EVALUATING EN ROUTE CONGESTION MANAGEMENT THROUGH INTERACTIVE SIMULATION

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Abstract

This paper describes a newly-available simulation environment focused on interactive strategic air traffic management in both the en route and arrival domains. It discusses its origins and how it can be used in Human in the Loop tests to evaluate and improve new procedures and technologies for Traffic Flow Management.

It then provides an illustration of how it can be used to investigate management initiatives by using the environment to evaluate both the current approach and potential alternatives to dealing with en route traffic in the face of convective weather. The illustration shows that the current methods are both inefficient and ineffective, and that proposed new technologies will greatly reduce the cost of en route disruption. It further shows that in a least some cases a solution that involves multiple initiatives of differing type provides the best solution.

Introduction

Simulation has long played a central role in the advancement of aviation. There are generally three types of simulation. The first type facilitates pilot and controller training, usually by recreating the cockpit or traffic control tower environments [1] [2]. The second type evaluates air traffic control procedures and emerging technologies by simulating an environment in which pilots and controllers can interact [3] [4]. The third type, and the target of this paper, tries to capture system-wide effects by modeling the flow of aircraft through the airports and airspace. Queuing models or fast-time event-driven simulators modeling the interactions of discrete flights provide high fidelity analyses of actual and proposed system capabilities under a wide variety of situations [Odoni].

High-fidelity simulation models for analyzing tactical ATM behavior became popular in the 1980's. Tools such as SIMMOD, TAAM, and RAMS admit detailed planning of airports and airspace [ATAC] [Preston] [Euro]. The current trend in air transportation simulation favors the usefulness in guiding investment decisions, rather than on the accuracy of the model per se.

Recognizing that airline behavior varies over time, several simulation efforts have used agent-based modeling techniques to study the actions of air carriers under irregular operating conditions. Efforts such as [Nied] can explore the interaction of FAA policy changes, technology improvements, and airline operational behavior. The MIT Extensible Air Network Simulation (MEANS) is designed to measure the disruptive effects on passengers, crew and aircraft that result from various combinations of airline operations reactions and air traffic control or management actions [Clarke]. SIMAIR models airline operational reactions to stochastic events such as arrivals, departures, and aircraft unscheduled maintenance [Rosenberger]. Lastly, the Airspace Concept Evaluation System (ACES) will enable comprehensive assessment of the impact of proposed tools, concepts, and architectures, through an agent-based modeling framework and a distributed simulation approach [ACES].

Jupiter Simulation Environment

Several years ago Metron Aviation saw the need for a simulation system with a particular focus. To expedite the development and deployment of new technologies and procedures in Traffic Flow Management (TFM) a method was required to study not only the movement of aircraft but the behavior of the decision-makers in TFM and how their responses to evolving conditions would interact and in turn affect the conditions. This inspired the development of the Jupiter Simulation Environment (JSE), which was first put into use in April of 2002. JSE is specifically designed to support Human in the Loop simulations (HITLs) to evaluate and perfect new concepts in TFM.

The core JSE functionality models the high-level behavior of flights and emulates the information exchange functions of the Enhanced Traffic

Management System (ETMS) [6], which supports Air Traffic Management (ATM) operations in the US. The key to Jupiter's usefulness is in its focus on connecting to external tools and systems that either are part of the existing set of software tools available to decision makers or are new or extended systems that are under evaluation. This design lets the aviation community see the effects of new concepts in the context of currently deployed systems, explore the interactions between user and service provider, and refine and perfect capabilities and procedures before live operations are affected. Effective simulation exercises also allow the development of detailed complete software requirements to provide to the development community for operational deployment.

For example, a proposed new way of implementing Ground Delay Programs (GDPs) might be built into a prototype version of the Flight Schedule Monitor (FSM). Specialists from the FAA would use the new software to impose a GDP based on simulated capacity/demand imbalance conditions. The flight delay information would be sent to JSE which would, playing the role of ETMS, distribute this information to the users' existing flight monitoring tools and decision aids. The users might in turn adjust to the FAA-imposed delays through substitutions, cancellations and reroutes. This information would be sent to JSE and incorporated into the common tactical picture. As time evolved, and JSE modeled the action of flights under the controls assigned by the FAA and the users, unforeseen problems may emerge, such as too many flights arriving over a single fix. Such a result would show that the concept was not ready for deployment until some changes had been made, in either the concept or the rules of procedure.

The initial release of JSE primarily modeled arrivals into airports. It has here shown the value of a flexible interactive simulation environment for rapid development and evaluation of new capabilities and procedures. It was central to the rapid development and deployment of Slot Credit Substitution procedures. It has been used to evaluate several concepts that seemed initially promising but after HITL evaluation were shelved, such as multi-fix and multi-airport GDPs and it is currently employed in the refinement of some soon-to-be-deployed technologies, such as improved popup management procedures and Adaptive Compression.

Expanding into En Route Modeling

Successes in the advancement of airport arrival technology and procedures inspired an effort to expand the simulation's capability into the exploration of potential TFM advances in the en route domain. This required a basic rewrite of the Jupiter internal architecture away from a time-step approach to an event oriented model. Trajectory prediction and airspace congestion models have been incorporated. The communication capabilities have been extended by adding interfaces to receive route information from various sources and to drive Aircraft Situation Display tools.

A major contribution to the range and effectiveness of the simulation environment in the airspace came from integrating Jupiter with the Future ATM Concepts Evaluation Tool (FACET), a NASA-developed simulation system, and with the FACET-based family of tools, which includes the Collaborative Routing Resource Allocation Tool (CRRAT) and the Flow Constrained Area Re-router (FCAR). This group provides the simulation with sophisticated resource rationing schemes, congestion monitoring functions, traffic management initiative (TMI) models, and a variety of displays. The merging of Jupiter and FACET into what is now called the Integrated Simulation Environment (ISE) has saved years of development time.

At the same time, new approaches for airspace congestion management and the supporting software tools have been under development [Burke]. Under Collaborative Decision Making (CDM) sponsorship FSM has been adapted to address constrained resources in the airspace, resulting in a prototype tool named the Airspace Flight Situation Monitor (AFSM). And a number of new approaches to improved route selection and management have emerged from the Integrated Concepts for the Evolution of Flow Management (ICE-FM) program.

All of these components are now coming together to form a new simulation environment where the community will be able to prototype, evaluate and perfect the TFM methods of the future. In this environment we are able to evaluate the practicality and effectiveness of new approaches, examine the interaction of multiple TMIs, measure the interaction of the responses of multiple players through the system, and test the robustness and flexibility of various approaches as conditions change through the simulation day.

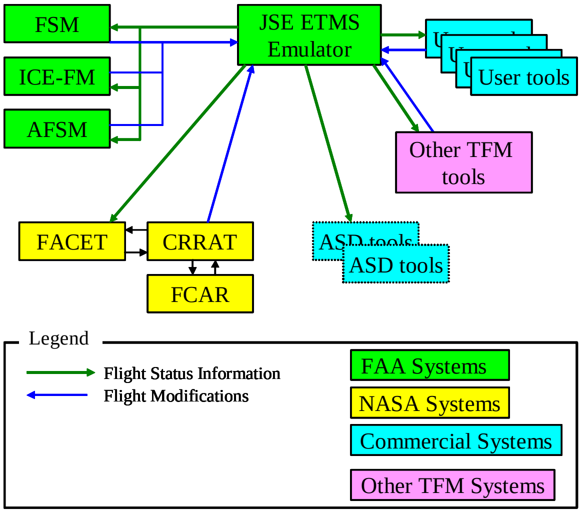


Figure 1: Schematic of Simulation Environment

Figure 1 shows a schematic of the ISE. The Jupiter core manages the inter-process communications and models the evolution of flights through their life cycles. Flight status information is distributed to each of the players in an HITL, who can view this information through established or prototype decision aids. Responses to the current situation in the form of flight modifications are sent in to the ETMS emulator, which distributes the new data to all appropriate systems.

The concepts of use for the ISE can be best illustrated through an example. Here we will show how some of these new capabilities can be used to evaluate various approaches to flow control during the planning stages of a TFM program

Applying the System to a Sample Scenario

As a starting point for an example simulation we will consider a typical bad-weather day in the NAS, July 7, 2004. On this day a string of thunderstorms moved across Cleveland center, impeding traffic flow on the critical routes between the Northeast and the Midwest. The procedures laid out here will show how the simulation environment might be used to model and evaluate several approaches to traffic management in the planning phase of the program, including both traditional methods and some new approaches made possible with new prototype capabilities

GDPs in Support of SWAP

When convective weather blocks critical air traffic routes, Traffic Managers at the FAA need to take actions that will reduce the volume of aircraft in the impacted area – they must implement Severe Weather Avoidance Procedures, or SWAP. For small weather systems rerouting flights around the problem areas can be sufficient. Too often the weather systems are so broad that reroutes alone aren't enough, and some flights must be held on the ground to adequately manage the demand

The only tools currently available to Traffic Managers that can impose coordinated ground delay are airport GDPs [7] and Ground Stops (GSs). These are procedures implemented through FSM that are designed to manage reduced arrival capacity at airports. These tools have by necessity been drafted into supporting en route congestion as well. The theory behind the use of GDPs in support of SWAP is that slowing the arrivals into the major airports around the perimeter of a major weather system will reduce the demand within the constrained area.

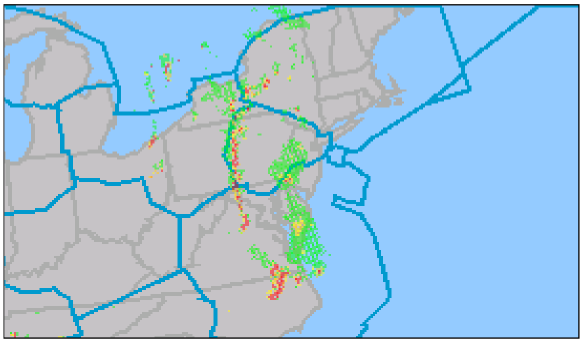


Figure 2. Weather situation on 07 July 2004

Figure 2 shows a snapshot of the weather situation on the sample day. To deal with the reduced en route capacity the managers executed GDPs for 10 airports: BOS, BWI, DTW, EWR, IAD, JFK, LGA, PHL, MDW, and ORD. The Flow Constrained Area (FCA) associated with the weather and the airports that were involved in GDPs caused by the en route weather are shown in Figure 3. By the end of the day, the impact of the TFM initiatives and the weather on the arrivals into those airports was dramatic, with a total of 151,445 minutes of delay and 597 cancellations, as shown in **Table 1**.

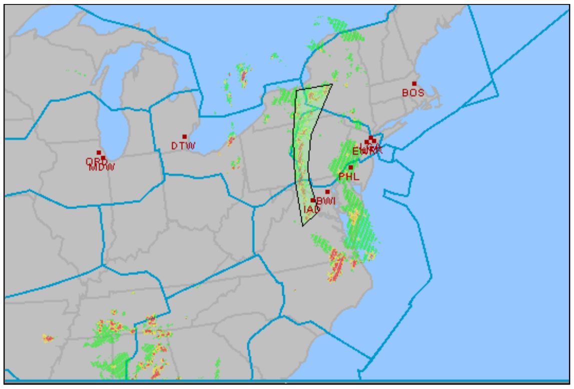


Figure 3: Weather FCA and GDP Airports

Table 1. Effect on Arrival Airports of GDPs in Support of Severe Weather on July 7

Airport	# Controlled flights	Total delay (min)	# Cnx
BOS	291	6,233	46
BWI	247	15,609	38
DTW	344	4,794	25
EWR	425	24,264	91
IAD	400	20,480	114
JFK	226	4,764	8
LGA	364	21,794	95
MDW	220	4,711	10
ORD	822	26,275	46
PHL	461	22,521	124
total	3,800	151,445	597

Efficiency of GDPs in Support of SWAP

It is well understood that GDPs in support of SWAP are an imperfect solution to the problem of en route congestion in an FCA. Among the principal drawbacks are that only some of the flights that are passing through the FCA are bound for one of the airports that receives a GDP, so many flights that should be delayed to provide equity are not affected at all. A second major drawback is that only some of the flights caught in the GDPs are anywhere near the constrained area, so many flights are unnecessarily delayed. This effect is represented schematically in **Figure 4**.

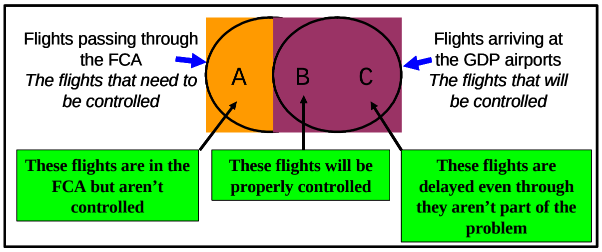


Figure 4: Drawbacks to GDPs in support of SWAP

While these liabilities were understood qualitatively there had never been any method to actually measure them. One of the first applications for the new ISE was to investigate the consequences of this approach to en route congestion management. For this study, GDPs similar to the ones actually executed at the 10 airports on July 7 were imposed through FSM in the ISE.

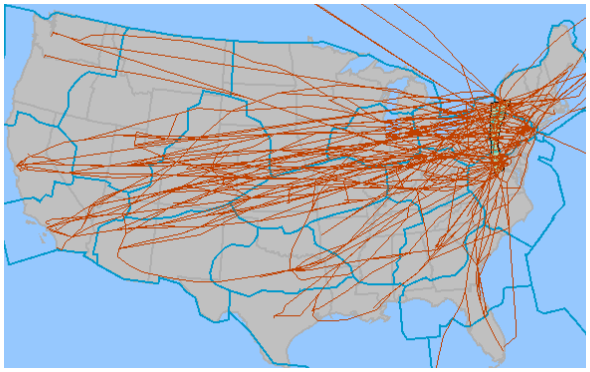


Figure 5: Flights Passing through the FCA

Figure 5 depicts the flight paths of the set of flights passing through the FCA during the constrained period. These are the flights that need to be controlled, either delayed or rerouted, to reduce the volume in the FCA to a manageable level.

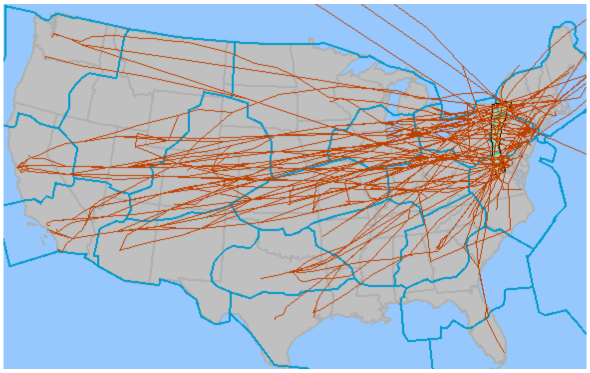


Figure 6: Uncontrolled Flights in the FCA

Figure 6, however, shows a subset of the flights in **Figure 5,** those that should be controlled that are not controlled at all because their destination airport was not among the 10 where GDPs were issued. Visually, it would appear from these figures that most of the flights that should have been controlled were not.

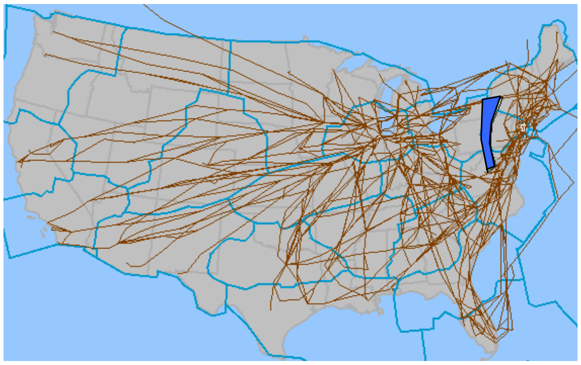


Figure 7: Delayed Flights not in the FCA

Figure 7 shows the paths of those flights that were delayed by the GDPs but did not pass through the FCA at all. These flights are taking unnecessary delay because of the limited set of tools available to the Traffic Managers. Graphically it appears that a large number of flights are suffering needlessly.

But these are still only qualitative views into efficiency of the running GDPs in support of SWAP. We still need to show quantitatively how efficient these procedures are.

Table 2 shows the effect of the 10 GDPs imposed in this scenario. Flights are partitioned into those that are controlled vs. those that are not, and those that are in the FCA vs. those that are not. Of the 2,872 flights that were controlled (a) only 583 actually went through the flow constrained area (b), and 2,289 controlled flights, (c), were not part of the problem as defined. That is, in GDPs in support of SWAP, up to 80% of the flights that are delayed are not in the constrained area. Additionally, 842 flights that did go through the area (d), or 60% of the flights in the area, weren't controlled at all. Over 86,000 minutes of delay were imposed (e), and over 69,000 minutes of that was imposed on flights not traversing the area.

Effectiveness of GDPs in Support of SWAP

So we see that the simulation environment can show how inefficient the currently available methods are. Another question is how effective GDPs in support of SWAP are for managing the demand in the FCA**. Figure 8** shows the demand profile for flights in the FCA before and then after the 10 GDPs were run. Each bar on the graph is the number of flights in the FCA during subsequent 15 minute intervals. The number of controlled flights in each interval is shown in yellow, uncontrolled flights in green. These graphs show the effect of the airport GDPs on the total demand during the interval was minimal, and the GDPs did nothing to smooth out the spikes in demand. These spikes will surely require additional initiatives, such as ground stops, to manage later.

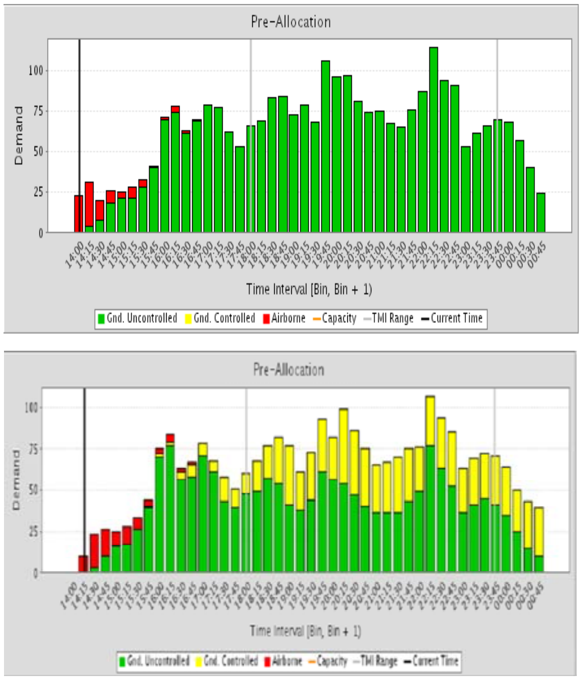
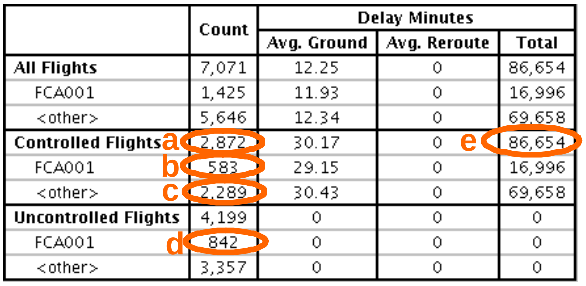


Figure 8: Effect on FCA Demand of 10 GDPs



	Count	Delay Minutes		
		Avg. Ground	Avg. Reroute	Total
All Flights	7,071	12.25	0	86,654
FCA001	1,425	11.93	0	16,996
<other>	5,646	12.34	0	69,658
Controlled Flights a	2,872	30.17	0 e	86,654
FCA001 b	583	29.15	0	16,996
<other> c	2,289	30.43	0	69,658
Uncontrolled Flights	4,199	0	0	0
FCA001 d	842	0	0	0
<other>	3,357	0	0	0

Table 2: Effect of 10 GDPs on Flights

Airspace Ground Delay Programs

This exercise dramatically shows both pictorially and statistically, what has long been understood intuitively - airport-based GDPs are a bad tool for effective management of en route traffic volume. This clear need for a capability to manage traffic through a designated piece of airspace the same way as traffic into an airport can be managed has led to the development of prototype tools, including AFSM and CRRAT, to fill this role.

Both of these tools can control demand in a section of airspace, an FCA, by imposing ground delay on flights such that their arrival at the constrained resource never exceeds its capacity. They differ mostly in their intended application. AFSM is a functional prototype of a capability that may, after thorough testing and evaluation, be deployed as part of ETMS. This means that it must support operational requirements such as communications integrity and robustness. CRRAT is designed for simulation use only, and has a wide variety of rationing options for the allocation of single or multiple resources. Since AFSM is still in the testing phase of development the initial studies of airspace demand control described in this paper use CCRAT as a rationing tool.

The new simulation environment allows us to explore the application of an airspace delay program to this en route problem. Assume for the purposes of this evaluation that the objective of the GDPs issued was to reduce the demand to no more than the minimal flow in any 15 minute period, 56 flights, much like setting an airport rate in FSM at the minimal flow. The demand profile resulting from the multiple GDP solution, depicted in the bottom image in **Figure 8,** shows that this approach did not meet this objective at all. An airspace delay tool, however, can achieve this result precisely.

Figure 9 shows the demand profile after CCRAT has been used to run a 56-rate program for the airspace. The demand during the constrained period, between the vertical lines, has been reduced uniformly to the requested rate. The sharp peaks during the thunderstorm period that would have required ground stops on top of the GDPs have been smoothed away.

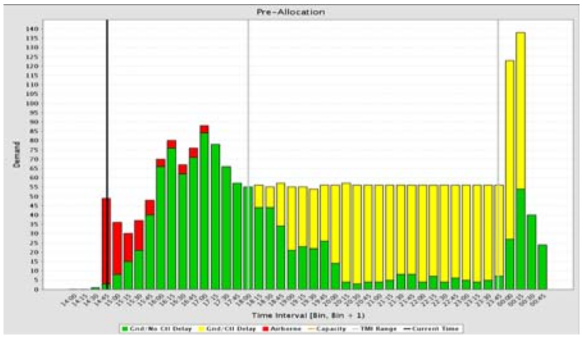
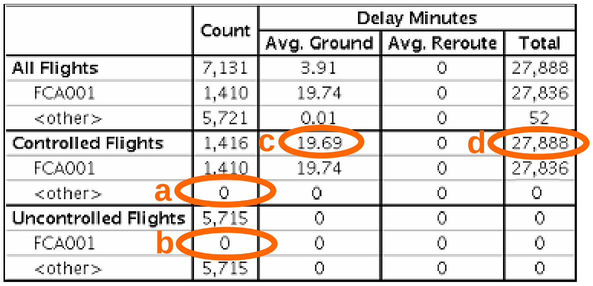


Figure 9. Effect of an Airspace Delay Program

Table 1 shows the delay statistics for the airspace GDP. We see that any of the flights not in the FCA (a) were not delayed and that no flights in the FCA (b) avoided being controlled. Further, we see that the average delay for flights in the FCA was only 20 minutes (c) and only 27,888 minutes of total delay (d) had to be imposed, in contrast to over 86,000 minutes through the airport GDP approach. Clearly better control at considerably less cost can be achieved when we have the appropriate tools.

Table 3: Delay Statistics for Airspace GDP



	Count	Delay Minutes		
		Avg. Ground	Avg. Reroute	Total
All Flights	7,131	3.91	0	27,888
FCA001	1,410	19.74	0	27,836
<other>	5,721	0.01	0	52
Controlled Flights	1,416	19.69	0	27,888
FCA001	1,410	19.74	0	27,836
<other>	0	0	0	0
Uncontrolled Flights	5,715	0	0	0
FCA001	0	0	0	0
<other>	5,715	0	0	0

Compound Initiatives - Airspace Delay Programs with Rerouting

In most situations no single initiative will be most effective and efficient for managing traffic flow, and strategically applied compound initiatives will usually be best. The simulation environment supports the exploration and evaluation of such hybrid solutions. We might consider, for example, a scenario in which some fraction of the flights is routed around the constrained area and an airspace delay program is then applied to the flights remaining.

Many new approaches to collaborative rerouting are being developed through the ICE-FM program. Figure 5 shows the interface for one new capability, Route Options Generation. This capability facilitates rapid rerouting by displaying, for selected city pairs, pre-coordinated routes (e.g. Preferred Routes, CDRs, Playbook Plays) that avoid designated constraints such as FCAs and congested fixes. Such tools would allow the operator, either traffic manager or dispatcher, to quickly find and select good routes for some fraction of the traffic through the FCA.

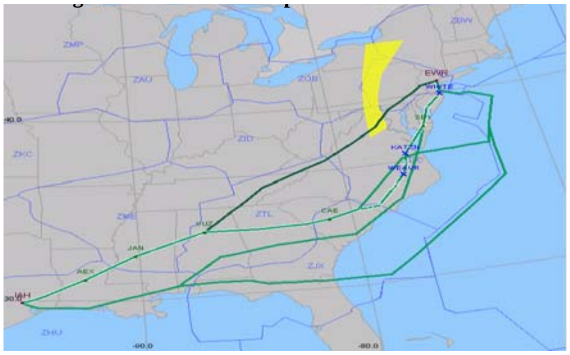


Figure 10: Route Options Generation

In our example scenario the players in the HITL reroute about 8% of the flights in the FCA around the constraint. **Figure 11** shows the demand profile for the FCA after these flights have been rerouted. The change in the demand is barely noticeable. But because of the non-linear relation between excess demand and delay small changes can have large effects.

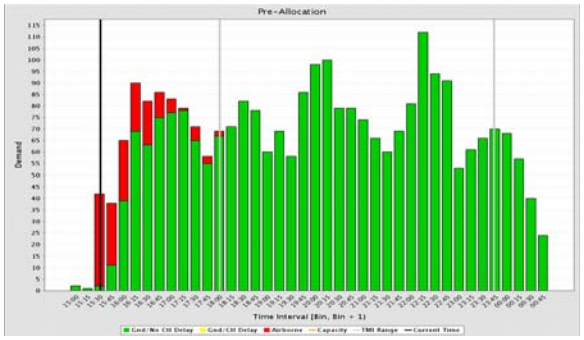
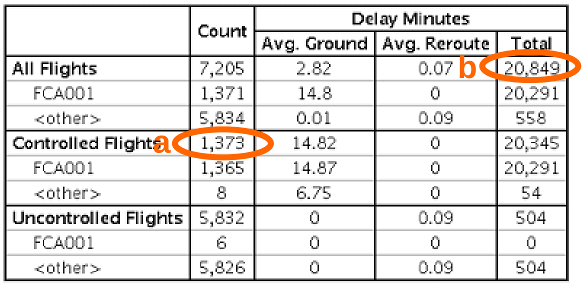


Figure 11: FCA Demand Profile after 8% Reroute

If we now run the same 56-rate airspace GDP on the demand shown in **Figure 11** we produce the statistics shown in **Table 4**. By reducing the demand in the FCA to 1,373 (a) we can reduce the total delay to 20,849 minutes (b), 7,000 fewer than with ground delay alone. These results show that in some cases mixed initiative will provide the best solutions to traffic management problems.

Table 4: Delay Statistics from Reroute and Airspace GDP



	Count	Delay Minutes		
		Avg. Ground	Avg. Reroute	Total
All Flights	7,205	2.82	0.07	20,849
FCA001	1,371	14.8	0	20,291
<other>	5,834	0.01	0.09	558
Controlled Flights	1,373	14.82	0	20,345
FCA001	1,365	14.87	0	20,291
<other>	8	6.75	0	54
Uncontrolled Flights	5,832	0	0.09	504
FCA001	6	0	0	0
<other>	5,826	0	0.09	504

Summary

An integrated simulation environment focused on interactive strategic air traffic management that can model both en route and arrival management, while by no means complete, is now ready for use in testing and evaluating new concepts in flow control. It supports HITL tests that allow service providers and system users to use, where applicable, their own familiar tools to play their respective roles while introducing new technologies and procedures into simulated operational situations. The environment can model the system effects of local actions (for example, the effect of a GDP on airspace demand) and the effect of the behavior of one player in the system on others (for example, the effect of airline substitutions on a traffic manager's flow strategy or the effect of a GDP revision on an airline's substitution plan). It can be used to evaluate not only the immediate consequences of actions and procedures but the robustness and flexibility of operations as a scenario plays out under changing conditions.

This capability, the Integrated Simulation Environment, has been built as a collaborative effort involving the FAA, NASA, MITRE and the airlines that have helped design the system through their participation in early HITLs. Efforts are underway to bring more collaborators into the project, including other research institutions and universities.

While the ISE's ability to model the dynamic evolution of the airspace has not yet been touched, applying the environment's system modeling capabilities to en route traffic management procedures in the planning phase has already yielded important and surprising results. These include illustrating the degree to which GDPs in support of SWAP are both inefficient and ineffective, and the benefits of mixed strategies including ground delays and reroutes to managing en route congestion.

Next Steps

The ISE will be employed over the next few months to develop technologies and procedures for some sort of airspace ground delay capability for expected deployment in the summer of 2006. It will also be used to evaluate new approaches to collaborative routing that promise to improve efficiency and flexibility while reducing workload. It is currently playing a role in the evaluation of parameter settings and procedural rules for new popup management procedures and adaptive compression in GDPs.

Future ISE development will expand both its range and its power. The interaction of surface operations with the rest of the NAS will be explored when departure flow management models and technologies are integrated into the system over the next year. The internal modeling of miles in trail and other TMIs will be improved by applying methods developed at other research institutions. And we hope to incorporate software agents emulating airline operations centers and other users, as developed by some of the universities, to increase the dynamism and fidelity of the simulations.

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Keywords

Event Driven Simulation

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En Route Congestion Management

Flow Constrained Areas

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GDP in support of SWAP

Biographies

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