted using the Airport and Airspace Simulation Model (SIMMOD), which has been validated by the Federal Aviation Administration (FAA), is an industry standard analysis tool used by airport planners and operators, airlines, airspace designers, and air traffic control authorities for conducting high-fidelity simulations of current and proposed airport and airspace operations.

SIMMOD *PRO!* is an addition to the SIMMOD maintaining all existing code. The addition provides the capability for the user to specify rules and rule processing logic to make decisions based on the state of the airport/airspace system and invoke the SIMMOD engine to perform in a manner consistent with the rules with outputs that provide results based on the use of the rules and the decisions made during the simulation.

A more detailed description of SIMMOD and SIMMOD PRO! can be found in Appendix B of this report.

7.2 Demand Scenarios

This section describes the traffic demand scenarios generated for the simulation-based evaluation of the alternative metroplex-wide traffic scheduling algorithms for each of the geometries. Traffic demand sets were generated to support evaluations for all the generic metroplex and New York metroplex geometries evaluated in this study. The demand sets were input to a queuing-based simulation of air traffic for each metroplex model.

7.2.1 Generic Metroplex

Traffic demand sets were developed to support scheduling algorithm evaluations for the 14 different generic metroplex models. Each generic metroplex model comprised two airports, Airport A and Airport B, and a set of arrival and departure fixes. The models differed in the runway configurations of the two airports, and in the configuration of the arrival and departure fixes. The models spanned 9 different runway configurations modeled from pair-wise interactions observed in current-day metroplexes. The models spanned two different arrival and departure fix configurations observed in current-day metroplexes; shared arrival and departure fixes and segregated arrival and departure fixes. The demand scenarios generated supported evaluating this range of generic metroplex geometries.

The demand sets were generated using the previously developed Metroplex Demand Analysis Tool [TI10]. The tool was developed during the previous NASA-funded metroplex research study led by Georgia Tech. The metroplex demand analysis tool adapts the traffic demand set of a real-world airport to meet the prescribed demand levels of the generic metroplex airport under study, as per the generic metroplex airport's specified capacity and demand/capacity ratio (a measure of airport capacity utilization). This ensures that subject airport scheduled arrival and departure demand, which in turn impacts flight delay accrual characteristics, are representative of real world traffic while complying with the parameters of the particular generic metroplex model under study. It also ensures the other traffic demand characteristics such as mix of aircraft types, equipage levels, and origin and destination airports also represent real-world traffic. In addition to generating a schedule of airport traffic, the tool also adapts the traffic demand to the particular subject airspace under study by assigning each flight to an arrival or departure fix in the terminal airspace, and by estimating the gate, runway and fix crossing times for each flight. For each traffic demand scenario, the metroplex demand analysis tool is used to generate a traffic demand set for each generic metroplex airport independently, and the demand sets are integrated into a single simulation input file.

The demand sets for this study were generated from a set of scheduled flights for Atlanta-Hartsfield International Airport (KATL) for September 26, 2006. The set of scheduled flights was obtained from a previous NASA project and were derived from Federal Aviation Administration (FAA) Enhanced Traffic Management System (ETMS) data.

7.2.2 Demand Levels

For this study, traffic demand sets were generated for Low, Medium and High generic metroplex demand scenarios. The number of arrival and departure flights for each generic metroplex airport, for each demand scenario, is depicted in the figure below. In each scenario, each generic metroplex airport has an equal number of arrivals and departures, and generic metroplex airport A has twice the quantity of flights as airport B. The demand scenarios span the range of airport traffic volumes (relative to capacity) identified through analysis of four different real-world metroplexes [ref]: Atlanta, Southern California, New York and Miami. The demand scenarios also capture the nominal relative traffic loading conditions among airport pairs in a metroplex as identified through analysis of the same four different real-world metroplexes.

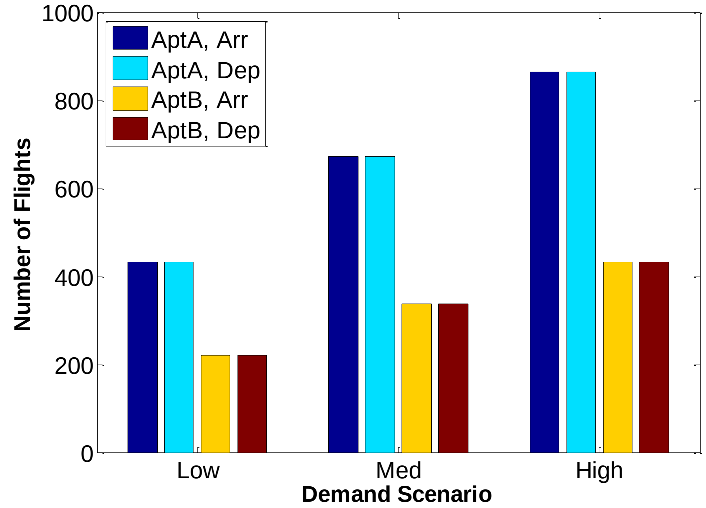


Figure 13. Numbers of scheduled arrival and departure flights for generic metroplex airports A and B for low, medium and high traffic demand scenarios.

In each demand scenario, generic metroplex airports A and B have equal capacities of 60 arrivals/hour and 60 departures/hour, consistent with the generic metroplex airspace models. The low, medium and high demand scenarios are created by successively increasing the demand/capacity ratios for the generic metroplex airports, while maintaining generic metroplex airport A demand/capacity ratio as twice that for generic metroplex airport B. The demand/capacity ratios for each demand scenario are listed below.

Table 13 Generic metroplex airports A and B demand/capacity ratios for each demand scenario

	Demand/Capacity	
Scenario	**Airport A**	**Airport B**
High	0.9	0.45
Medium	0.7	0.35
Low	0.45	0.225

In each of the 9 generic metroplex models, airports A and B had the same arrival and departure capacities. Thus, one traffic demand set was generated for each airport for a low, medium and high demand scenario, and the same the traffic demand set for each airport for each scenario was used for all 9 of the airport configurations assessed in this study.

7.2.3 Airspace Adaptation

Traffic demand sets were generated for generic metroplex airports A and B for the low, medium and high demand scenarios. As stated above, this set of common traffic demand scenarios applied to all 9 of the metroplex configurations assessed in this study. In turn, each traffic demand set was adapted to each of the two generic metroplex airspace fixes configurations assessed in this study: shared arrival and departure fixes and segregated arrival and departure fixes. The figure below depicts the two fixes configurations assessed in this study.

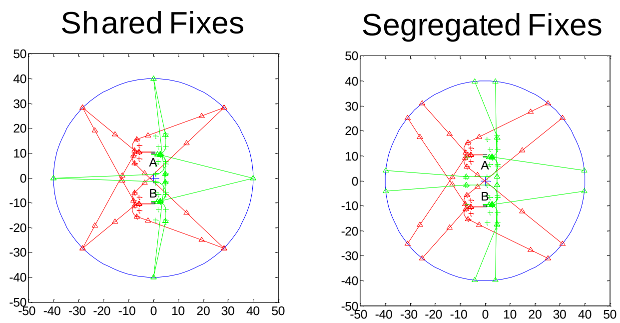


Figure 14. Two generic metroplex arrival and departure fixes configurations, shared fixes and segregated fixes, were evaluated at low, medium and high demand scenarios.

Airspace adaptation of the traffic demand set comprised assigning each flight to an arrival or departure fix on the generic metroplex airspace boundary aligned by the bearing of the arrival flight's origin airport and departure flight's destination airport relative to the generic metroplex location. The generic metroplex location was implied by the selected real-world airport from which the traffic demand sets were derived, and the origin or destination airport for each flight was that which was listed in the set of scheduled traffic for the real-world airport from which the traffic demand sets were derived. The figure below depicts the flight counts at the arrival and departure fixes resulting from adapting generic metroplex airports' A and B high demand traffic scenario to the generic metroplex airspace shared fixes geometry. In turn, flight crossing points to key scheduling points and candidate simulation injection points of interest, such as the fixes and runways, are estimated based on the resulting flight geometry.

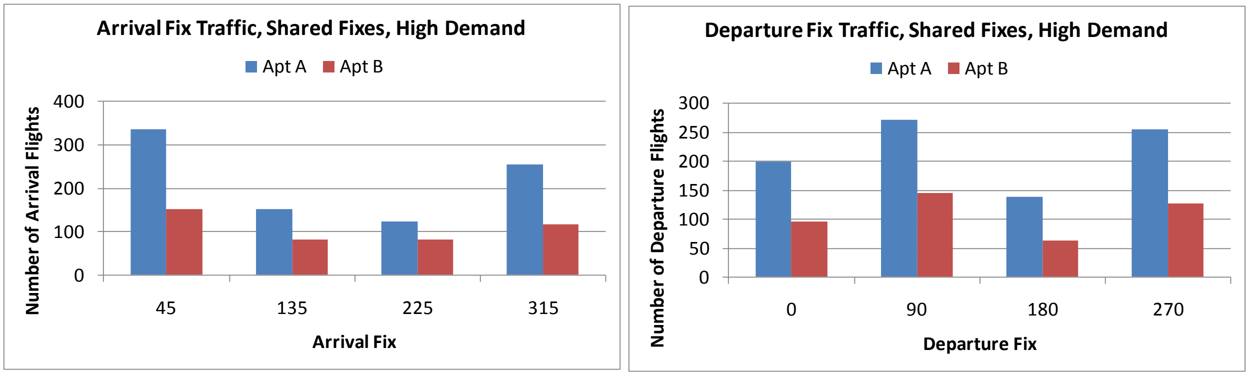


Figure 15. Arrival and departure fixes flight counts by generic metroplex airport for shared fixes configuration for the High demand scenario

Thus, each low, medium and high traffic demand scenario for each generic metroplex airport A and B was adapted to each shared and segregated airspace fixes configuration to yield the following demand sets:

Traffic Level	Airspace Configuration	Traffic Demand Set
Low	Shared	3xKATL-0.23D2C_OutputFDS_TC1-AptB_20100727.csv
		3xKATL-0.45D2C_OutputFDS_TC1-AptA_20100727.csv
	Segregated	3xKATL-0.23D2C_OutputFDS_TC3-AptB_20100727.csv
		3xKATL-0.45D2C_OutputFDS_TC3-AptA_20100727.csv
Medium	Shared	3xKATL-0.35D2C_OutputFDS_TC1-AptB_20090925.csv
		3xKATL-0.70D2C_OutputFDS_TC1-AptA_20090925.csv
	Segregated	3xKATL-0.35D2C_OutputFDS_TC3-AptB_20090925.csv
		3xKATL-0.70D2C_OutputFDS_TC3-AptA_20090925.csv
High	Shared	3xKATL-0.45D2C_OutputFDS_TC1-AptB_20100727.csv
		3xKATL-0.90D2C_OutputFDS_TC1-AptA_20100727.csv
	Segregated	3xKATL-0.45D2C_OutputFDS_TC3-AptB_20100727.csv
		3xKATL-0.90D2C_OutputFDS_TC3-AptA_20100727.csv

Finally, each generic demand set was adapted to each of the 19 generic metroplex configurations under study by recomputing the arrival flights' landing and gate "in" times and departure flights' departure fix crossing times as per the unconstrained transit times estimated for the arrival and departure route structure for that particular configuration.

7.2.4 Additional Demand Variables

This study focused on metroplex traffic volume as the primary demand variable. However, additional demand variables including the relative traffic volumes of the generic metroplex airports and the directional distributions of traffic and may also affect metroplex-wide flight delay and fuel burn performance.

The relative traffic levels of the two generic metroplex airports determine their degree of contention for shared metroplex resources (e.g., airspace fixes). Increasing contention for shared resources places increasing demand on metroplex-wide scheduling to coordinate the multi-airport traffic flows. This parameter could be varied to assess the impact of relative traffic volume distribution on metroplex-wide scheduling effectiveness.

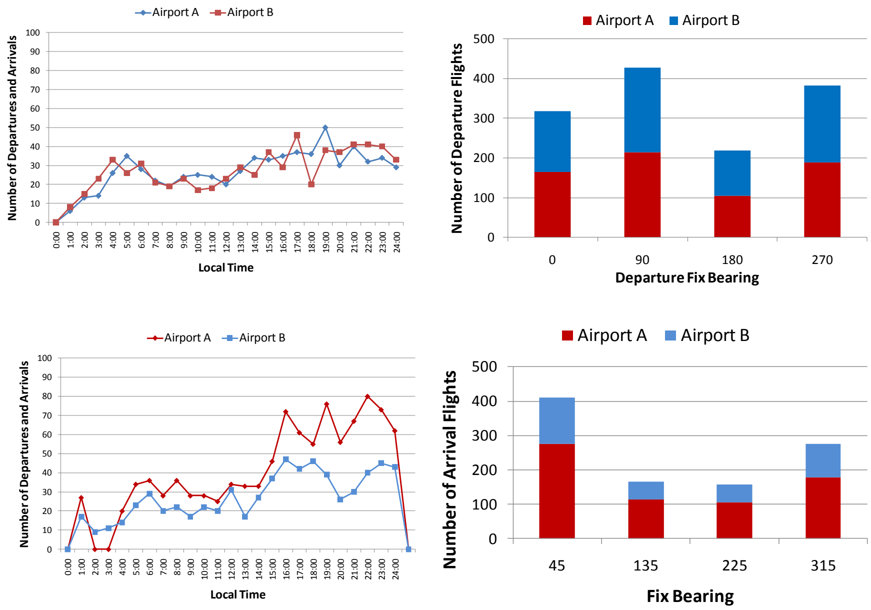


Figure 16. Time-based (left) and fix-based (right) traffic distributions for equal (top) and unequal (bottom) metroplex airports A and B traffic levels.

The directional distributions of the two generic metroplex airports determines the demand for particular shared metroplex resources, and also determines the degree of contention between the airports for use of those resources. This parameter could be varied to assess the impact of relative traffic spatial distribution on metroplex-wide scheduling effectiveness.

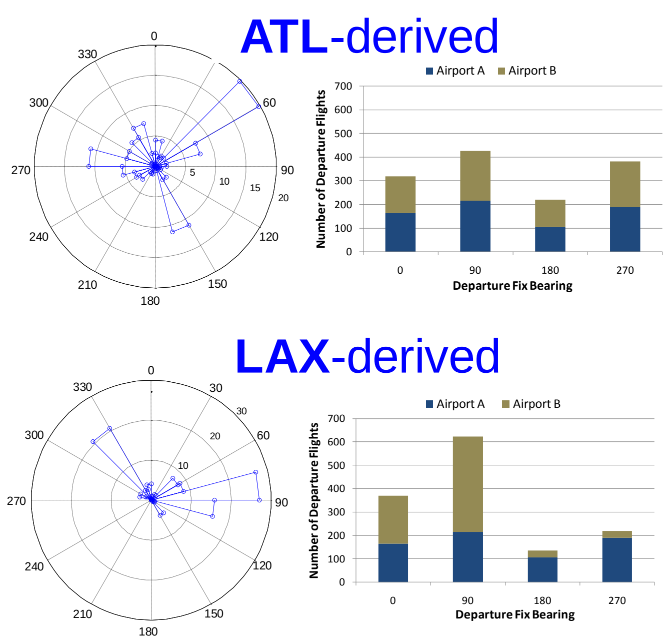


Figure 17. Bearing directional (left) and fix-based (right) traffic distributions for more balanced (top) and less balanced (bottom) metroplex airport traffic distributions.

Additional demand parameters include the relative temporal traffic distributions of metroplex airports A and B as in phase or out of phase in determining the level of contention for shared metroplex resources.

7.3 New York Metroplex

Traffic demand sets were developed to support scheduling algorithm evaluations for the 2 different models of the New York metroplex: one model reflecting the current metroplex route structure, and another model representing a candidate future metroplex route structure enabled by aircraft area navigation and required navigation performance (RNAV/RNP) capabilities. Both of the New York metroplex models comprised primary airports JFK, LGA, EWR, TEB and satellite airports ISP, HPN, SWF, and FRG.

The demand sets were generated using the previously developed AvDemand demand generation tool [HU04] [HU07]. AvDemand was developed through NASA SBIR Phase I (2003) and Phase II (2004) projects and further enhanced via multiple NASA, FAA and JPDO contracts. The tool creates future demand sets (both flight schedules and flight plans) from current day baseline flight demand data. Alternative demand generation approaches include homogeneous or heterogeneous (e.g., FAA Terminal Area Forecast (TAF)) airport growth rates and operations- or passenger-weighted demand growth. The tool balances arrival and departure flights among the origin-destination airports captured in the input demand set. The tool includes a trajectory generator for flight time estimation based on Eurocontrol Base of Aircraft DAta (BADA). Lastly, the tool features multiple methods to shape the demand characteristics and distributions

The demand sets for this study were generated from a set of scheduled flights for the aforementioned airports from September 26, 2006. The set of scheduled flights was obtained from a previous NASA project and were derived from FAA ETMS data.

7.3.1 Demand Levels

For this study, New York metroplex traffic demand sets were created for three demand scenarios: current-day traffic, future traffic 1.2 times current day, and future traffic 1.6 times current day. The quantities of arrival and departure flights for each metroplex airport are depicted in the tables below for each demand scenario. The demand scenarios represent the range of future airport traffic volumes estimated for different future NextGen timeframes.

Table 14. New York metroplex airport traffic demand levels for current day scenario

'Airport'	'Departures'	'Arrivals'	Total	Growth
'KJFK'	554	535	1089	N/A
'KLGA'	610	607	1217	N/A
'KEWR'	631	621	1252	N/A
'KTEB'	305	280	585	N/A
'KFRG'	32	33	65	N/A
'KSWF'	26	23	49	N/A
'KISP'	62	59	121	N/A

'KHPN'	193	184	377	N/A
Total			4755	N/A

Table 15. New York metroplex airport traffic demand levels for future 1.2 times current day traffic scenario

'Airport'	'Departures'	'Arrivals'	Total	Growth
'KJFK'	667	648	1315	1.21
'KLGA'	748	748	1496	1.23
'KEWR'	761	748	1509	1.21
'KTEB'	344	314	658	1.12
'KFRG'	34	33	67	1.03
'KSWF'	28	25	53	1.08
'KISP'	73	69	142	1.17
'KHPN'	218	210	428	1.14
Total			5668	1.19

Table 16: New York metroplex airport traffic demand levels for future 1.6 times current day traffic scenario

'Airport'	'Departures'	'Arrivals'	Total	Growth
'KJFK'	884	845	1729	1.59
'KLGA'	941	938	1879	1.54
'KEWR'	990	971	1961	1.57
'KTEB'	510	469	979	1.67
'KFRG'	58	62	120	1.85
'KSWF'	45	40	85	1.73
'KISP'	104	98	202	1.67
'KHPN'	328	316	644	1.71
Total			7599	1.60

The individual demand scenarios achieve the target metroplex-wide traffic growth amounts, with the individual airport traffic volumes at or near the target scaling. The individual airport traffic volumes vary due to the balancing of arrival and departure traffic among the origin and destination airports in the demand set, with the smaller airports exhibiting greater sensitivity to the different traffic levels arising due to this demand balancing.

Throughout the demand generation process, the temporal traffic demand profile for each airport is retained, as this is an important demand characteristic which in part determines delay accrual profiles.

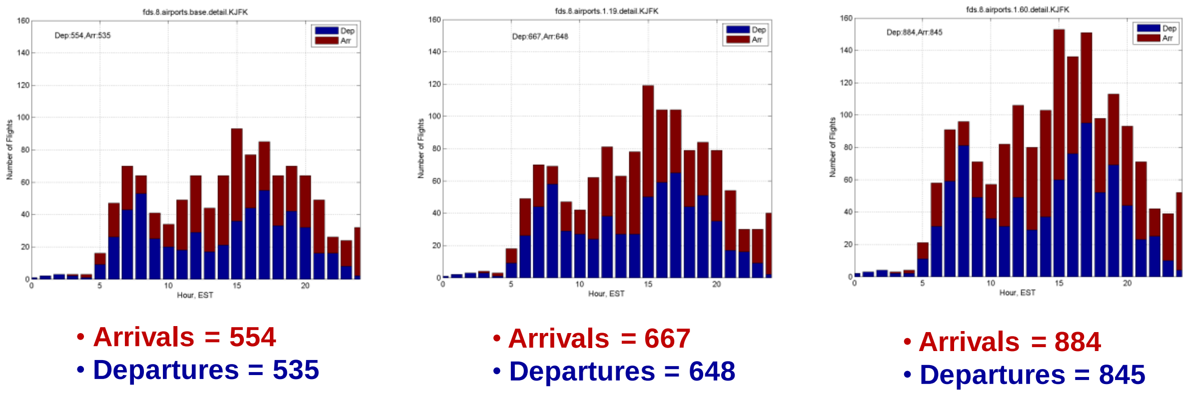


Figure 18. JFK arrival and departure demand profiles for current day (left), future 1.2x (center) and future 1.6x (right) traffic levels.

7.3.2 Airspace Adaptation

Following generation of the traffic demand scenarios, the traffic demand sets for each airport were updated to assign each arrival flight to an arrival fix or each departure flight to an airport runway at the physical boundaries of the New York metroplex airspace model, and to estimate arrival fix crossing times or runway entry times for the arrival and departure flights. These were estimated from nominal fix and runway assignments and transit times characterized from historical traffic data.

8 Results

8.1 Generic Geometries

Rather than present the results for all the generic airports, which are very similar in terms of the level of delay reduction, we will only present the results for the two generic metroplexes that are based on the Miami TRACON. Results for all other generic geometries are present in Appendix C.

As you may recall, a key feature of all the generic geometries is that in the cases where there are dual arrival fixes at each corner post, there are only merge points – one at each arrival fix and one near each runway; and in the cases where there is a single arrival fix at each corner post, there is a combined merge and crossing point at each arrival fix and a merge point near each runway. Thus we expected that the Multiplexer will determine the true minimum delay as it explicitly consider these merges and crossing, while we do not expect the same from TMA due to the way in which it computes and distributes delay.

The benefit of the Multiplexer is shown convincingly by the data in Table 17 and Table 18. As may be seen in the tables, all the delays are less with the Multiplexer than with TMA. This indicates, especially in the case of the total delay, than the Multiplexer is properly advancing traffic through upstream crossings (the entry fixes serving multiple runways) so that there is no starvation of downstream resources (the runways). Further, by breaking away from the precedence order that is followed by TMA and explicitly considering runway operation in the determination of the fix schedule, the Multiplexer is able to generate a better runway schedule. The net result is that all the aircraft are able to land sooner.

Table 17: Total, En Route, and Terminal Area Delays at Low, Medium, and High Traffic for the Miami-based Metroplex with a Single Arrival Fix at Each Corner-Post

Table 18: Total, En Route, and Terminal Area Delays at Low, Medium, and High Traffic for the Miami-based Metroplex with a Single Arrival Fix at Each Corner-Post

8.2 New York Geometries

The total, en route and terminal area arrival delays are listed in **Table 19** (as determined via SIMMOD *PRO!* simulations with TMA and the Multiplexer) for four scenarios: the current airspace geometry with current traffic levels, the NextGen airspace geometry with current traffic levels, the NextGen airspace geometry with 1.2 times current traffic levels, the NextGen airspace geometry with 1.6 times current traffic levels.

As indicated by a comparison of the first three rows of data in the table, changes in the airspace geometry provide a greater reduction in the total arrival delay than the introduction of the Multiplexer. This might seem counter to our previous results, but it is not, as we are now comparing the Multiplexer to TMA as opposed to an unscheduled situation (which is what we had done in our prior work). In other words, TMA has accrued some of the benefits of scheduling that were estimated in our prior work.

However, the Multiplexer still provides significant benefits, and most importantly at all traffic levels, as evidenced by a comparison of the bottom six rows of data in the table. This is an indication of how important it is to consider the impact of crossings and merge points on downstream resources. Even though the Multiplexer does no explicitly consider all the crossing and merge points in the New York Metroplex, the fact that is does consider the common entry fixes and the runways jointly means that the resulting schedule has a better chance of success even after uncertainties come into play.

The results in the table are also interesting from another perspective. TMA is designed to limit the delay in the terminal area for any given aircraft to 5 minutes. Thus, it seems odd that the average terminal area delay would be greater than 5 minutes. However, TMA in its current instantiation would not consider all the crossing and merge points within the metroplex, thus it would not be able to account for the impact that these might have on the traffic flows (i.e. a controller might have to slow or vector and aircraft to allow another aircraft to cross or merge before it).

Table 19. New York Metroplex Arrival Delays (minutes)

	Total Arrival Delay	En Route Arrival Delay	Terminal Arrival Delay
Current 1.0			
TMA	3.62	1.39	2.23
Multiplexer	2.22	0.51	1.71
NextGen 1.0			
TMA	1.97	0.55	1.42
Multiplexer	1.77	0.54	1.23
NextGen 1.2			
TMA	21.41	12.25	9.16
Multiplexer	19.90	10.37	9.52
NextGen 1.6			
TMA	93.05	80.59	12.46
Multiplexer	81.88	66.78	15.10

9 Conclusions

As indicated by the results presented in the previous section, scheduling in the form of the Multiplexer will provide benefits across the entire range of metroplexes in the NAS (i.e. from simplistic abstractions to complex metroplexes such as the New York Metroplex).

That being said, the important things to note in this regard are:

1. There are significant benefits to explicitly considering all the constraints on timing that are made manifest at crossing and merge points, as each crossing or merge point becomes an opportunity to magnify uncertainties (i.e. a small variation in fix crossing time can result in a significant change in future crossing times and trajectory);

2. By properly advancing traffic through upstream crossings (the entry fixes serving multiple runways) so that there is no starvation of downstream resources (the runways), and by explicitly considering runway operation in the determination of the fix schedule, it is possible to generate a better runway schedule and thereby enable all aircraft to land sooner.

3. The Multiplexer provides significant benefits in terms of delay reduction even though TMA has, because it is a scheduler, accrued some of the total benefits (estimated in our prior work) that are due to scheduling;

4. Even after the benefits of TMA are subtracted, the benefits of scheduling and the benefits of airspace redesign are of similar magnitude, which indicates that schedule remains the more beneficial of the two control strategies.

Given these findings, we developed a concept of operations for the Multiplexer in the hope that it would provide impetus for it adoption in one form or the other, perhaps by way of enhancements to TMA.

10 Implementation Issues and Concept of Operations

10.1 Today's Metroplex Inefficiencies

At major US metropolitan area airports with nearby airports, there are inevitably air traffic flow interdependencies for flows into and out of the proximate airports. These interdependencies along with factors such as poor situational awareness and traffic predictability lead to significant congestion for the major metropolitan area airports as well as inefficiencies at the proximate airports and the surrounding airspace. This metroplex congestion and inefficiencies are exacerbated by other major factors such as traffic volume, convective weather, reduced-visibility conditions, conservative air traffic spacing, unbalanced air traffic flows, and mixing of different aircraft types and performance levels.

These metroplex inefficiencies are commonly seen at major US metroplexes of varying levels of air traffic and airspace complexity. As identified in the RTCA Taskforce 5 report [RT09], key US metroplexes include those of least complexity (such as Atlanta, Charlotte, Dallas-Ft. Worth, Houston, Las Vegas, Minneapolis, and Phoenix), greater complexity (e.g., Boston, Denver, Detroit, Memphis, Philadelphia, San Francisco, and Washington, DC), and the most complex (Chicago, New York/New Jersey, and Southern California). Also, as predicted in NASA research efforts such as McClain, et al., [MC09] the number and complexity of US metroplexes are forecasted to grow with the expected growth of air traffic.

The FAA is attacking the metroplex problem with a near-term focus on optimizing Area Navigation (RNAV) operations and a mid-term focus on integrating procedures that deconflict airports, establishing and maximizing use of 3 nm terminal separation rules, and leveraging more advanced Performance-based Navigation (PBN) solutions where needed. However, more can be done. The RTCA TF5 report recommended the additional development of "ATC, flow, and surface management tools" but was not specific in what technical solutions would be appropriate. One potential mid-term technical solution would be the development and implementation of the Georgia Tech Metroplex NRA team's "Multiplexer" concept.

10.2 A Potential Metroplex Solution: the "Multiplexer"

In a metroplex environment, multiple proximate airports vie for the concurrent usage of shared resources like common points in the airspace (e.g., arrival fixes, departure fixes, other merge points), common routes in the airspace (e.g., Standard Arrival Routes (STARs), Departure Procedures (DPs)), or common volumes of airspace (e.g., arrival corridors). Air Navigation Service Provider (ANSP) responses to such cross-airport interactions encompass the entire spectrum from pure temporal separation where the ANSP works to regulate the times at which aircraft enter the TRACON airspace or times at which aircraft cross certain points in the airspace, to pure spatial separation where the ANSP provides guidance to traffic flows to multiple interacting airports by separating them vertically or laterally.

The Georgia Tech Metroplex NRA team's "Multiplexer" concept is focused on the pure temporal separation of traffic. A decision support tool that will enable the ANSP to temporally separate interacting traffic flows to and from multiple metroplex airports is needed to enable more 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 arrival/departure routes with the ANSP providing temporal controls to enable more efficient use of the available metroplex airspace and current metroplex airspace design while maintaining safe separations.

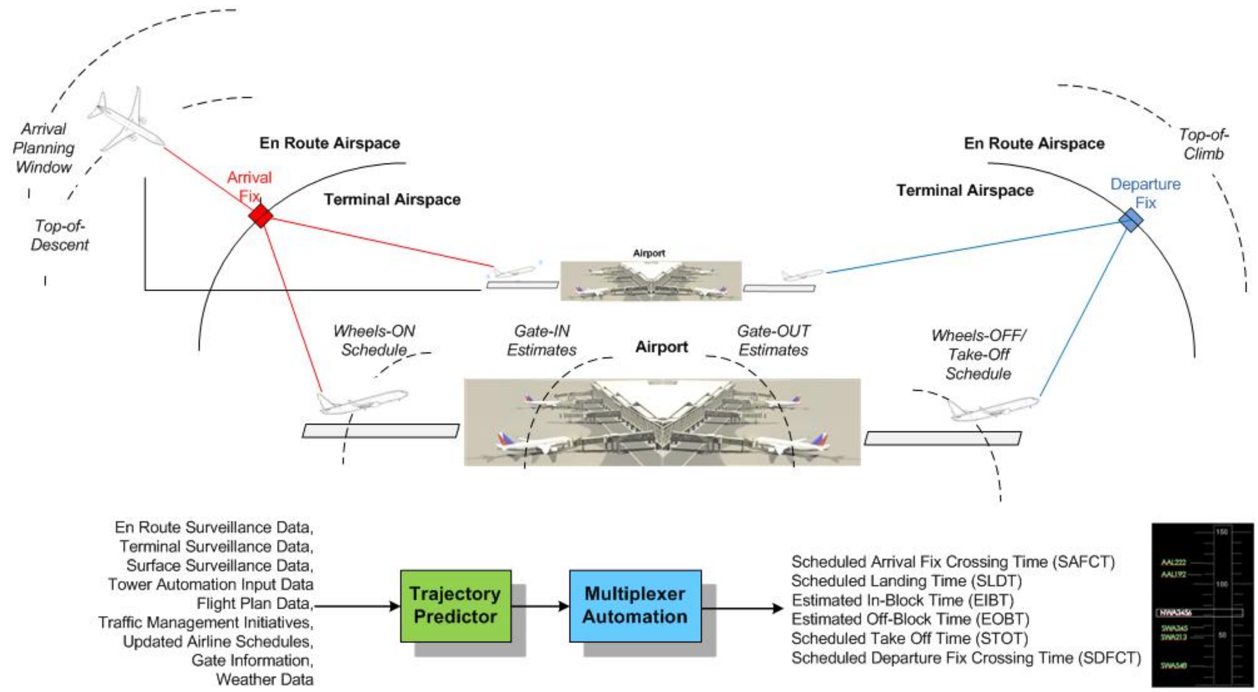


Figure 19: The Multiplexer Automation provides scheduled air traffic times at key nodes throughout the metroplex to support more efficient metroplex air traffic planning.

The Multiplexer concept builds off of the original ideas of the concept from the previous Georgia Tech Metroplex NRA team research defined in [RC10]. The Multiplexer concept applies a Time Division Multiple Access (TDMA) approach to solving the metroplex aircraft network problem. Wikipedia defines TDMA as: “a channel access method for shared medium (usually radio) networks. It allows several users to share the same frequency channel by dividing the signal into different time slots. The users transmit in rapid succession, one after the other, each using their own time slot. This allows multiple stations to share the same transmission medium (e.g., radio frequency channel) while using only a part of its channel capacity.” [W11]

The Georgia Tech Metroplex NRA team proposes a similar temporal separation tool for allocation of shared airspace resources like meter fixes, STARs, DPs, and corridors of airspace. 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 and this schedule shall be computed by optimizing traffic coming from all metroplex airports. For example, in the case of New York metroplex, the busiest departure fix – ELIOT – is commonly shared between LaGuardia airport (LGA), Newark Liberty International Airport (EWR), and Teterboro Airport (TEB) departures. The proposed Multiplex temporal scheduler computes an optimized departure fix crossing schedule and optimized wheels-OFF schedules for all flights expected to depart from all three airports within a given look-ahead time window.

10.3 Expected Benefits

Effective use of the Multiplexer tool will result in a wide set of overall benefits to a range of metroplex stakeholders including:

- Reducing flight delays and actual block times
- Improving flight and flow predictability
- Reducing schedule block times
- Increasing metroplex airport capacity and throughput
- Reducing fuel burn, emissions, and noise, and
- Reducing controller workload

The Multiplexer tool's advisories, enhanced situational awareness, and predictions will assist:

- Ramp controllers with determining improved departure and arrival sequences and target gate-out and gate-in times.
- The Ground controllers at individual metroplex airports in determining more efficient and TMI-compliant departure sequence by providing target take-off time constraints
- The Local controllers at individual metroplex airports by delivering aircraft with efficient separation (i.e., separation as close as possible to the minimum required spacing) on the final approach
- The TRACON arrival and departure controllers by providing target meter-fix crossing times for arriving and departing flights
- The TRACON arrival and departure controllers in a more efficient handling of merging and crossing traffic within the metroplex by providing target intermediate-fix crossing times, target landing/take-off times, etc., and by de-conflicting traffic at the merge/cross points
- ARTCC sector controllers with more accurate arrival fix crossing times and reduced workload due to a smoother departure flow integration into ARTCC airspace
- Traffic management coordinators in identifying metroplex flow "hot spots" and supporting strategic decision making to match dynamic metroplex demands to metroplex airport and airspace capacities
- Aircraft Operator flight dispatchers with more accurate predictions on when aircraft will be crossing key NAS thresholds enabling more accurate gate arrival and push-back times. By using Aircraft Communications Addressing and

Reporting System (ACARS), the flight dispatchers can relay this information to pilots and, subsequently, passengers as well.

Air Navigation Service Provider potential benefits can be summarized as follows. The Multiplexer tool can reduce controller workload by providing the controllers with de-conflicted target fix-crossing times and target landing or take-off times. Also, improved flow management will enable more efficient utilization of metroplex resources (e.g., boundary fixes, runways, terminal routes) during peak traffic periods, resulting in increased throughput.

Aircraft Operator potential benefits can be summarized as follows. Improved flow management in the metroplex can reduce delays for aircraft that arrive into major hub airports during heavy traffic periods as well as reduce the standard deviation of aircraft transit times thereby increasing the predictability of aircraft operations and improving fuel efficiency. This can improve on-time departures and arrivals and schedule reliability that can enable the aircraft operators to reduce scheduled block times, thereby decreasing operating costs and increasing revenues as well.

10.4 Functional Overview

10.4.1 Roles

In the case of the ANSP and Ramp Control personnel, the Multiplexer tool expects certain inputs and provides useful outputs. Metroplex surface and terminal operational procedure adaptation data input and updating is required for effective Multiplexer prediction and operation. Also, dynamic input of planned airport configuration changes is expected by the appropriate ATCT Supervisors in the metroplex. The Multiplexer tool is expected to be used in a number of different ways by the different ANSP personnel. The Multiplexer automation is used by the TRACON controllers 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. The tool is also used by the TRACON controllers to handle merging and crossing traffic by utilizing the tool-provided target fix-crossing times. The tool is also used by airport Ground Controllers as guidance for building the sequence of departures so that the departure traffic load is balanced across all available airport runways, TRACON departure sectors and departure fixes. The tool will also simplify the job of airport Local Controllers by delivering a sufficiently spaced and order-optimized sequence of aircraft on final approach. ARTCC Controllers also can use the Multiplexer to ensure en route arrival traffic flows take into account expected metroplex air traffic dependencies. Finally, Ramp Controllers can also use the tool for guidance in building more efficient pushback sequences. In general, the Multiplexer is expected to not only provide automatic advisories, but also mechanisms to incorporate dynamic controller-desired flight constraints (e.g., enabling personnel to input additional slots, assign aircraft specific slots, enforce desired aircraft sequences, and prioritize emergency flights).

In the case of the Flight Operator personnel, the Multiplexer tool also expects certain inputs and provides useful outputs. The Multiplexer tool expects that the Flight Operators will be sharing flight specific updated departure and arrival gate information for the purpose of providing aircraft intent as early as possible. The concept also enables Flight Operator personnel to input flight specific preferred runway use and have them incorporated into the Multiplexer scheduling. Flight Operator Dispatchers and ATC Coordinators can use their interface into the Multiplexer automation to obtain improved predictability on actual take-off time and gate arrival time. In addition, the Dispatchers can relay these predicted times to Pilots with ACARS messages or radio communication.

10.4.2 Responsibilities

There is no change in the legal responsibilities of the operational personnel under the Multiplexer concept; the Multiplexer tool acts as an advisory decision support tool only. The ultimate responsibility of separating traffic remains with the controllers and is expected to reduce their workload and increase overall efficiency.

10.4.3 System Function

The Multiplexer tool acts as a decision support tool for ARTCC, TRACON, ATCT, and Ramp controllers. The Multiplexer provides a Metroplex ARTCC-TRACON-Airport time-based metering system function with a surface traffic prediction module and integrated arrival/departure Multiplexer scheduling. The nominal operation of the Multiplexer is now described.

The position, ground speed, and intent of each aircraft are obtained by an ERAM, STARS/ARTS, or ASDE-X data feed, depending on where the aircraft is located. Traffic Management Initiative intent is provided by the TFMS feed. Estimates of winds aloft are provided by the National Weather Service Rapid Update Cycle (RUC) weather model to determine aircraft speeds (Mach, CAS, and TAS). Site-adapted Airport, TRACON, and ARTCC routes are used to predict the aircraft position/trajectory from each gate to runway threshold to top-of-climb and vice versa starting with top-of-descent to the arrival gate. Metroplex Trajectory Synthesis (TS) algorithms combine the previously mentioned synthesized position and aircraft intent data with: aircraft type, gate, flight plan information, airport configuration, and any AOC user preferences to generate company-preferred trajectories that are used to build an estimated time of arrival (ETA) schedule for the expected runways and fixes.

The real-time Multiplexer scheduler then builds an optimal recommended aircraft sequence and scheduled time of arrival (STA) at fixes and runways that comply with all restrictions in effect including the incorporation of airport configuration information, aircraft separation rules, and TRACON acceptance rates. The Multiplexer scheduler is refreshed every twelve seconds, corresponding to the rate of a secondary radar data feed from the ERAM system, and uses a look ahead time window of 1 hour. Freeze horizons, where the traffic sequences are frozen, are built into the metering processes prior to the critical metering points. The freeze horizons are based on the uncertainties inherent in the aircraft trajectories, and, as such, vary with the different phase of flight.

The Multiplexer tool computes the scheduled time-access times for each shared metroplex resource; arrival/departure fix, merge/crossing-point, runway, or shared airspace corridor, by using a mathematical optimization based scheduling algorithm. The optimized de-conflicted crossing /landing/take-off times are routed back to the ARTCC, TRACON, ATCT, and Ramp controllers and accessible by Traffic Flow Management specialists and Flight Operator personnel. The Multiplexer tool also displays predicted and actual crossing times. The controllers use these times as guidance for metering the traffic within their sphere of control.

10.4.4 Operational Scenarios

The use of the Multiplexer tool to support operations can be described in a few operational scenarios. In the figures below, we develop one set of Multiplexer departure procedures (Figure 20) and one set of arrival procedures (Figure 21) which are focused on two flights; Mesaba Airlines Flight 123 (MES123) flying from Washington National Airport (DCA) to John F Kennedy International Airport (JFK), and Atlantic Southeast Airlines Flight 345 (ASQ345) flying from Washington Dulles International Airport (IAD) to LaGuardia International Airport (LGA). For the sake of brevity and clarity, not all the procedural steps are shown.

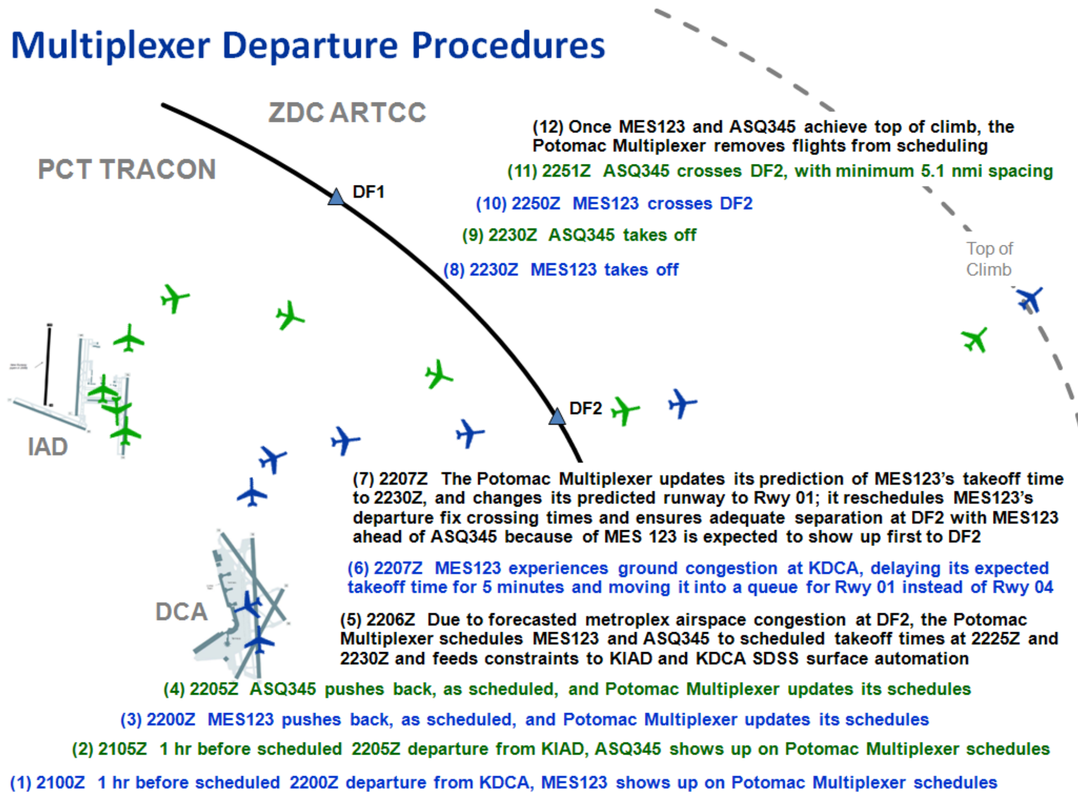


Figure 20: The Multiplexer Automation supports enhanced departure procedures for more efficient operations through the metroplex (MES123-focused actions in blue; ASQ345-focused actions in green; ANSP-focused actions in black).

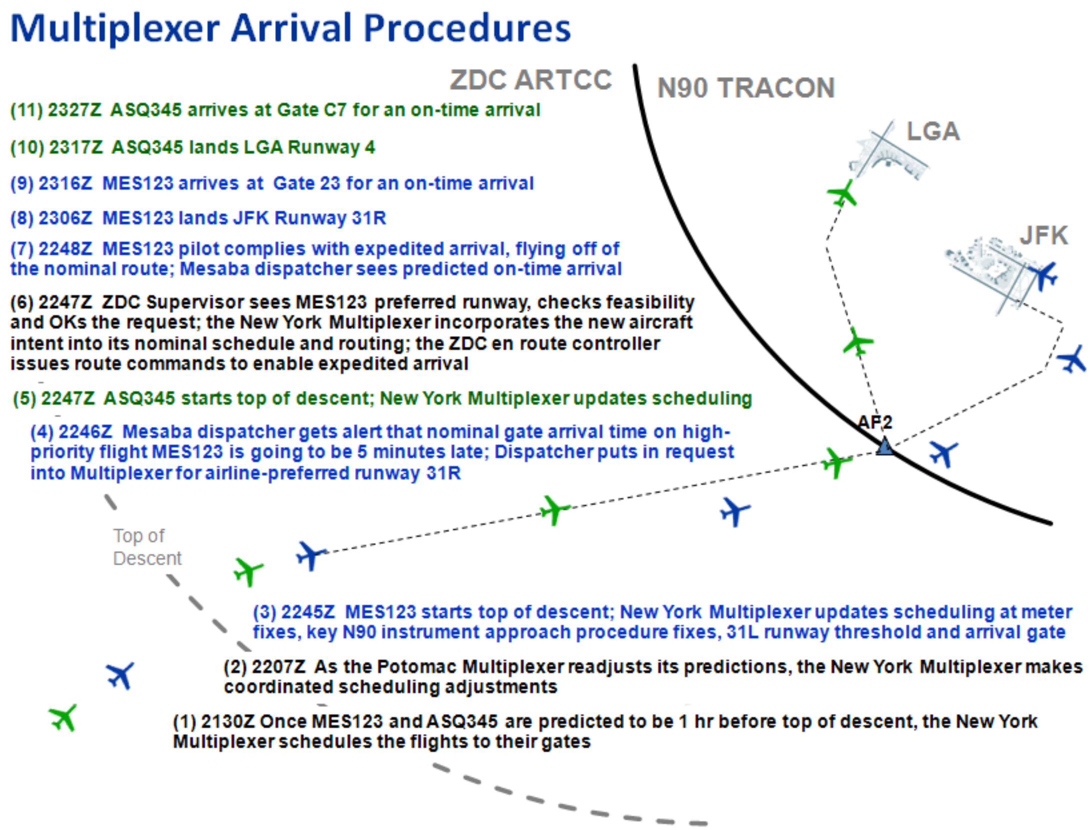


Figure 21: The Multiplexer Automation supports enhanced arrival procedures for more efficient operations and incorporation of user preferences through the metroplex (MES123-focused actions in blue; ASQ345-focused actions in green; ANSP-focused actions in black).

10.5 Flight Applicability

10.5.1 User Classes

The Multiplexer concept provides services for all user class operations including Air Carrier, Air Taxi, General Aviation, and Military flights.

10.5.2 Flight Rules

To benefit from the scheduling capabilities of the Multiplexer tool, IFR flight plans will be required for all aircraft requesting access to the metroplex resources. All VFR overflight traffic is expected to self-separate and is not incorporated into Multiplexer scheduling. VFR and other (e.g., military) arriving/departing traffic who are not on IFR flight plans need to be incorporated into Multiplexer scheduling at the runways through air traffic controller inputs.

10.5.3 NAS Domains

The Multiplexer tool is currently designed for arrival and departure aircraft in a metroplex environment (i.e., the extended terminal and airport surface domains). Therefore, flights in current ARTCC and TRACON airspaces or on airport ramps or other movement areas will be affected.

10.6 New System Architecture Requirements

10.6.1 Aircraft Equipage

The Multiplexer concept requires no explicit aircraft equipage.

10.6.2 Communication, Navigation, and Surveillance (CNS)

The accuracy of the aircraft position information input to the Multiplexer tool will have a direct effect on the effectiveness of the calculated schedules, so it is easily understood that the more accurate the surveillance data is, the better the NAS performance will be when using the Multiplexer schedules. Therefore, the increased usage of high-accuracy surveillance sources like GPS-driven ADS-B surveillance is preferred (but not required).

10.6.3 Facilities

The Multiplexer concept will impact all of the key air traffic facilities in a given metroplex including: ARTCCs, TRACONs, ATCTs, Ramp Towers, and Flight Operator Operational Control Centers.

10.6.4 Weather

No special requirements, but understood that accurate trajectory prediction is dependent on accurate current and future wind information. To ensure all-weather use of the Multiplexer, integration of metroplex weather impacts on aircraft routing is desired.

10.6.5 Software

The Multiplexer automation is expected to be implementable in a software architecture that can mimic the current NASA CTAS software architecture with some modifications (see Figure 22). On the input software processing, we envision a new process, here called "XDR" that would process the airport ASDE-X data that would be required for the surface movement predictions. These additional data would require routing through the CTAS Input Source Manager (ISM) and the Communication Manager (CM) and used by enhanced Route Analyzer (RA) and Trajectory Synthesizer (TS) algorithms. In addition, the Multiplexer scheduling algorithms would be integrated into a new Dynamic Planner (DP) process, here known as the "Metroplex Dynamic Planner" (MDP) that would provide the metroplex-wide arrival and departure scheduling algorithms.

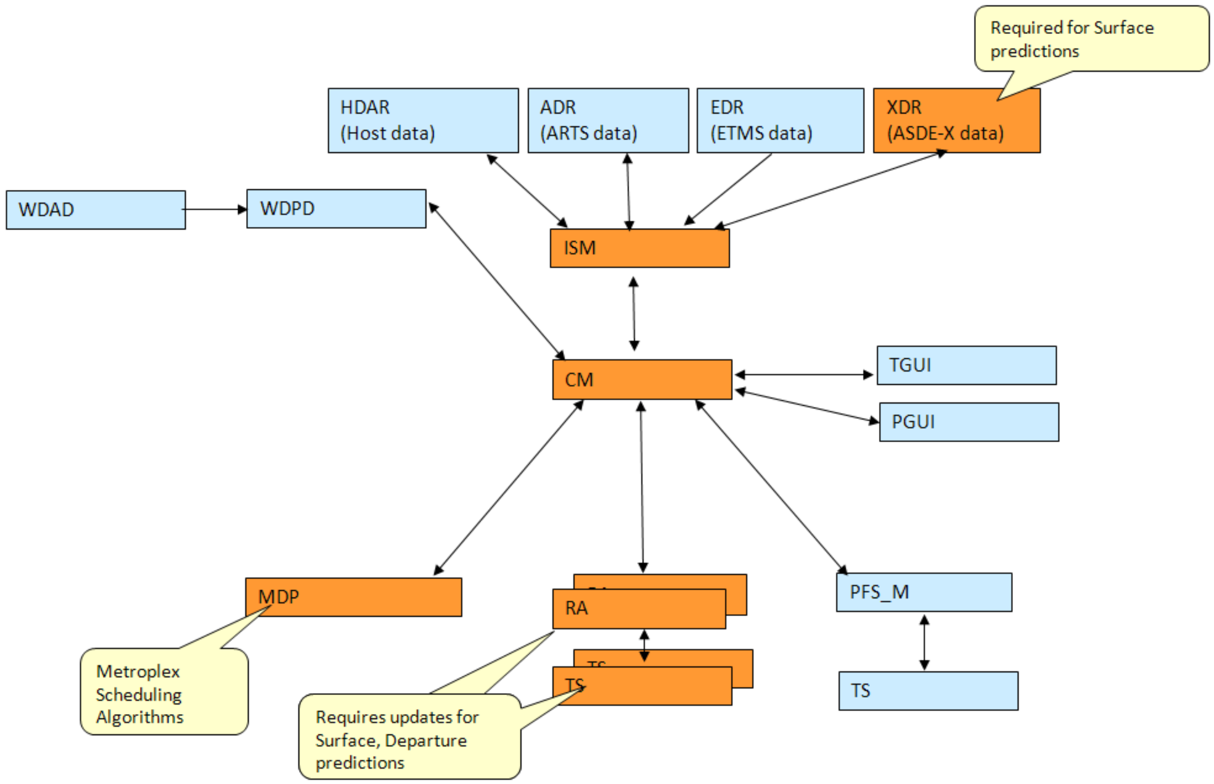


Figure 22: The expected nominal Multiplexer software architecture would require some enhancements to the typical NASA CTAS software processes (in orange).

10.6.6 NAS System

The Multiplexer automation is expected to interface with a number of existing and planned NAS systems (see Figure 23). On the input side, the Multiplexer would interface with a host of traffic and weather surveillance systems and datalink systems including ASDE-X (Airport Surveillance Detection Equipment, Model X), ITWS (Integrated Terminal Weather System), CIWS (Corridor Integrated Weather System), RUC (Rapid Update Cycle), ACARS (Aircraft Communications Addressing and Reporting System), and ARTCC, TRACON, and Ramp surveillance systems. The En Route Automation Modernization (ERAM) and Traffic Flow Management System (TFMS) automation would be integrated as well along with, when available, the Tower Flight Data Management (TFDM) ATCT automation systems. Ideally the interface would be through a System Wide Information Management (SWIM) Server. The Multiplexer Automation itself would support multiple Graphical User Interfaces (GUI) across the multiple operational personnel involved in air traffic management from the ramp tower to the en route controllers including an airline's ATC Coordinator. Any Multiplexer information useful for the pilot such as predicted takeoff times can be relayed by the airline ATC coordinator. For efficiency and cost purposes, it is expected that the Multiplexer automation would interface directly with the FAA's Traffic Management Advisor (TMA) for the en route controller and, whenever deployed by the FAA, the TFDM Arrival/Departure Management Tool (A/DMT) GUIs expected to be part of the future TFDM system [R09].

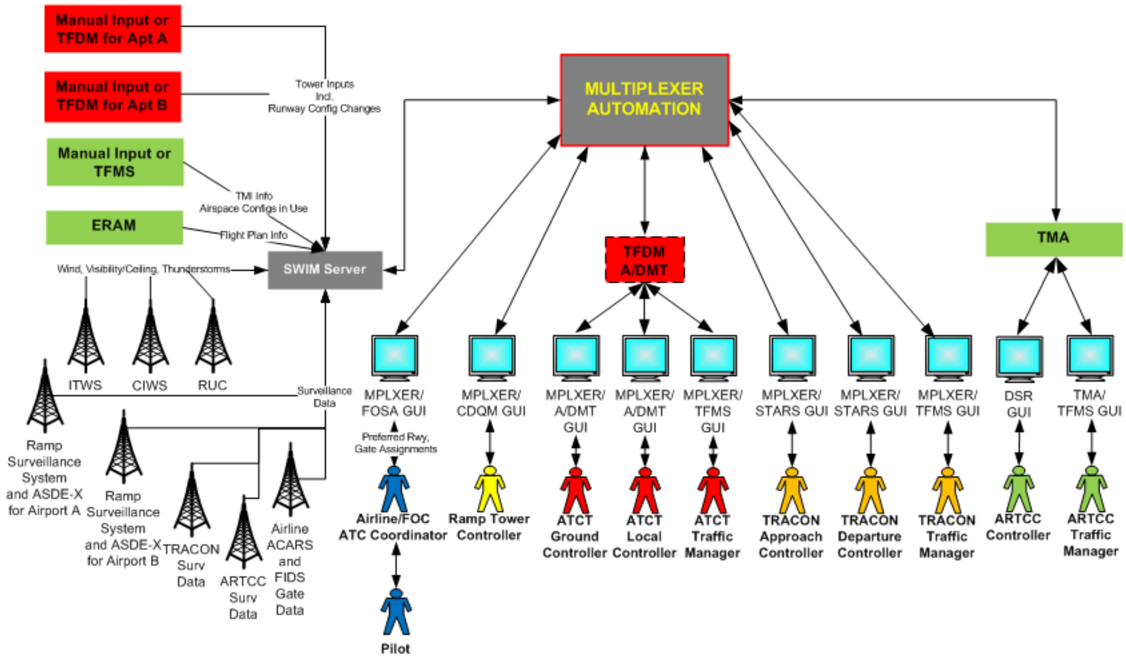


Figure 23: Nominal Multiplexer Automation System Interfaces

10.7 Human/System Interface

10.7.1 Air Traffic Controller Interface

Graphical User Interfaces (GUIs) for displaying the Multiplexer tool-generated target crossing times and assumed runway and fix assignments will be required. As shown in Figure 24, TMA-like time based metering displays in terms of either metering lists for the R-side controllers or timelines for the Traffic Management Units would be displayed on the appropriate TRACON displays (i.e., Standard Terminal Automation Replacement System (STARS)) or ARTCC displays (i.e., Display System Replacement (DSR) and TMA GUI). The assumed Multiplexer runway and fix assignments can be integrated into the far right, lowest line of the appropriate STARS or ERAM datablocks.

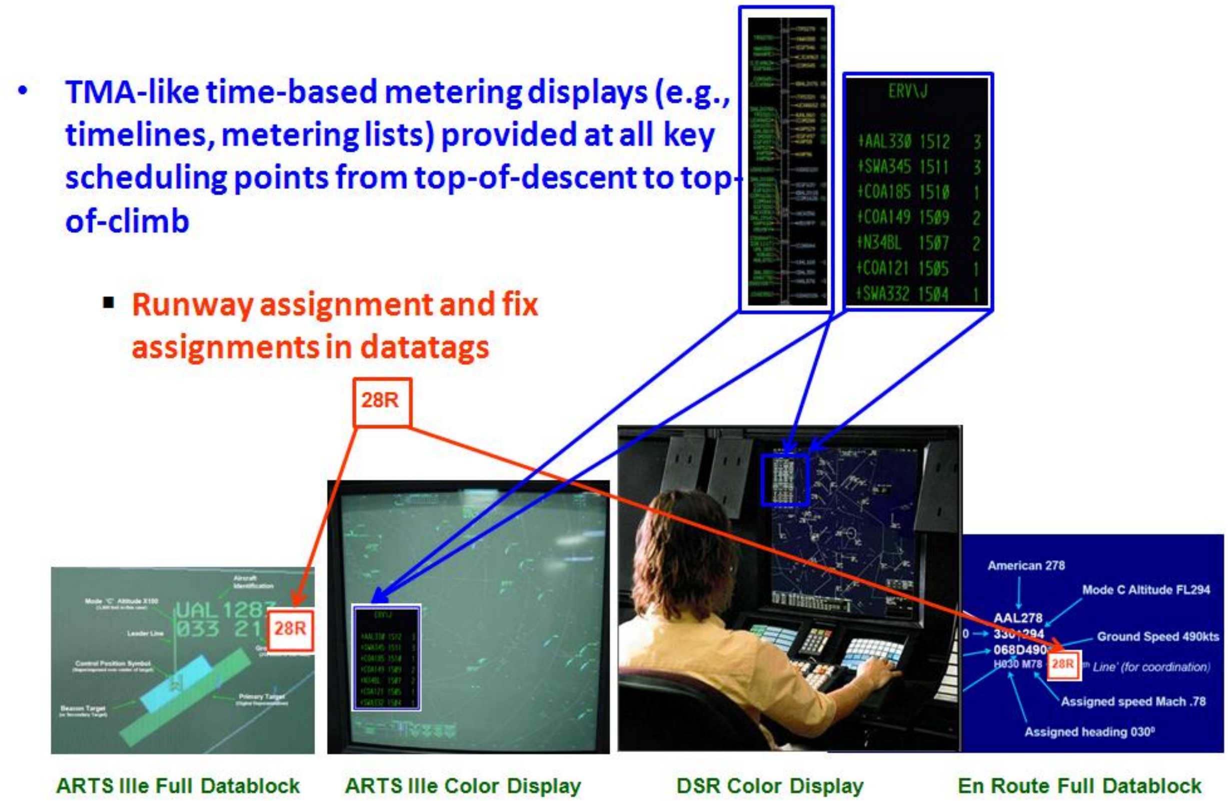


Figure 24: Nominal Air Traffic Controller Human/System Interfaces

10.7.2 Flight Deck Interface

There is no planned direct interface between the flight deck and the Multiplexer tool, but the AOC flight dispatcher can relay specific flight information via ACARS to the flight deck.

10.7.3 Airline Operations Center (AOC) Interface

AOCs will need to input dynamic AOC-driven information such as gate assignments. The Multiplex tool needs to communicate its planned take-off, landing, gate-in, and gate-out times with the AOC so that the AOC can plan optimal terminal-gate usage accordingly.

10.7.4 Traffic Flow Management (TFM) Interface

Airport surface /metroplex airspace congestion needs to trigger upstream TFM restrictions when necessary. Therefore, there is a need for an interface between the Multiplexer tool and the Traffic Flow Management System (TFMS). Also, certain dynamic information such as airport configuration, plans, and airspace configurations (e.g., SIDS, STARS, and RNAV) routes in use will require input by metroplex TFM specialists. Also, as shown in Figure 7.6, TMA-like time based metering displays in terms of timelines for the Traffic Managers would be displayed on the appropriate integrated TFMS or TMA GUIs.

10.8 Development Challenges

We expect the successful development and deployment of the Multiplexer automation to have a range of technical and other challenges. Some of the more prominent challenges are mentioned below.

10.8.1 Technical Challenges

Some of the key technical challenges that the development and deployment of the Multiplexer automation will encounter include:

- Development of fast and accurate aircraft flight prediction, scheduling, and sequencing algorithms for flights across an entire metroplex over the desired 1 hour look-a-head time,
- Development and integration of the Multiplexer scheduler output User Interface into existing or new decision support platforms (e.g., ERAM, ARTS, TFDM),
- Development of an integrated sensor and communication network backbone for the Multiplexer, and
- Integration of metroplex weather impacts on aircraft routing predictions to facilitate all-weather use of the Multiplexer.

10.8.2 Other Challenges

Some of the key other challenges that the development and deployment of the Multiplexer automation will encounter include:

- Establishment of aircraft operator to ANSP data exchanges (e.g., gate information),
- Integration of other potential overlapping planning systems (e.g., TMA, SDSS),
- Provision of a reliable source of: airport configuration status, plans, gate pushback predictions, and runway assignments, and
- ANSP acceptance of dynamic user trajectory preferences.

10.9 Future Multiplexer Capabilities

The Multiplexer concept described herein could be extended in a number of useful ways. Some of these potential future concept enhancements will now be discussed.

- The Multiplexer concept could be enhanced beyond pure metering to incorporate runway and fix change advisories. These advisories, if operationally acceptable, will provide future metroplex benefits.

- Promising new convective weather planning tools are currently being researched which could be integrated [DR08] [SB09]. The Multiplexer concept can incorporate convective weather and generate metering advisories to ensure all-weather peak metroplex performance.

- The Multiplexer scheduling algorithms could be leveraged to support increasing levels of ANSP automation support including the enabling of "what if" metroplex configuration (both airspace and airport) impact assessments that could be used to analyze more efficient metroplex configurations. This idea could be further expanded to provide particular metroplex configuration switch recommendations or provide dynamic metroplex-focused Traffic Management Initiatives.

- Another category of enhancements would be through the incorporation of advanced procedures. The Multiplexer scheduling can be adapted to incorporate new "best-equipped/best-served" policies that are being discussed by key aviation stakeholders [M09]. The incorporation of these policies on metroplex flights will incentivize the adoption of aircraft avionics that will support improved aircraft trajectory predictability which in turn can lead to improved metroplex efficiencies.

- The Multiplexer scheduling can be adapted to more precise 10-second increments. This will require new air traffic control procedures and adaptation on the air traffic control automation platforms, but this can result in improved metroplex performance.

- To ensure the full incorporation and integration of flights from all airports in a metroplex into the Multiplexer scheduling, the development of lower-cost ATCT metering displays and inputs for non-major US airports would be helpful.

- Advanced terminal procedures that use dynamic reconfiguration of routes and flows to and from "dynamic anchor points" [F07] could be incorporated into the Multiplexer concept and this can benefit metroplexes that are particularly impacted by dynamic weather and those that typically use non-static ATC routing to deal with this [SR09].

Finally, the Multiplexer concept is integratable with other NextGen concepts being developed concurrently. Some of these concepts being developed include: System-Oriented Runway Management (SORM) [LB11], Airborne Precision Spacing (APS)/Interval Management (IM) [B06], Terminal Area Precision Scheduling and Spacing (TAPSS) system [ST11], and Controller Managed Spacing (CMS) [KC11].

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