SUMMARY OF ADVANCED AIR TRANSPORTATION TECHNOLOGIES (AATT) PROJECT BENEFITS STUDIES

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Chapter 1
Introduction

Since 1997, the Advanced Air Transportation Technologies (AATT) Project has been the focal point of NASA's research into air traffic management (ATM) decision support tools (DSTs) and innovative operational concepts. The Benefits and Safety Assessments (B&SA) sub-project of AATT is responsible for conducting periodic studies to ensure that the research is fruitful and worth pursuing. Aligned with the NASA Technology Readiness Level scale, the studies include single-year National Airspace System (NAS)-wide benefits and life-cycle cost-benefit analyses which are required as the research matures.

To encapsulate the benefits assessment work done under AATT, in this report we provide summaries of the major studies done for each DST and concept along with a comprehensive bibliography of all the reports commissioned by the B&SA sub-project. This report includes summaries of the following AATT DSTs:

- *Surface Management System (SMS)*—Advises airlines, ramp controllers, and air traffic control on push-back and taxi navigation for efficient surface operations.

- *Direct-To (D2)*—Provides conflict advisories, advisories of direct conflict-free routes, and a highly automated route planning capability to Air Route Traffic Control Center (ARTCC) sector controllers.

- *Multi-Center Traffic Management Advisory (McTMA)*—Provides aircraft sequence and scheduling information to air traffic control for metering arrivals from multiple ARTCCs into a single Terminal Radar Approach Control (TRACON).

- *Regional Metering (RM)*—Complements arrival and sector metering tools by effectively extending the metering horizon to upstream ARTCCs and helping traffic managers efficiently plan, coordinate, and implement metering restrictions.

- *Traffic Flow Management Research and Development (TFM R&D) (System-Wide Evaluation and Planning Tool and Future Air Traffic Management Concepts Evaluation Tool-Airline Operations Center [SWEPT and FACET-AOC])*—Provides a flexible simulation tool for airline traffic managers to forecast various traffic scenarios, enabling development of efficient plans to address weather, traffic density, and other airspace issues.

- *Traffic Flow Automation System (TFAS)*—Improves the accuracy of the Enhanced Traffic Management System (ETMS) Monitor Alert function.

- *Distributed Air/Ground Traffic Management Concept Elements 5 (DAG-TM CE-5)*—Appropriately equipped aircraft are given the authority to fly their preferred trajectories, subject to full responsibility for maintaining separation from other aircraft and conforming to traffic flow constraints.

- *Distributed Air/Ground Traffic Management Concept Element 6 (DAG-TM CE-6)*—Through the integration of controller DST capabilities and the flight deck via data link, the flight deck and the ground can exchange automated trajectory and clearance related data and negotiate user-preferred trajectory requests.

- *Distributed Air/Ground Traffic Management Concept Element 11 (DAG-TM CE-11)*—Appropriately equipped aircraft are cleared to merge into an arrival stream and self-space behind a lead aircraft.

- *Expedite Departure Path (EDP)*—Coordinates departure sequencing and scheduling to enable efficient departure ascent and merges.

- *En Route/Descent Advisor (EDA)*—Provides advisories to ARTCC sector controllers on merging, sequencing, and spacing of aircraft for efficient climb, cruise, and descent constraints and flow management.

- *En Route Data Exchange (EDX)*—Enables real-time data exchange between aircraft and ground information systems.

- *Collaborative Arrival Planner (CAP)*—Accommodates user preferences in arrival flow management through collaborative decision support tools for users and air traffic service providers.

- *Conflict Prediction and Trial Planning (CPTP)*—Extends the conflict prediction and resolution functions developed by previous decision support tools.

- *Traffic Management Advisor (TMA)*—Provides aircraft sequence and scheduling information to air traffic control for metering arrivals from a single ARTCC into a TRACON.

- *Surface Movement Advisor (SMA)*—Free Flight Phase 1 Automated Radar Terminal System (ARTS) Data Gatherer; Atlanta: initial SMS demonstration of shared airline planning and NAS status information.

- *Passive Final Approach Spacing Tool (pFAST)*—Provides arrival aircraft runway and sequence advisories to TRACON arrival controllers.

- *Active Final Approach Spacing Tool (aFAST)*—Provides arrival aircraft speed and heading advisories to TRACON arrival controllers.

Each of the subsequent chapters in this report is devoted to one of the decision support tools and concept elements listed above. The organization of each summary is as follows:

- A brief description of the DST or concept element and the reference citation for the source study report
- Functions, benefit mechanisms, and metrics
- Modeling and analysis approach
- Results, findings, and conclusions.

We note that we liberally used material directly from the source documents, including text and graphics, in order to most effectively summarize the prior work.

Chapter 2
Surface Management System (SMS)—Summary of Single-Year NAS-Wide Benefits and Life-Cycle Cost/Benefit Assessments

INTRODUCTION

The Surface Management System (SMS), being developed by NASA Ames Research Center, provides decision support capabilities to improve airport surface movement efficiency and flexibility. SMS provides air traffic control tower (ATCT) controllers with complete and precise information about departure demand, arrival demand, predicted pushback times, and runway utilization. SMS information is conveyed via a graphical interface that incorporates at-a-glance traffic information and decision support advisories to help ATCT controllers manage surface movement. SMS information is also provided to ramp controllers and air traffic service providers (ATSPs) in air route traffic control centers and Terminal Radar Approach Control (TRACON) facilities to enhance collaborative decision-making.

Benefits expected from SMS include reduced delays, reduced taxi time, improved NAS-wide predictability, and improved adherence to schedule priorities.

This summary of SMS is based on Raytheon's SMS life-cycle benefit/cost assessment produced by the Raytheon Air Traffic Management System Development and Integration (ATMSDI) team. The full citation for the assessment is:

> *Air Traffic Management System Development and Integration (ATMSDI), CTO-05 - Surface Management System (SMS), CTOD-5.25.3—Final Life-Cycle Benefits/Cost Assessment,* NASA Prime Contract NAS2-00015, 30 June 2004.

FUNCTIONS, BENEFIT MECHANISMS, AND METRICS

Table 2-1 shows the general benefit mechanisms and corresponding technical performance metrics addressed by SMS.

Table 2-1. General Benefit Mechanisms and Metrics

Benefit mechanism	Performance metric
Reduced delay	Delay cost savings
Reduced taxi time	Fuel cost savings
Improved NAS-wide predictability	Delay cost savings
Improved adherence to scheduled priorities	Delay “bucket” swaps

Table 2-2 shows the specific benefit mechanisms analyzed in this study that correspond to SMS modeling scenarios.

Table 2-2. Analysis-Specific Benefit Mechanisms

Mechanism	Abbreviation
Departure Prediction	DP
Arrival/Departure Trade-Off	AT
Efficient Spot	ES
Runway Allocation	RA
Pushback Scheduling	PS

Table 2-3 shows the linkage among SMS capabilities, deployment builds, modeling scenarios, and benefit mechanisms.

Table 2-3. SMS Capability, Build, Scenario, and Benefit Mechanism Linkage

SMS capabilities	SMS build	Modeling scenario	Benefit mechanism
Integrated graphical display of flight information	Build 1 TM/CT	SMS ES scenario	Reduced delay
Coordination and display of airport information	Build 1 TM		Reduced delay
Display of departure queues	Build 1 TM	SMS RA scenario	Reduced delay
Runway allocation—flight specific	Build 1 CT	SMS RA scenario	Reduced delay
Runway allocation—departure runway scenario	Build 1 TM		Reduced delay
Arrival/departure trade-off	Build 1 TM	Arrival/departure trade-off model	Reduced delay
Departure time prediction for NAS-wide use	Build 1 TFM	Departure predictions model	NAS-wide predictability
Staging flight to meet downstream restrictions	Build 1 CT		NAS-wide predictability
Sequencing handoff at spots	Build 1 CT	Flight prioritization model	Adherence to schedule priorities
Runway sequencing for prioritization	Research SMS	Flight prioritization model	Adherence to schedule priorities
Runway sequencing for efficiency	Build 1 CT		Reduced delay
Pushback scheduling	Research SMS	SMS PS Scenario	Reduced taxi time
Taxi routing	Research SMS		Reduced delay

MODELING AND ANALYSIS APPROACH

Background

The SMS research program has developed and tested several air traffic management decision aids that exploit the computational power to process real-time surveillance and flight plan data and display information to air traffic managers and controllers. The benefit/cost analysis addresses a subset of these aids identified for near-term, Build 1, deployment. Build 1 includes three separate groups of tools described as follows.

Build 1 TFM (Traffic Flow Management) Products (Build 1 TFM) represents the capabilities of SMS to provide information and support for TFM activities. The improved prediction of 'off' times being provided to the Enhanced Traffic Management System (ETMS) system is the core capabilities of Build 1 TFM Products. This build can be deployed and used by the FAA using a completely separate equipment deployment approach than the other SMS builds. No equipment would need to be installed at the field site, as the Build 1 TFM Products will use ETMS data and the real-time Out, Off, On and In (OOOI) data provided through the ETMS data feed. The real-time OOOI data may be provided by airlines, or it may be derived from surface surveillance data by systems other than SMS and conveyed through ETMS to the Build 1 TFM Products version of SMS.

Build 1 Traffic Management (Build 1 TM) represents the core capabilities of SMS that are intended for local traffic management use at the deployment site. The Build 1 Traffic Management includes the SMS capabilities and tools that are intended for use by the Tower Traffic Management Coordinator (TMC), the TRACON TMC, the ARTCC TMC, the Ramp Tower supervisor and the AOC dispatcher. These tools support the planning and coordination of activities on the surface, but there are no SMS displays provided directly to the Local or Ground Controller in the ATC Tower. SMS displays will be provided to the TMCs (Tower, TRACON and ARTCC) and the Ramp Tower Supervisor and AOC dispatcher. At some facilities, a TMC position does not exist. In such cases, the SMS TM capabilities and displays will be used by the supervisor or cab coordinator who is responsible for traffic management decisions. This SMS build provides much of the benefit of SMS without requiring an additional display for the safety-critical role of the controller. Information from SMS helps the TMC make decisions more effectively, but the decisions are communicated to the controller by voice instruction, or otherwise, in the same manner as they are today.

Build 1 Controller Tools (Build 1 CT) adds the full set of SMS capabilities, advisories and displays for the Local and Ground Controller in the ATC Tower and the Ramp Controller in the Ramp Tower to the Build 1 Traffic Management capabilities. This build includes a display for these controller positions that would be used to convey critical information for the conduct of the controllers' role. The deployment approach for the Build 1 Controller Tools will be significantly different than the Build 1 Traffic Management, because any controller tools will need to be integrated into existing, certified tower controller systems.

Note that some of the SMS capabilities that will be described below do not fall into any of these Build 1 releases. Any SMS capabilities that are not included in Build 1 are included in the Research SMS build. Also note that only the benefits and costs associated with Build 1 are included in the life-cycle benefit/cost assessment.

MODELING AND ANALYSIS

The primary model used for estimating benefits is the "Simple" version of the SMS Model, which employs the actual SMS airport simulation algorithms. Several additional models are used to estimate benefits not measurable with the SMS Model. Table 2-4 lists the full suite of models and the benefit scenarios analyzed.

Table 2-4. Analysis Models

Model	Benefit scenarios
SMS "Simple" Model	Runway Allocation (RA), Efficient Spot (ES), Pushback Scheduling (PS)
Airport Resource Management Model	Airport Resource Management (AT)
Flight Prioritization Benefits Model	Delay "bucket" swaps to avoid high cost delays, such as missed connections
Departure Predictions (DP) Benefit Model	Reduced NAS-wide delay due to reduced number and severity of miles-in-trail restriction
Expected Departure Clearance Time (EDCT) Benefit Model	Reduced NAS-wide delay due to improved accuracy of arrival predictions during ground delay program (GDP) operations
Departure Release Approval Request (APREQ) Adherence Benefit Model	Reduced departure delay due to more accurate departure scheduling of APREQ flights

The SMS and other models are run for a limited number of airports and weather/demand days, and the results are extrapolated to sets of 8, 18, and 52 airports, with the 52-airport case defined as the NAS. Table 2-5 shows the categorization used to extrapolate the airport results. Benefits are expressed as savings per arrival/departure operation or savings per day. Future year benefits are calculated by multiplying the savings per operation by the projected operations in the FAA Terminal Area Forecast (TAF).

Table 2-5. Airport Categories

Size Category	Delay Category	Representative Airport	Number of Airports	Airport List
Small	Low		7	ADW, BDL, DAY, FAI, MSY, OGG, ONT
Large	High	"DFW-like"	4	DFW, ATL, ORD, LAX
Medium/Small	Low	"MEM-like"	26	ABQ, ANC, BNA, BWI, CLE, FLL, HNL, HOU, HPN, IND, MCI, MEM, MCO, MDW, PBI, PDX, RDU, SAT, SAN, SJC, SJU, SLC, TPA, SFB, SNA, TUS
Medium/Small	High	"JFK-like"	3	DCA, JFK, TEB
Medium/Large	Low	"DEN-like"	7	CLT, CVG, DEN, LAS, OAK, PIT, SEA
Medium/Large	High	"PHL-like"	12	BOS, DTW, IAD, IAH, EWR, LGA, MIA, MSP, PHL, PHX, SFO, STL

SMS Model

Baseline (BA) versions of the SMS Model were developed for the Atlanta (ATL), Dallas-Fort Worth (DFW), New York Kennedy (JFK), and Memphis (MEM) airports. Model performance was verified, and model parameters were calibrated using 3 days of data (January 29–31, 2002) from the following data sources:

- Bureau of Transportation Statistics (BTS) Out, Off, On, and In (OOOI) times
- ETMS flight data and departure fixes
- Flight Information Display System (FIDS) gate assignments
- Aviation System Performance Metrics (ASPM) runway configurations.

Verification involved ensuring that the model simulations exhibited the same qualitative and quantitative behavior as the data. Calibration involved adjusting the taxi speed and departure separations in the SMS models to minimize the average off and in errors as compared to the BTS data for all three days.

Data from the Future Flight Central Simulation Facility (FFC) Simulation #2 (DFW) and the Operational Trial at MEM were used to develop the technology parameters needed for SMS model.

Runway Allocation (RA): Simulation #2 results were examined to quantify controller use of Runway 17C at DFW to minimize departure delay as a function of baseline and SMS technologies. Under baseline conditions, controllers used the runway 75 percent of the time they used it with SMS technology. This value was used to set the runway allocation parameter in the SMS models. The parameter was set to 75 percent for the baseline and 100 percent for the SMS case. Note that no runway allocations were allowed for JFK because the departure runway is not changed.

Efficient Spot (ES): Spot processing time data times for baseline and SMS technologies were determined from Simulation #2. These time distributions were then used in the SMS model to randomly sample spot processing times.

Pushback Scheduling (PS): The goal of pushback scheduling is to absorb the maximum amount of departure delay at the gate to minimize fuel costs. Pushback savings are limited by the need to have aircraft available when departure slots occur. Also, arriving aircraft need the gates. The SMS models calculate the potential pushback savings subject to requirements for departure aircraft and arrival gates.

Benefit Extrapolation: The SMS model benefits are calculated separately for all the runway configurations used more than 5 percent of the time at each of the four airports. The total benefit is then calculated by adding the benefits for each configuration weighted by their frequency of use. The benefits for the three

calibration days based on their actual recorded configurations are also calculated. The results from the weighted calculations and three-day calculations are averaged to determine the airport benefit for the analysis.

Tables 2-6 through 2-9 show the results for DFW, MEM, ATL, and JFK respectively.

Table 2-6. DFW Overall Delay Savings

DFW	SMS benefit models		
	ALL Cfgs.	Jan 29–31	AVG
ES benefit (sec)	–13.64	7.71	–2.97
RA benefit (sec)	–20.12	–20.85	–20.48
PS benefit	$5,884	$10,771	$8,327

Table 2-7. MEM Overall Delay Savings

MEM	SMS benefit models		
	ALL Cfgs.	Jan 29–31	AVG
ES benefit (sec)	–0.41	–2.68	–1.54
RA benefit (sec)	–33.44	–41.26	–37.35
PS benefit	$4,333	$2,160	$3,246

Table 2-8. ATL Overall Delay Savings

ATL	SMS benefit models		
	ALL Cfgs.	Jan 29–31	AVG
ES benefit (sec)	–4.37	–3.12	–3.74
RA benefit (sec)	–17.18	–39.17	–28.17
PS benefit	NA	NA	NA

Table 2-9. JFK Overall Delay Savings

JFK	SMS benefit models		
	ALL Cfgs.	Jan 29–31	AVG
ES benefit (sec)	–3.87	–3.44	–3.65
RA benefit (sec)	0.00	0.00	0.00
PS benefit	$1,586	$1,610	$1,598

The results above were used for the benefits at DFW, MEM, ATL, and JFK and were also used to derive benefits for other airports. Table 2-10 shows the delays savings used for extrapolation.

Table 2-10. Delay Savings by Airport Category

	Delay savings per flight (sec)		Fuel cost savings per day
	ES benefit	RA benefit	PS benefit
Large airports	3	24	$8,000
Medium/large airports	3	24	$5,000
Medium/small airports	3	24	$3,000

Airport Resource Management (AT) Benefit Model

This benefit includes delay savings that can be achieved by optimizing airport capacity for demand. In Simulation #2, the operational rules for DFW were changed to allow both arrival/departure jet operations on runway 17C. Differences in delay were measured for the baseline and SMS technologies. The result was a 14 percent reduction in delay.

The DFW results were extrapolated to other airports using specific airport reduction factors to account individual airport environments. SMS models that allowed configuration optimization were also developed and run, but the results were considered too optimistic for use in the benefit analysis. Table 2-11 shows the AT benefits calculated for DFW, MEM, ATL, and JFK. Benefits are only available for airports that have at least three runways and have configurations that allow the number of arrival and departure runways to vary. Atlanta and New York Kennedy do not meet these criteria.

(Note that the Memphis benefit is 18 seconds per flight. The Raytheon report later uses 21 seconds per flight for Memphis without explanation for the change.)

Table 2-11. Arrival/Departure Resource Management (AT) Model Results

Airport	2001 Taxi-Out Delay (Min)	Potential AT Delay Reduction (Sec)	Reduction Factor	AT Benefit	AT Benefit (Sec/Flight)
DFW	6.79	57	0.50	NO	0
MEM	3.55	30	0.60	YES	18
ATL	5.26	44	0.40	NO	0
JFK	5.47	46	0.20	YES	9

Flight Prioritization Benefits Model

Flight prioritization involves swapping departure slots among aircraft in order to avoid the most costly delays. Table 2-12 shows the cost versus delay "buckets" used in the report.

Table 2-12. Delay Buckets

Bucket	Minutes of delay	Operational considerations
1	0–14	DOT on-time performance
2	15–20	Baggage misconnection
3	21–40	Passenger misconnection
4	41–50	Crew misconnection or legality issues
5	51–60	Down-line equipment shortage
6	61–90	Aircraft maintenance issues
7	>90	Cancellation

Note: DOT = Department of Transportation.

Flight prioritization benefits are calculated using an analysis of historical BTS OOOI data (March through April 2001) for 13 airports.[1] The model tracks the arrival and departure delays and identifies cases where switching slots would reduce the delay bucket for one flight while not affecting the other. Analyses were performed for both inter-carrier and intra-carrier trades. Table 2-13 shows the results for the inter-carrier swaps, and Table 2-14 shows the results for the intra-carrier swaps.

Table 2-13. Inter-Carrier Flight Prioritization Results

	DFW	ATL	LAX	ORD	MEM	CLE	DCA	JFK	PIT	DEN	LGA	BOS	PHL
Flights/Day	900.95	713.42	656.00	957.88	161.78	161.66	266.97	180.89	302.98	381.69	353.13	383.31	346.65
Swaps/Day	123.85	94.23	59.52	108.57	8.72	6.51	15.86	13.04	16.65	19.25	45.28	31.67	43.02
Mins/Swap	4.59	4.74	5.07	5.07	4.94	7.12	6.43	7.20	5.53	5.26	7.07	6.03	5.97
Flights/Swap	7.23	7.57	11.02	8.82	18.56	24.83	16.83	13.88	18.20	19.82	7.80	12.10	8.06
On-Time Perf (%)	66.94	64.15	69.29	64.52	78.84	81.72	77.53	61.47	78.30	72.51	49.56	62.41	57.45
Increase Perf (%)	7.12	6.56	4.33	4.62	2.74	2.00	2.91	3.16	2.92	2.32	4.96	3.28	5.20
B2-B1 Swaps	62.42	45.08	27.04	42.71	4.32	2.74	7.37	4.88	8.26	8.34	15.43	11.49	16.57
	Large				MS/Low		MS/High		ML/Low		ML/High		

Table 2-14. Intra-Carrier Flight Prioritization Results

	DFW	ATL	LAX	ORD	MEM	CLE	DCA	JFK	PIT	DEN	LGA	BOS	PHL
Swaps/Day	103.25	81.06	27.29	80.40	7.78	2.83	5.44	6.05	13.86	13.03	20.91	12.72	30.82
Increase Perf (%)	6.15	5.70	2.21	3.58	2.51	0.86	1.08	1.48	2.50	1.58	2.40	1.34	3.73
B2-B1 Swaps	53.19	39.38	12.82	31.81	3.92	1.40	2.65	2.18	7.09	5.68	6.02	4.31	11.63
Diff Swaps	-20.59	-13.17	-32.23	-28.17	-0.93	-4.15	-10.42	-6.98	-2.79	-6.22	-24.37	-18.95	-12.20
Diff On-Time (%)	-0.98	-0.86	-2.12	-1.04	-0.23	-1.14	-1.83	-1.68	-0.42	-0.73	-2.56	-1.94	-1.47
	Large				MS/Low		MS/High		ML/Low		ML/High		

The results for 13 airports were extrapolated to determine NAS-wide results based on the airport categories discussed above. Tables 2-15 and 2-16 show the extrapolated results.

[1] DFW, ATL, LAX, ORD, MEM, CLE, DCA, JFK, PIT, DEN, LGA, BOS, PHL.

Table 2-15. NAS-Wide Inter-Carrier Flight Prioritization Benefits

Airport	Swaps per day	Number airports per category	Swaps per category	B2 - B1 Swaps	Annual swaps
8 SMS Sites	514	8	514	224	187,610
18 SMS Sites	888	18	888	361	324,120
Med/small/low	8	26	208	91	75,920
Med/small/high	14	3	42	18	15,330
Med/large/low	18	7	126	58	45,990
Med/large/high	40	12	480	174	175,200
Large	97	4	388	177	141,620
NAS-Wide		52	1,244	518	454,060

Table 2-16. NAS-Wide Intra-Carrier Flight Prioritization Benefits

Airport	Swaps per day	Number airports per category	Swaps per category	B2 - B1 Swaps	Annual swaps
8 SMS Sites	362	8	362	161	132,130
18 SMS Sites	561	18	561	226	204,765
Med/small/low	5	26	130	68	47,450
Med/small/high	6	3	18	7	6,570
Med/large/low	14	7	98	45	35,770
Med/large/high	22	12	264	88	96,360
Large	73	4	292	137	106,580
NAS-Wide		52	802	345	292,730

Departure Predictions Benefit Model

Improved departure predictions can potentially reduce en route delay caused by en route miles-in-trail restrictions. Three days of data for five airports (MEM, ATL, JFK, DTW, and DFW) were analyzed to compare the departure time prediction accuracy of ETMS versus SMS. The SMS improved departure predictions by 20 percent.

For benefit analysis, miles-in-trail restrictions are calculated based on both ETMS and SMS predictions, and these are used in an en route NAS model to calculate the delay due to miles-in-trail restrictions at center boundaries. The benefit is based on the difference in delays. Model results for September 10, 2001, show 138,426 minutes of delay for ETMS and 136,458 minutes of delay for SMS. The savings of 1,968 minutes, divided by 34,458 flights, results in 3.4 seconds of delay reduction per flight.

Expected Departure Clearance Time (EDCT) Benefits Model

The EDCT benefit model is used to estimate reductions in delay due to improved compliance with ground delay program (GDP) schedules. SMS is assumed to provide improved compliance with controlled departure times (CDTs). A hypothesized arrival time is calculated by adding the actual time en route to the CDT to find a hypothetical actual time of arrival (HARTA). Delay reductions are estimated by calculating the difference between the actual time of arrival and the HARTA. The analysis used 3 months of Aggregate Demand Lists (ADLs) for March, May, and August 2001. Results were estimated for SMS deployed at 26 and 52 airports, with savings of 2 and 3 seconds per flight, respectively. The analysis assumes that improvements in departure time compliance result in corresponding improvements in arrival time compliance.

Analysis of historical data from March, May, and August of 2001 and 2003 indicates that such correlation does not exist. Additional analysis was conducted to determine the relative impact of estimated time en route (ETE) error. It turns out that the ETE error is on the order of minutes and is widely dispersed, totally swamping any benefits from improved departure time predictions. The report concludes that no quantifiable savings can be claimed for this SMS departure benefit mechanism.

Departure Release Approval Request (APREQ) Benefits Model

The APREQ benefit model is used to estimate the reduction in delay possible when SMS is used to coordinate approved departure times between the ARTCC TMU and the ATC Tower.[2] The APREQ benefit estimate is based on the ability of SMS to provide perfect compliance with APREQ release times.

Data from the MEM operational trial were used to estimate the benefit. The average delay between the start of the APREQ window and the SMS predicted off time for the 44 accepted APREQ flights handled by SMS at MEM was 2.1 minutes. This is identified as the “maximum potential” benefit per APREQ flight, as opposed to an expected benefit. Based on demand data from the TAF and the number of APREQ flights during the operational trial, it was determined that 5 percent of the MEM departures are APREQ flights. Based on TAF estimates of 30,137 MEM departures in 2004, the report predicts $170,000 delay savings per day for MEM and $62 million per year.

[2] APREQ departure times are set for departures headed to congested airports or sectors. ARTCC traffic management coordinators assign the departure times such that aircraft will fill planned “slots” in the en route and arrival streams.

The report emphasizes that these benefits are the maximum possible. It also notes that that the SMS OFF time prediction errors corresponding to the APREQ requests had a standard deviation of 4.6 minutes and that a reduction factor (unspecified) should be applied to the benefits.

RESULTS, FINDINGS, AND CONCLUSIONS

Single-Year Arrival/Departure Benefit Results

The report includes single-year (2004) benefit estimates for the 8-,18-, and 52-airport (NAS-Wide) deployments. Dollar values of the benefits are based on a value of $53.15 per minute. The demands used in the estimate are from the 2004 TAF. The report explicitly notes the following "assumptions and limitations":

1. For many benefit mechanisms, the SMS model itself was used to conduct the necessary modeling to assess benefits. The SMS model was calibrated before use for this assessment. There is no indication of bias in prediction of benefits in the SMS model after calibration (i.e., we do not feel the use of the SMS model led to significant over-estimation or underestimation of benefits).

2. For the ES benefit mechanism, our use of data collected from FFC Simulation #2 assumes that this data is representative of the 'real' use that will be made of SMS after it is deployed. There is no reason to doubt this assumption and there is no indication of bias in prediction of benefits due to this assumption.

3. For the RA benefit mechanism, results of FFC Simulation #2 were again used to set parameters for the use of alternate runways. We expect that the ability to use alternate runways will vary significantly by airport, but there is no indication that our use of DFW simulation results causes any bias in the prediction of benefits. Note that the analysis approach used for this study maintains the RA and AT benefit mechanisms as separate and independent benefits. The AT SMS capability allows airport configurations to be changed while strictly obeying the departure scenario runway assignment rules, whereas the RA SMS capability allows optimized runway assignments that do not follow the departure scenario runway assignment rules. In analyzing the results of FFC Simulation #2, parameters have been used to separate out these two factors as accurately as possible.

4. The AT benefit mechanism analysis used results of FFC Simulation #2 as well. In FFC Simulation #2, all traffic scenarios included only heavy rush periods. As a result, the AT capability of SMS was able to have maximum effect. In real operations, AT benefits may be lower than estimated in this study (i.e., the results in this study may be over-estimated), especially at airports that have significant operations outside of heavy rush periods.

5. The extrapolation of SMS benefits results to the NAS from the four detailed airports used the airport categorization approach. Extrapolation values for each type of airport and each benefit mechanism were used. For the ES and RA benefit mechanism, an average number of seconds of delay savings per flight was used to extrapolate. However, extrapolation using this approach may not be properly adjusted to the nominal delay levels at each airport. True SMS benefits may be more or less than the extrapolated values, dependent on the nominal level of delay at each airport as compared to the nominal delay levels of the modeled airports. However, overall there is no indication of bias in assessment of benefits through this approach.

6. The DP and AT benefits assessment were conducted at a less detailed level than the RA, ES and PS benefit mechanisms. The DP benefit mechanism, in particular, should be viewed as a 'maximum potential' benefit for the DP mechanism, as opposed to an estimate of the expected benefit.

7. The Flight Prioritization Benefits model estimated the upper bound of the benefits achievable through the Research SMS capabilities that address prioritization.

8. Only a subset of the overall SMS benefit mechanisms have been assessed in this study. Although these SMS benefit mechanisms are expected to be the most beneficial elements of SMS when considered NAS-wide, there are some airports at which the analyzed benefit mechanisms do not apply, but benefit mechanisms that we have not analyzed may apply. We believe that with the exception of the DP benefit mechanism, the potential SMS benefits are underestimated in this assessment in general, and may be significantly underestimated at some airports.

Table 2-17 shows the Departure Prediction (DP) benefits for one year.

Table 2-17. Single Year Departure Prediction (DP) Benefits

Year	52 airports 2004 departures	DP savings seconds/flight	DP annual benefit (minutes)	DP annual savings
2004	9,951,391	3.4	563,912	$31,782,089

Tables 2-18, 2-19, 2-20, and 2-21 show the airport-specific and summed benefits for Arrival/Departure Trade-Off (AT), Efficient Spot (ES), Runway Allocation (RA), and Pushback Scheduling, respectively.

Table 2-18. Single-Year Arrival/Departure Trade-Off (AT) Benefits

Airport	Airport category	AT benefit	Avg benefit per flight (sec)	2004 departures	Annual benefit (min)	Savings (2004 dollars)
MEM	MS/Low	YES	21	208,358	72,925	$4,110,070
DFW	Large	NO	0	411,491	0	$0
DTW	ML/High	YES	15	256,047	64,012	$3,607,702
ORD	Large	YES	17	519,964	147,323	$8,303,132
ATL	Large	NO	0	485,762	0	$0
LAX	Large	NO	0	321,568	0	$0
EWR	ML/High	YES	20	219,849	73,283	$4,130,230
BOS	ML/High	YES	14	194,917	45,481	$2,563,288
8 SMS Sites					**403,024**	**$22,714,422**
STL	ML/High	YES	26	156,400	67,773	$3,819,705
IAH	ML/High	YES	25	249,742	104,059	$5,864,775
IAD	ML/High	YES	8	190,000	25,333	$1,427,787
MIA	ML/High	YES	20	215,819	71,940	$4,054,520
MSP	ML/High	YES	37	269,030	165,902	$9,350,227
PHX	ML/High	YES	22	296,019	108,540	$6,117,331
PHL	ML/High	NO	0	232,941	0	$0
SFO	ML/High	NO	0	178,821	0	$0
LGA	ML/High	NO	0	195,013	0	$0
JFK	MS/High	YES	9	152,284	22,843	$1,287,409
18 Sites					**969,414**	**$54,636,176**
ABQ	MS/Low	NO	0	117,235	0	$0
ANC	MS/Low	NO	0	152,574	0	$0
BNA	MS/Low	YES	8	116,447	15,526	$875,060
BWI	MS/Low	YES	7	151,479	17,673	$996,025
CLE	MS/Low	NO	0	132,506	0	$0
CLT	ML/Low	YES	16	231,615	61,764	$3,481,019
CVG	ML/Low	YES	8	264,466	35,262	$1,987,374
DCA	MS/High	NO	0	130,917	0	$0
DEN	ML/Low	YES	18	281,848	84,554	$4,765,486
FLL	MS/Low	NO	0	149,609	0	$0
HNL	MS/Low	YES	22	156,379	57,339	$3,231,624
HOU	MS/Low	NO	0	124,704	0	$0
HPN	MS/Low	NO	0	94,672	0	$0
IND	MS/Low	NO	0	104,184	0	$0
LAS	ML/Low	YES	17	271,318	76,873	$4,332,587
MCI	MS/Low	YES	10	88,892	14,815	$834,992
MCO	MS/Low	YES	11	156,037	28,607	$1,612,278
MDW	MS/Low	NO	0	163,164	0	$0
PBI	MS/Low	NO	0	100,015	0	$0
PDX	MS/Low	NO	0	140,133	0	$0

Table 2-18. Single-Year Arrival/Departure Trade-Off (AT) Benefits (Continued)

Airport	Airport category	AT benefit	Avg benefit per flight (sec)	2004 departures	Annual benefit (min)	Savings (2004 dollars)
PIT	ML/Low	YES	10	183,334	30,556	$1,722,117
RDU	MS/Low	NO	0	114,547	0	$0
SAT	MS/Low	NO	0	127,684	0	$0
SAN	MS/Low	NO	0	107,120	0	$0
SEA	ML/Low	NO	0	182,410	0	$0
SJC	MS/Low	NO	0	115,850	0	$0
SJU	MS/Low	NO	0	102,457	0	$0
SLC	MS/Low	YES	21	211,468	74,014	$4,171,418
TEB	MS/High	NO	0	110,112	0	$0
TPA	MS/Low	NO	0	120,284	0	$0
OAK	ML/Low	NO	0	183,946	0	$0
SFB	MS/Low	NO	0	191,923	0	$0
SNA	MS/Low	NO	0	185,811	0	$0
TUS	MS/Low	NO	0	132,241	0	$0
NAS-Wide					**1,466,397**	**$82,646,157**

Table 2-19. Single-Year Efficient Spot (ES) Benefits

Airport	Airport category	ES benefit	Avg benefit per flight (sec)	2004 departures	Annual benefit (min)	Savings (2004 dollars)
MEM	MS/Low	YES	2	208,358	6,945	$391,435
DFW	Large	YES	3	411,491	20,575	$1,159,582
DTW	ML/High	YES	3	256,047	12,802	$721,540
ORD	Large	YES	3	519,964	25,998	$1,465,259
ATL	Large	YES	4	485,762	32,384	$1,825,170
LAX	Large	YES	3	321,568	16,078	$906,179
EWR	ML/High	YES	3	219,849	10,992	$619,534
BOS	ML/High	YES	3	194,917	9,746	$549,276
8 SMS Sites					**135,521**	**$7,637,975**
STL	ML/High	YES	3	156,400	7,820	$440,735
IAH	ML/High	YES	3	249,742	12,487	$703,773
IAD	ML/High	YES	3	190,000	9,500	$535,420
MIA	ML/High	YES	3	215,819	10,791	$608,178
MSP	ML/High	YES	3	269,030	13,452	$758,127
PHX	ML/High	YES	3	296,019	14,801	$834,182
PHL	ML/High	YES	3	232,941	11,647	$656,428
SFO	ML/High	YES	3	178,821	8,941	$503,918
LGA	ML/High	YES	3	195,013	9,751	$549,547
JFK	MS/High	YES	4	152,284	10,152	$572,182
18 Sites					**244,863**	**$13,800,463**

Table 2-19. Single-Year Efficient Spot (ES) Benefits (Continued)

Airport	Airport category	ES benefit	Avg benefit per flight (sec)	2004 departures	Annual benefit (min)	Savings (2004 dollars)
ABQ	MS/Low	YES	3	117,235	5,862	$330,368
ANC	MS/Low	YES	3	152,574	7,629	$429,954
BNA	MS/Low	YES	3	116,447	5,822	$328,148
BWI	MS/Low	YES	3	151,479	7,574	$426,868
CLE	MS/Low	YES	3	132,506	6,625	$373,402
CLT	ML/Low	YES	3	231,615	11,581	$652,691
CVG	ML/Low	YES	3	264,466	13,223	$745,265
DCA	MS/High	YES	3	130,917	6,546	$368,924
DEN	ML/Low	YES	3	281,848	14,092	$794,248
FLL	MS/Low	YES	3	149,609	7,480	$421,598
HNL	MS/Low	YES	3	156,379	7,819	$440,676
HOU	MS/Low	YES	3	124,704	6,235	$351,416
HPN	MS/Low	YES	3	94,672	4,734	$266,786
IND	MS/Low	YES	3	104,184	5,209	$293,591
LAS	ML/Low	YES	3	271,318	13,566	$764,574
MCI	MS/Low	YES	3	88,892	4,445	$250,498
MCO	MS/Low	YES	3	156,037	7,802	$439,712
MDW	MS/Low	YES	3	163,164	8,158	$459,796
PBI	MS/Low	YES	3	100,015	5,001	$281,842
PDX	MS/Low	YES	3	140,133	7,007	$394,895
PIT	ML/Low	YES	3	183,334	9,167	$516,635
RDU	MS/Low	YES	3	114,547	5,727	$322,793
SAT	MS/Low	YES	3	127,684	6,384	$359,814
SAN	MS/Low	YES	3	107,120	5,356	$301,864
SEA	ML/Low	YES	3	182,410	9,121	$514,031
SJC	MS/Low	YES	3	115,850	5,793	$326,465
SJU	MS/Low	YES	3	102,457	5,123	$288,724
SLC	MS/Low	YES	3	211,468	10,573	$595,917
TEB	MS/High	YES	3	110,112	5,506	$310,296
TPA	MS/Low	YES	3	120,284	6,014	$338,960
OAK	ML/Low	YES	3	183,946	9,197	$518,360
SFB	MS/Low	YES	3	191,923	9,596	$540,839
SNA	MS/Low	YES	3	185,811	9,291	$523,615
TUS	MS/Low	YES	3	132,241	6,612	$372,655
NAS-Wide					**504,732**	**$28,446,682**

Table 2-20. Single-Year Runway Allocation (RA) Benefits

Airport	Airport category	RA benefit	Avg benefit per flight (sec)	2004 departures	Annual benefit (min)	Savings (2004 dollars)
MEM	MS/Low	YES	37	208,358	128,487	$7,241,552
DFW	Large	YES	20	411,491	137,164	$7,730,544
DTW	ML/High	YES	24	256,047	102,419	$5,772,324
ORD	Large	YES	24	519,964	207,986	$11,722,068
ATL	Large	YES	28	485,762	226,689	$12,776,188
LAX	Large	YES	24	321,568	128,627	$7,249,429
EWR	ML/High	YES	24	219,849	87,940	$4,956,276
BOS	ML/High	YES	24	194,917	77,967	$4,394,209
8 SMS Sites					**1,097,278**	**$61,842,590**
STL	ML/High	YES	24	156,400	62,560	$3,525,882
IAH	ML/High	YES	24	249,742	99,897	$5,630,184
IAD	ML/High	YES	24	190,000	76,000	$4,283,360
MIA	ML/High	YES	24	215,819	86,328	$4,865,424
MSP	ML/High	YES	24	269,030	107,612	$6,065,012
PHX	ML/High	YES	24	296,019	118,408	$6,673,452
PHL	ML/High	NO	0	232,941	0	$0
SFO	ML/High	Minimal	0	178,821	0	$0
LGA	ML/High	NO	0	195,013	0	$0
JFK	MS/High	Minimal	0	152,284	0	$0
18 Sites					**1,648,082**	**$92,885,903**
ABQ	MS/Low	NO	0	117,235	0	$0
ANC	MS/Low	NO	0	152,574	0	$0
BNA	MS/Low	YES	24	116,447	46,579	$2,625,181
BWI	MS/Low	YES	24	151,479	60,592	$3,414,943
CLE	MS/Low	YES	24	132,506	53,002	$2,987,215
CLT	ML/Low	YES	24	231,615	92,646	$5,221,529
CVG	ML/Low	YES	24	264,466	105,786	$5,962,122
DCA	MS/High	NO	0	130,917	0	$0
DEN	ML/Low	YES	24	281,848	112,739	$6,353,981
FLL	MS/Low	NO	0	149,609	0	$0
HNL	MS/Low	YES	24	156,379	62,552	$3,525,408
HOU	MS/Low	YES	24	124,704	49,882	$2,811,327
HPN	MS/Low	NO	0	94,672	0	$0
IND	MS/Low	YES	24	104,184	41,674	$2,348,724
LAS	ML/Low	YES	24	271,318	108,527	$6,116,593
MCI	MS/Low	YES	24	88,892	35,557	$2,003,981
MCO	MS/Low	YES	24	156,037	62,415	$3,517,698
MDW	MS/Low	YES	24	163,164	65,266	$3,678,369
PBI	MS/Low	NO	0	100,015	0	$0
PDX	MS/Low	YES	24	140,133	56,053	$3,159,158

Table 2-20. Single-Year Runway Allocation (RA) Benefits (Continued)

Airport	Airport category	RA benefit	Avg benefit per flight (sec)	2004 departures	Annual benefit (min)	Savings (2004 dollars)
PIT	ML/Low	YES	24	183,334	73,334	$4,133,082
RDU	MS/Low	YES	24	114,547	45,819	$2,582,348
SAT	MS/Low	NO	0	127,684	0	$0
SAN	MS/Low	NO	0	107,120	0	$0
SEA	ML/Low	YES	24	182,410	72,964	$4,112,251
SJC	MS/Low	YES	24	115,850	46,340	$2,611,722
SJU	MS/Low	YES	24	102,457	40,983	$2,309,791
SLC	MS/Low	YES	24	211,468	84,587	$4,767,335
TEB	MS/High	NO	0	110,112	0	$0
TPA	MS/Low	YES	24	120,284	48,114	$2,711,682
OAK	ML/Low	NO	0	183,946	0	$0
SFB	MS/Low	NO	0	191,923	0	$0
SNA	MS/Low	NO	0	185,811	0	$0
TUS	MS/Low	YES	24	132,241	52,896	$2,981,241
NAS-Wide					**3,066,387**	**$172,821,584**

Table 2-21. Single-Year Pushback Scheduling (PS) Benefits

Airport	Airport category	PS benefit per day	Savings (2004 dollars)
MEM	MS/Low	$3,492	$1,274,580
DFW	Large	$8,958	$3,269,670
DTW	ML/High	$5,000	$1,825,000
ORD	Large	$8,000	$2,920,000
ATL	Large	$8,000	$2,920,000
LAX	Large	$8,000	$2,920,000
EWR	ML/High	$5,000	$1,825,000
BOS	ML/High	$5,000	$1,825,000
8 SMS Sites		**51,450**	**$18,779,250**
STL	ML/High	$5,000	$1,825,000
IAH	ML/High	$5,000	$1,825,000
IAD	ML/High	$5,000	$1,825,000
MIA	ML/High	$5,000	$1,825,000
MSP	ML/High	$5,000	$1,825,000
PHX	ML/High	$5,000	$1,825,000
PHL	ML/High	$5,000	$1,825,000

Table 2-22. Single-Year Pushback Scheduling (PS) Benefits (Continued)

Airport	Airport category	PS benefit per day	Savings (2004 dollars)
SFO	ML/High	$5,000	$1,825,000
LGA	ML/High	$5,000	$1,825,000
JFK	MS/High	$1,719	$627,435
18 Sites		**$98,169**	**$35,831,685**
ABQ	MS/Low	$3,000	$1,095,000
ANC	MS/Low	$3,000	$1,095,000
BNA	MS/Low	$3,000	$1,095,000
BWI	MS/Low	$3,000	$1,095,000
CLE	MS/Low	$3,000	$1,095,000
CLT	ML/Low	$5,000	$1,825,000
CVG	ML/Low	$5,000	$1,825,000
DCA	MS/High	$3,000	$1,095,000
DEN	ML/Low	$5,000	$1,825,000
FLL	MS/Low	$3,000	$1,095,000
HNL	MS/Low	$3,000	$1,095,000
HOU	MS/Low	$3,000	$1,095,000
HPN	MS/Low	$3,000	$1,095,000
IND	MS/Low	$3,000	$1,095,000
LAS	ML/Low	$5,000	$1,825,000
MCI	MS/Low	$3,000	$1,095,000
MCO	MS/Low	$3,000	$1,095,000
MDW	MS/Low	$3,000	$1,095,000
PBI	MS/Low	$3,000	$1,095,000
PDX	MS/Low	$3,000	$1,095,000
PIT	ML/Low	$5,000	$1,825,000
RDU	MS/Low	$3,000	$1,095,000
SAT	MS/Low	$3,000	$1,095,000
SAN	MS/Low	$3,000	$1,095,000
SEA	ML/Low	$5,000	$1,825,000
SJC	MS/Low	$3,000	$1,095,000
SJU	MS/Low	$3,000	$1,095,000
SLC	MS/Low	$3,000	$1,095,000
TEB	MS/High	$3,000	$1,095,000
TPA	MS/Low	$3,000	$1,095,000
OAK	ML/Low	$5,000	$1,825,000

Table 2-23. Single-Year Pushback Scheduling (PS) Benefits (Continued)

Airport	Airport category	PS benefit per day	Savings (2004 dollars)
SFB	MS/Low	$3,000	$1,095,000
SNA	MS/Low	$3,000	$1,095,000
TUS	MS/Low	$3,000	$1,095,000
NAS-Wide		**$214,169**	**$78,171,685**

Single-Year Benefits Summary

Tables 2-22 and 2-23 summarize the NAS-Wide (52 airport) single-year benefits. Table 2-24 contains the performance metrics, and Table 2-25 contains the dollar values of the benefits for the Build 1 technologies.

Table 2-24. Single-Year SMS Benefits Summary by Performance Metric (2004 Dollars)

Benefit Model	SMS Build	Performance Metric	8 Sites	18 Sites	NAS-Wide
Departure Prediction	Build 1 TFM	Delay Min Saved			535,006
Arrival/Departure Tradeoff	Build TM	Delay Min Saved	391,758	1,020,683	1,519,867
Efficient Spot	Build 1 CT	Delay Min Saved	139,430	262,254	542,499
Runway Allocation	Build 1 CT	Delay Min Saved	1,122,319	1,749,036	3,270,137
Pushback Scheduling	Research SMS	Fuel Cost Savings	$18,779,205	$35,831,617	$78,171,617
Flight Prioritization	Research SMS	% Imp On-Time Perf	0.77%	1.20%	1.80%
Flight Prioritization	Research SMS	Delay Bucket Savings	187,610 Swaps/Yr	324,120 Swaps/Yr	454,060 Swaps/Yr

Table 2-25. Build 1 Single-Year Economic Benefits Summary (2004 Dollars)

Benefit Model	SMS Build	Build 1 SMS Cost Savings		
		8 Sites	18 Sites	NAS-Wide
Departure Predictions	Build 1 TFM			$31,782,089
Arrival/Departure Tradeoff	Build 1 TM	$22,714,388	$54,636,102	$82,646,038
Efficient Spot	Build 1 CT	$7,637,966	$13,800,447	$28,446,640
Runway Allocation	Build 1 CT	$61,842,516	$92,885,796	$172,821,353
Total - Build 1		$92,194,871	$161,322,345	$315,696,120

Life-Cycle Benefit/Cost Analysis

The report concludes with a life-cycle benefit/cost estimate for three versions of Build 1 SMS. The first version, Build 1 TFM, provides NAS-wide benefits of 3.4 seconds per flight for 26 airports in 2006 and 52 airports for 2007 through 2027. The second and third versions, Build 1 Traffic Management (TM) and Build 1 Controller Tools (CT), include airport-specific benefits. TM and CT benefits are estimated for 8- and 18-airport deployments for the years 2007 through 2027. Life-cycle costs are estimated for each deployment. Net present values are

calculated using a base year of 2004 and a discount rate of 7 percent. The results are shown in Table 2-26.

Table 2-26. Summary of Economic Metrics for SMS Build 1 Deployment Scenarios

	Build 1 TFM	Build 1 TM 8 sites	Build 1 TM 18 sites	Build 1 CT 8 sites	Build 1 CT 18 sites
Total disc life-cycle benefit	$363,701,857	$628,748,458	$957,068,373	$1,371,981,896	$2,056,187,917
Total disc life-cycle cost	$58,784,394	$99,141,446	$128,831,900	$122,728,059	$158,166,797
Breakeven year	2008	2008	2008	2008	2008
NPV	$284,969,592	$440,173,994	$774,052,778	$1,167,526,951	$1,773,851,514
B/C ratio	6.19	6.34	7.43	11.18	13.00

Chapter 3
Direct-To (D2)—Summary of Single-Year NAS-Wide Benefits and Life-Cycle Cost/Benefit Assessments

INTRODUCTION

The mission of the air traffic controller is to ensure the safe and efficient operation of today's air traffic system, and to prepare to meet the challenges of tomorrow. These new challenges include increases in system safety, capacity, and productivity.

There is presently very little automation support for air traffic controllers under the current Air Traffic Management System. With increasing traffic congestion and the demand for improved efficiency and capacity in the NAS, air traffic controllers need more automation or decision support tools (DSTs) to make their job easier.

Direct-To (D2) is a DST for en route radar controllers that helps improve airspace efficiency, simplifies the analysis and input of route and altitude changes, and facilitates flying-time savings for airspace users. It is based on the Center-TRACON Automation System (CTAS) trajectory analysis methodology and software. D2 was developed under NASA's Advanced Air Transportation Technologies (AATT) Project.

D2 continuously analyzes all aircraft for potential traffic conflicts and for direct routing opportunities. Conflict advisories and direct routing advisories are provided with minimal additional impact to the controller's display; information is added to the Flight Data Block (FDB) and can be accessed through optional lists. Track-ball clicks are used to display a graphical depiction of potential conflict geometry, activate a trial-planning function, or activate an altitude probe.

A highly automated trial planning function allows controllers to quickly visualize, evaluate, and input route and altitude amendments. The trial-planning function graphically displays the route with an analysis of potential traffic conflicts, special use airspace, preferential routes, and flying time. The controller can then use the trial planner to modify the route easily by a point-and-click action and select either a different fix or add an auxiliary waypoint, and then input the flight plan amendment to the Host computer. The altitude probe computes and displays the conflict status for all relevant transitioning (climb or descent) and level trajectories.

This summary presents the findings from both the single-year NAS-wide benefits assessment and the life-cycle cost/benefit assessment (LCCBA) of D2. The findings from the two reports are presented together, with the single-year details preceding those from the full LCCBA.

The benefit mechanisms and potential benefits for D2 were identified from operational tests, field evaluations, and controller-in-the-loop simulation evaluations. The potential benefits of D2 include:

- Reduced number of operational errors
- Reduced ATC workload
- Time/fuel/operating cost savings.

This summary of the single-year assessment is primarily based upon the analysis by the Computer Sciences Corporation (CSC), Federal Sector–Civil Group. The full citation is:

> *Benefits of the Direct-To Controller Tool, Release 5.1,* Computer Sciences Corporation. Contract NAS2-00014, July 23, 2004.

The LCCBA considered two deployment scenarios for D2: a base case DST economic service life (ESL) of 20 years; and an alternative, shorter case with an ESL of 10 years. These deployment scenarios are otherwise identical, and consider D2 life-cycle costs and benefits for incorporating the capabilities of D2 into the FAA's CTAS system NAS-wide. Life-cycle benefits were based upon the prior work by CSC. Life-cycle costs included hardware, software, and other cost drivers such as in-service support, and FAA program management. Using an LCCBA model, three key economic metrics were assessed (net present value, benefit-to-cost ratio, and breakeven point).

This summary of the life-cycle cost/benefit assessment is primarily based upon the analysis by ASRC Aerospace Corporation (ASRC). The full citation is:

> *Life-Cycle Cost Benefit Assessment of Direct-To (D2) [Draft],* Jianzhong Jay Wang, ASRC Aerospace Corporation. Contract NAS2-03145, task order 480021, September 10, 2004.

FUNCTIONS, BENEFIT MECHANISMS, AND METRICS

Any future air traffic control system will need to incorporate new automated capabilities and advanced information technologies into existing systems and procedures. A main focus of these new enhancements will be to safely move more aircraft through the aviation system with less delay. A strategy for achieving this objective is to optimize the use of the current infrastructure and equipment. D2 provides air traffic controllers with advances and enhancements from their current suite of equipment.

The cornerstone of the CTAS system of tools functionality is the ability to create four-dimensional trajectories (x position, y position, altitude, time) to predict the future position of aircraft. CTAS, and therefore D2, use the current aircraft state, aircraft performance characteristics, atmospheric conditions such as wind and pressure, planned route of flight, and flight procedures for computing flight trajectories. There are four primary D2 functions.

- *Conflict Probe Alerts*: Currently, air traffic controllers have limited conflict-alerting automation. The Conflict Alert used today is a basic 3-minute look-ahead with dead reckoning trajectories utilizing only constant heading, speed and altitude rates to predict potential conflicts. The D2 conflict probe utilizes both dead reckoning trajectories and real-time, four-dimensional trajectory synthesis predictions. These predictions are based on route analysis, radar track, and flight plan data from the FAA center host computer, atmospheric data from the National Oceanic and Atmospheric Administration (NOAA) Rapid Update Cycle (RUC) forecast model, and aircraft performance models. D2's dead reckoning and trajectory synthesis trajectories are updated in response to each new radar track position (every 12 seconds), flight plan updates (when received), and atmospheric data updates (hourly). D2 automatically analyzes all combinations of its aircraft trajectories for traffic conflicts every 6 seconds. When a conflict is predicted, it is presented to the controller in the FDB as time in minutes to first loss of separation, and in the form of a conflict list view.

- *Route Trial Planning*: The D2 route trial planner is a highly automated controller-driven rapid feedback feature that helps controllers visualize, analyze, and implement routing changes for any aircraft. The trial planner may be used to check the conflict and flying-time status for a direct route and automatically input a flight plan amendment to the center host computer. The route trial planner can help build a conflict resolution vector or a vector to avoid weather, or it may be used to simply visualize current routing. The Trial Planner View allows the controller to select a different D2 fix, shows the status of the fast loop conflict and flying-time analysis, and facilitates the automated flight plan amendment function.

- *Altitude Trial Planning*: The D2 altitude trial planner allows the controller to automatically assess trajectories to multiple altitudes. The controller initiates altitude trial planning by a track ball dwell and click over the altitude field in the flight data block. Upon activation, D2 computes a set of climb or descent trajectories to multiple altitudes depending on the status of the aircraft (level, climb, or descent). Each trajectory is automatically conflict-probed against all other traffic, and the conflict status is displayed on the traffic situation display via a pop-up menu.

- *Wind-Favorable Direct Routing Advisories*: The D2 route advisory automatically computes a wind-route and conflict analysis on all aircraft to identify those that could save at least 1 minute flying-time and fly

conflict-free directly to a downstream fix. Candidate D2 fixes are within a limited region so as not to advise a route that would take an aircraft substantially off of its planned route of flight or put it on a route that would be operationally unacceptable. Route advisories that meet the criteria are then sent to the display of the controller who has operational responsibility for the aircraft. Using the trial planner, the controller may bring up a graphic display of the route, modify it if necessary, select a different D2 fix, and automatically input a direct route amendment to the center host computer. If for any reason the controller is unable to issue a redirection, the controller may disregard the advisory until a later time or delete it from the display.

The four primary D2 functions and their associated benefit mechanisms and metrics are shown in Table 3-1.

Table 3-1. D2 Benefit Mechanisms and Metrics

D2 function	Benefit mechanisms	Metrics
Conflict probe alerts	Increased ATC situational awareness Improved conflict detection	Reduced number of operational errors Reduced ATC workload Time/Fuel/Operating cost savings
Route trial planning	Increased ATC situational awareness Decreased number of maneuvers Automated host flight plan amendments	Reduced number of operational errors Reduced ATC workload Time/fuel/operating cost savings
Altitude trial planning	Increased ATC situational awareness Decreased number of maneuvers Automated host flight plan amendments	Reduced number of operational errors Reduced ATC workload Time/fuel/operating cost savings
Wind-favorable direct routing advisories	Increased ATC situation awareness Decreased number of maneuvers Automated host flight plan amendments Reduced flying distances	Reduced number of operational errors Reduced ATC workload Time/fuel/operating cost savings

MODELING AND ANALYSIS APPROACH

The benefits assessment methodology included data collection, estimating raw D2 time-savings information, statistical analysis to estimate net time savings, extrapolation to other ARTCCs, and the life-cycle cost/benefit assessment.

Data Collection

Data for this study used FAA center host computer NAS radar track and flight plan data collected through CTAS for three en route facilities. The chosen facilities included two where the User Request Evaluation Tool (URET) was already in place. These ARTCCs were Cleveland (ZOB) and Indianapolis (ZID). URET was originally deployed as a prototype system at ZID, and ZOB received URET as part of the FAA's "Core Capability Limited Deployment" production version of URET. The third ARTCC analyzed was Denver (ZDV), which did not have URET at the time of the study.

Three days of data from each facility were collected and used for the study. Each day's radar data began at local midnight and ran for a 24-hour period. The presence of significant weather events was considered in selecting which days to use for this study. Archive weather data from organizations such as the National Weather Service was checked for precipitation, frontal passage, and wind velocities, and days were chosen that had little activity within and around each center to eliminate route changes due to weather. Weather represents a transient phenomenon and wasn't intended to be a focus of this study. However, the D2 field test showed significant flying-time savings from D2 bringing to controllers' attention workable direct routes for aircraft flying obsolete weather avoidance routes.

The CTAS family of tools uses information known as a NAS adaptation to tailor the software for each particular airspace; this approach is based upon the same method that each center host computer uses. A D2 adaptation is partially derived from the corresponding center's NAS adaptation. NAS Chart Change Updates (CCUs) are the 8-week cycle updates to center NAS adaptations; they address, among other data, items such as waypoints, air traffic routes, boundaries, and airport information. A CCU occurred on December 25, 2003, and the D2 adaptation used during the study was current with this CCU.

Rapid Update Cycle (RUC) forecast weather data is used by D2. RUC data provides near-term forecast wind and barometric pressure data versus altitude for a grid resolution of either 20, 40, or 80 kilometers. Weather data for RUC forecasts are collected hourly and then short-term forecasts are created—generally for 1, 2, 3, 6, 9, and 12 hours out. The 2-hour forecasted data with an 80-kilometer grid were used during the study.

Raw D2 Savings

Using the CTAS-collected radar track and flight plan data, the D2 adaptation for each study center, and RUC data, D2 playbacks were performed to collect the raw time-savings information. Potential savings were the result of direct routes—with winds taken into account—that would provide a flying-time savings of at least 1 minute. Flights to major airports within the ARTCC airspace were excluded, since these aircraft must be sequenced into the airport's surrounding TRACON.

D2 time-savings playback results were collected for each of 3 days per each of the three centers, for a total of 9 days of data. Information gathered included cumulative potential time-savings data, number of flights, and various amendment data.

Statistical Analysis

To estimate the net NAS-wide time-savings for the D2 tool, the time savings calculated by the D2 tool were adjusted to compensate for both controller-issued route clearances and D2 list overlap between centers. Information in the data collected for this study was sufficient to measure the percentage of aircraft on D2 lists that were issued route clearances. Statistical information in these data was also sufficient to determine a generalized estimate of the D2 list overlap for the centers in this study.[1]

Since the overall scaling factors vary for the three centers in this study, factors corresponding to each center were used to estimate the net time-savings for the individual centers.[2] Net time-savings for the three centers in this study are presented in Table 3-2.

[1] If the chance for an aircraft on the D2 list to be amended by a controller is independent of D2 list overlap, the net time-savings can be estimated using multiplicative scaling factors for these two parameters. Results from this study indicate that on average, these parameters are indeed independent.

[2] The overall scaling factor indicates that on average, 34.1 percent of the total time-savings from the D2 tool is not affected by controller issued amendments or D2 list overlap. The error analysis for the overall scaling factor indicates that for the Centers in this study, the actual net time-savings for each Center may be 7.6 percent higher or lower than estimates for the net time-savings.

Table 3-2. Net Time Savings for Three Centers

ARTCC examined	Aircraft on D2 list	Total savings in minutes	Total savings in minutes adjusted for overlap and in-center amendments	Net time-savings with error estimate
ZDV 3-Day Average	829	2,196.09	854.28	854 ± 65
ZID 3-Day Average	2,129	4,945.79	1,296.82	1,297 ± 99
ZOB 3-Day Average	1,986	4,403.95	1,642.92	1,643 ± 125
Average	1,648	3,848.48	1,264.72	1,265 ± 96

Extrapolation to Other ARTCCs

No D2 data were available for the other CONUS centers; however, the savings estimates from ZDV, ZID, and ZOB (Table 3-2) were used to extrapolate potential savings at the other facilities.[3] This extrapolation is shown in Table 3-3.

Table 3-3. Extrapolated Results by Center

ARTCC	CY 2003 operations per year	Extrapolated daily time savings (min.)	Extrapolated annual time savings (min.)
ZOB	2,974,999	1,525	556,890
ZTL	2,958,905	1,517	553,895
ZAU	2,852,161	1,462	533,866
ZNY	2,804,662	1,438	525,068
ZID	2,712,992	1,390	507,846
ZDC	2,595,036	1,330	485,758
ZJX	2,274,389	1,165	425,670
ZME	2,227,935	1,142	417,059
ZMA	2,182,498	1,118	408,448
ZFW	2,130,759	1,092	398,902
ZKC	2,052,519	1,052	384,301
ZMP	2,041,234	1,046	382,055
ZLA	2,020,612	1,036	378,311
ZHU	2,004,771	1,028	375,316
ZBW	1,780,341	912	333,198

[3] The estimated net time-savings from the D2 tool were used to calculate a time-savings factor for each Center based on the number of annual operations that these Centers handled. The three Centers studied have a mean time-savings factor of 0.513 minutes saved per day per 1,000 yearly operations and a standard deviation of 0.04 minutes saved per day per 1,000 yearly operations.

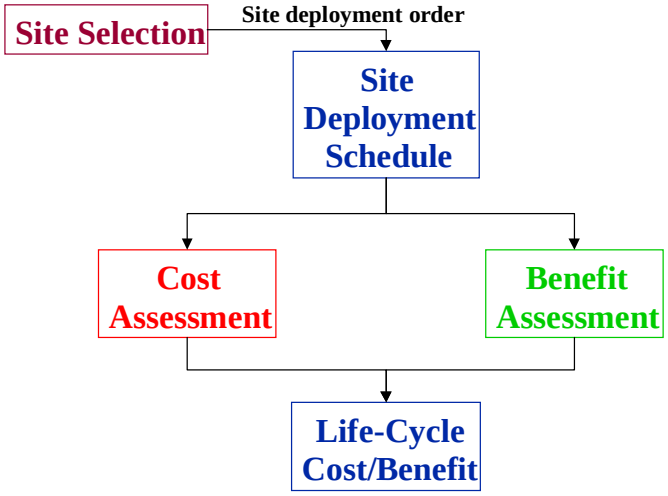
Table 3-3. Extrapolated Results by Center (Continued)

ARTCC	CY 2003 operations per year	Extrapolated daily time savings (min.)	Extrapolated annual time savings (min.)
ZAB	1,700,948	872	318,410
ZDV	1,683,765	863	315,228
ZOA	1,600,522	821	299,691
ZLC	1,460,557	749	273,484
ZSE	1,271,711	652	238,106

Life-Cycle Cost/Benefit Assessment

The methodology employed by ASRC for the D2 LCCBA has been used for several previous life-cycle assessments of AATT DSTs. The methodology (summarized in Figure 3-1) includes site selection analysis, site deployment schedule development, cost and benefit assessment models, and the life-cycle cost/benefit assessment. The site selection analysis provides a prioritized list of deployment sites. A siting schedule is developed using this ordered list and the site deployment scheduling methodology. Given the schedule of deployment at the various sites, DST annual costs and benefits are estimated, and these costs and benefits are then combined in an LCCBA.

Figure 3-1. Overview of Life-Cycle Cost/Benefit Assessment Methodology



The economic service life of D2 was assumed to be 20 years. While this assumption is consistent with published FAA guidelines, the FAA typically uses a 10-year life cycle in its DST investment analyses. Thus, a 10-year ESL case was also analyzed as an alternative deployment scenario. All costs and benefits for the

LCCBA were expressed in 2004 dollars, and a discount rate of 7 percent was used.[4]

D2 was assumed to be deployed at the various CONUS ARTCCs in descending order of potential 2003 economic benefits, as estimated in the prior CSC study.[5] Therefore, ZNY is assumed to have D2 installed beginning in March 2007, while ZSE is assumed to have D2 installed beginning in March 2017. Time between installation and initial daily use (IDU) at a site is assumed to be 1.0 years, and time between IDU and planned capability available (PCA) is assumed to be an additional 0.5 years.

ASRC assumed that—should the FAA decide to deploy D2—it would be integrated with the FAA's CTAS program and deployed NAS-wide. Another assumption is that TMA would be deployed at 17 of the 20 centers prior to D2. Consequently, ASRC used a life-cycle cost model calibrated with historical TMA-SC Free Flight Phase 1 (FFP1) cost data—and validated with more recent TMA-SC cost data from the FAA—to estimate D2 life-cycle costs

Life-cycle benefits were derived from the CSC estimates of the single-year, NAS-wide D2 benefits for 2003 and 2015 demand levels.[6] Recognizing that more traffic will result in fewer direct routes, a linear rather than exponential benefit extrapolation scheme was used to estimate benefits beyond the year 2015.

Three key economic metrics (net present value,[7] benefit-to-cost ratio,[8] and break-even point[9]) were then assessed. In addition, a sensitivity case was examined.

[4] Discounting is a method of evaluating an investment by estimating future cash flows and taking into consideration the time value of money.

[5] With the exception of ZFW, which was assumed to be NASA's demonstration site. Installation at ZFW was assumed to begin in September 2005.

[6] The ASRC work updated the CSC benefits assessment to reflect more current FAA operations data for 2003. Demand was decreased by 0.63 percent and estimated benefits fell by 0.27 percent as a consequence.

[7] Net present value (NPV) is the difference between the discounted present value of benefits and the discounted present value of costs. To be beneficial, an investment should have a NPV greater than zero.

[8] Benefit to cost ratio (B/C ratio) is the ratio of the present value of benefits to the present value of costs. This ratio must be greater than 1 to justify a project.

[9] Break even point (BEP) is the year at which the DST's net present value of realized benefits just equals its net present value of incurred costs. Generally, it is the time required to recoup the initial investment made for acquiring and implementing the alternative technology.

RESULTS, FINDINGS, AND CONCLUSIONS

Controller Benefits

Conflict Probe Alerts: The tactical nature of the D2 conflict probe can benefit controllers by assisting them in identifying potential conflicts earlier, thus reducing operational errors. In a follow-on study, Tactical Separation Assured Flight Environment (TSAFE), the short-term trajectory model has been modified to improve tactical conflict detection performance over a zero- to 3-minute time horizon. Preliminary results utilizing data from 44 actual operational errors show that the conflict warning times given by the TSAFE conflict detection would be considerably greater than those given by the modern day Conflict Alert. In fact, in six of nine cases where Conflict Alert failed to warn the controller at all, the TSAFE conflict detection gave between 30 seconds and 3 minutes warning time, potentially enough time to avert the impending operational error.

Route Trial Planning: During field tests and controller simulation evaluations of D2, controllers were using the route trial planning function successfully while performing other tasks such as radio communications and inter-sector hand-offs. Observations of and controller commentary about the field tests and simulation operations using various traffic scenarios clearly show that D2 could provide substantial benefits to controllers during all levels of traffic density.

Altitude Trial Planning: The altitude trial planner function, as currently implemented, has not been evaluated in a field or simulation environment but has undergone various engineering evaluations that included controller input. All indications are that the Altitude Trial Plan feature will also be a true benefit to the set of controller support tools.

Wind-Favorable Direct Routing Advisories: Field test experience shows that there are usually no more than two or three, and often no, direct route advisories in any given sector at any given time. This, of course, will vary with center geometry and wind conditions. D2 studies also indicate that the controllers may not require a D2 list view but that the time-saving information is very useful when combined with trial planning.

Airspace User Benefits

Direct routing capability also has the potential to deliver several advantages to the airline passenger and air carriers. For the airline passenger, a direct route will most often translate into a shorter flight. For the airlines, a shorter flight means less fuel burn and operating cost savings.

The FAA’s Office of Aviation Policy and Procedures (APO) provides valuable information regarding future traffic forecasts as well as aviation cost data. One

report[10] provides not only cumulative forecasted traffic loads for each center through 2015, but it also breaks those forecasts down by aircraft category. The four aircraft categories are air carrier (AC), air taxi/commuter (AT), general aviation (GA), and military (MIL). This breakdown is important due to the difference in operating cost of each category. AC category aircraft include the large air carriers such as American Airlines, United, Delta, and so on. It also includes large air freight carriers such as FedEx and UPS. AT category aircraft generally include turboprop aircraft that fly the regional routes. GA and MIL aircraft are self-explanatory.

Scaling factors (see footnote 3) were applied to each category of aircraft for each center. After the annual D2 time-savings are known by center and aircraft category, operating cost conversion factors were needed. The FAA provides operating cost information[11] for each of the aircraft categories (measured in 2002 dollars). Multiplication of the operating costs by the estimated 2003 time-savings yields the hypothetical economic savings[12] of D2 for that year. The values are shown in Table 3-4 (note the 2003 economic savings have not been adjusted to most current FAA operations data for 2003).

Table 3-4. Potential Economic Savings in Year 2003 by Center and Type of Aircraft

ARTCC	AC	AT	GA	MIL	Total (2002 dollars)
ZNY	$21,463,437	$352,743	$699,356	$1,088,305	$23,603,842
ZOB	13,789,813	2,478,773	843,882	1,244,600	18,357,067
ZTL	13,486,935	1,893,112	1,272,278	1,305,789	17,958,113
ZAU	13,901,749	2,118,854	1,014,381	792,084	17,827,067
ZID	12,883,628	2,303,557	867,945	616,947	16,672,077
ZDC	11,584,150	1,443,962	858,512	2,420,115	16,306,740
ZME	12,881,619	363,974	953,513	1,732,252	15,931,358
ZMA	13,592,404	616,595	1,083,106	259,953	15,552,057
ZLA	12,628,744	877,386	583,007	765,410	14,854,547
ZJX	11,740,801	1,021,072	1,086,074	871,974	14,719,921
ZFW	11,300,355	1,115,100	698,315	1,228,831	14,342,601
ZKC	11,004,753	936,315	860,766	878,016	13,679,849
ZMP	10,070,466	1,314,486	912,383	393,895	12,691,229
ZHU	9,477,151	1,049,185	806,527	1,334,479	12,667,341
ZAB	9,850,263	644,860	455,690	1,331,216	12,282,028

[10] *Forecasts of IFR Aircraft Handled by FAA Air Route Traffic Control Centers FY 2003-2015*, FAA, Office of Aviation Policy and Plans, May 2004.

[11] *Economic Values for Evaluation of FAA Investment and Regulatory Decisions, Executive Summary*, FAA, Office of Aviation Policy and Plans. Retrieved April 29, 2004 from http://apo.faa.gov/economic/EXECSUMM.PDF.

[12] Economic value of passenger time savings was not estimated by CSC in their study.

Table 3-4. Potential Economic Savings in Year 2003 by Center and Type of Aircraft (Continued)

ARTCC	AC	AT	GA	MIL	Total (2002 dollars)
ZDV	9,614,678	1,038,549	488,136	479,189	11,620,552
ZOA	8,990,955	828,685	428,730	948,695	11,197,064
ZLC	8,219,560	692,024	328,356	1,161,805	10,401,744
ZBW	7,494,847	1,791,795	541,435	411,847	10,239,925
ZSE	5,269,271	1,054,500	388,418	786,626	7,498,815
Total	$229,245,576	$23,935,524	$15,170,808	$20,052,028	$288,403,936

Year 2015 User Benefits

Since D2 is not currently deployed, it is desirable to use future traffic loads when developing the economic analysis. Using the FAA's forecast of ARTCC traffic loads[13] and the scaling factors calculated from this study, it was possible to estimate the nation-wide time-savings for the D2 tool for the year 2015. Multiplying the aircraft operating cost factors by the estimated time-savings yielded the potential economic savings of D2 in 2015. The values (measured in 2002 dollars) are shown in Table 3-5.

Table 3-5. Potential Economic Savings in Year 2015 by Center and Type of Aircraft

ARTCC	AC	AT	GA	MIL	Total (2002 dollars)
ZNY	$30,662,993	$549,054	$859,142	$790,458	$32,861,647
ZTL	18,821,613	2,622,887	1,568,859	1,395,663	24,409,022
ZOB	18,947,589	3,357,712	995,608	1,345,000	24,645,908
ZAU	18,415,520	3,095,737	1,197,927	872,737	23,581,920
ZID	17,678,837	3,384,737	1,053,392	594,210	22,711,176
ZDC	16,617,887	2,217,932	1,065,052	2,730,115	22,630,986
ZMA	19,753,235	957,230	1,386,744	413,958	22,511,167
ZME	18,754,422	457,649	1,168,491	1,740,137	22,120,699
ZLA	17,906,828	1,101,727	735,524	918,926	20,663,005
ZJX	16,880,775	1,437,528	1,375,002	949,552	20,642,857
ZFW	16,012,253	1,434,741	860,071	1,291,442	19,598,507
ZKC	14,316,399	1,324,773	1,032,333	961,105	17,634,610
ZMP	14,382,984	1,779,823	1,079,862	382,768	17,625,438

[13] See note 4.

Table 3-5. Potential Economic Savings in Year 2015 by Center and Type of Aircraft (Continued)

ARTCC	AC	AT	GA	MIL	Total (2002 dollars)
ZAB	14,328,523	898,571	569,287	1,301,710	17,098,091
ZHU	13,184,425	1,539,417	997,897	1,371,289	17,093,029
ZDV	13,910,778	1,494,342	591,264	550,995	16,547,378
ZOA	13,208,305	1,052,866	517,148	1,077,189	15,855,508
ZLC	11,645,908	851,033	396,785	1,150,289	14,044,015
ZBW	10,382,025	2,145,565	651,267	403,132	13,581,988
ZSE	7,235,474	1,383,122	439,051	737,895	9,795,541
Total	$323,046,774	$33,086,447	$18,540,703	$20,978,570	$395,652,494

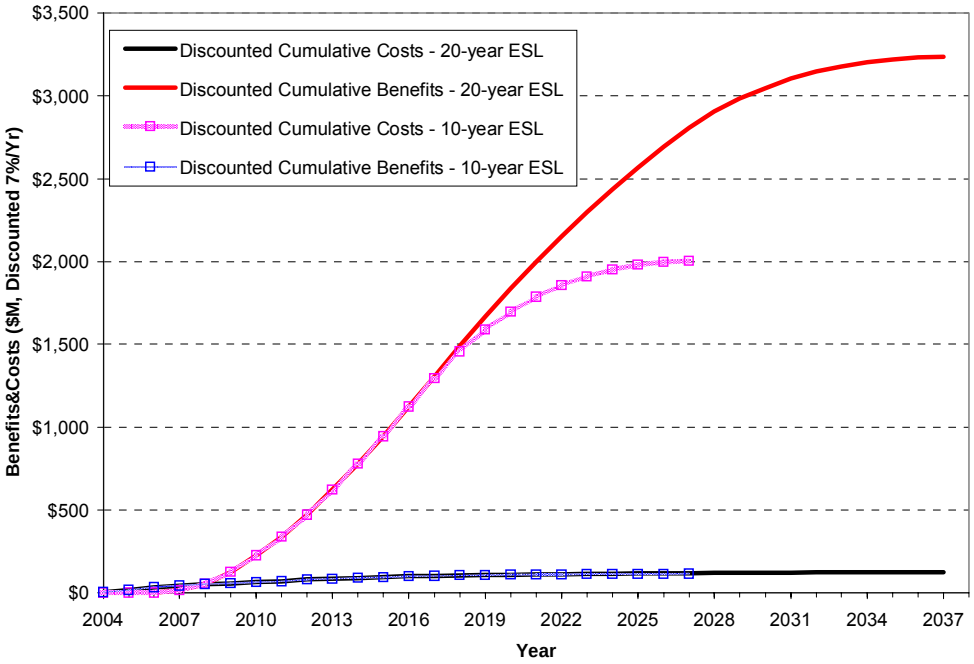
LCCBA Results

Life-cycle cost/benefit assessments were performed for the two deployment scenarios considered (ESLs of 20 and 10 years). Table 3-6 summarizes the discounted costs and benefits, as well as the benefit-to-cost ratios, net present values, and breakeven points. The benefit-to-cost ratios range from 17:1 for the 10-year ESL case to 26:1 for the 20-year ESL case. The very high benefit-to-cost ratios and net present values indicate that D2 is potentially a very beneficial DST. In all cases, the breakeven point was the second year of operations—very early in the DST life cycle. Figure 3-2 is a graphical representation of the discounted life-cycle costs and benefits.

Table 3-6. D2 Life-Cycle Cost/Benefit Assessment Results

Scenario	Discounted benefits (2004 $M)	Discounted costs (2004 $M)	Benefit-to-cost ratio	Net present value (2004 $M)	Breakeven point
20-year ESL	$3,234.6	$125.2	25.8	$3,109.4	2008
10-year ESL	$2,004.2	$115.7	17.3	$1,888.5	2008

Figure 3-2. Life-Cycle Costs and Benefits for D2



A sensitivity analysis was performed. Even if projected benefits were reduced by half, net present values, benefit-to-cost ratios, and breakeven points remain favorable for both scenarios and indicate that a strong investment case can be made for D2.

Chapter 4

Multi-Center TMA (McTMA)—Summary of Single-Year NAS-Wide Benefits and Life-Cycle Cost/Benefit Assessments

INTRODUCTION

The Multi-Center Traffic Management Advisor (McTMA) is a direct enhancement of the Single-Center TMA system that is operating at several Air Route Traffic Control Centers (ARTCCs, or Centers) around the United States. McTMA is designed for use where more than one ARTCC is responsible for managing the traffic flow into and out of a common Terminal Radar Approach Control (TRACON). By implementing the TMA system in multiple centers, collaboration and communication between traffic controllers can be improved, and thus the efficiency of traffic management advanced. Specifically, this will be accomplished by the following functions: Time Based Metering with Delay Feedback and Capacity Distribution, Dynamic Metering, Tiered Metering, Demand Visualization, Multiple Facility Coordination, Internal Departure Scheduling, Runway Assignment.

This summary presents the findings from both the single-year assessment and the full life-cycle cost benefit assessment (LCCBA) of the McTMA DST. The findings from the two reports are presented together, with the single-year report details preceding those for the LCCBA.

Benefits resulting from the use of the McTMA tool were derived through the modeling of functions and benefit mechanisms enabled by those functions. The various capabilities of McTMA allow the facilities in which it is use to realize a number of operational improvements. In broad categories, the benefits from McTMA are:

- Increased throughput
- Reduced average delay
- Reduced fuel burn.

In turn, these three benefits result in specific economic benefits:

- Reduced aircraft direct operating costs
- Increased passenger time value
- Increased airline revenue.

This assessment reviews the functions of the McTMA by applying them to the traffic flows into the Philadelphia (PHL) and New York (N90) TRACONs. The goals of the assessment included identifying the benefit mechanisms of the McTMA, extrapolating the benefits to 2015, and providing a methodology by which NASA could further extend the review in order to create a full life-cycle cost-benefit assessment of the McTMA.

This single-year summary is based on the following final report:

> *Single-Year NAS-Wide Benefits Assessment of Multi-Center TMA.* Husni Idris, Ph.D., Anthony Evans, Simon Evans. NASA Ames Research Center. Moffett Field, CA. Titan Corporation, June 18, 2004.

As mentioned above, this chapter also includes a documentation of the life-cycle cost/benefit assessment (LCCBA) of the McTMA decision support tool (DST) described above. The study utilizes two scenarios to model McTMA deployment: a base case for an economic service life (ESL) of 20 years, and a shorter case for an ESL of 10 years. In both cases, the benefits of time-based metering of arrival flows are calculated for the major Philadelphia (PHL), New York (N90), and Potomac (PCT) airports during times when demand exceeds capacity. To extrapolate life-cycle benefits of the system, the study is based on the results from the single-year benefits study cited above.

Benefits resulting from the use of the McTMA tool were derived by modeling functions and benefit mechanisms enabled by those functions. The various capabilities of McTMA allow the facilities in which it is use to realize a number of operational improvements. In broad categories, the benefits from McTMA are:

- Increased throughput
- Reduced average delay
- Reduced fuel burn.

In turn, these three benefits result in specific economic benefits:

- Reduced aircraft direct operating costs
- Increased passenger time value
- Increased airline revenue.

This LCCBA summary is based on the report for the ASRC Aerospace Corporation. The full citation is as follows:

> *Final Life-Cycle Cost/Benefit Assessment of Multi-Center TMA (McTMA)*. Jianzhong Jay Wang. Contract NAS2-03145. Task Order 480021 ASRC Aerospace Corporation NASA Ames Research Center, Moffett Field, CA. July 23, 2004.

FUNCTIONS AND BENEFIT MECHANISMS

Associated with each of the functions of McTMA, there are several mechanisms that result in common benefits. Additionally, the functions and mechanisms apply to both the single-year and LCCBA reports, and so are presented only once. Table 4-1 outlines these.

Table 4-1. Functions and Benefit Mechanisms

McTMA functions	Benefit mechanisms	Benefits
Time-based metering	Freeze horizon	Reduced average delay Increased throughput
	Aircraft by aircraft metering	
	Independence from aircraft speed variability	
	High resolution metering	
	Delay feedback	Reduced fuel burn Reduced average delay Increased throughput
	Capacity distribution	Increased throughput
Dynamic metering	Dynamic adjustment of metering according to changing constraints	Increased throughput
	Dynamic balancing of arrival streams according to changing relative demand	Reduced average delay Increased throughput
Tiered metering	Delay absorbed over multiple airspaces	Enables delay feedback Enables improved demand visualization
	Aircraft included earlier upstream	Enables improved demand visualization Reduced fuel burn Increased throughput
	More accurate ETAs	Reduced average delay Increased throughput
	Close gaps from upstream	Increased throughput

Table 4-1. Functions and Benefit Mechanisms (Continued)

McTMA functions	Benefit mechanisms	Benefits
Demand visualization	Decision to start/stop metering	Enables multiple facility co-ordination Increased throughput Reduced average delay
	Decision to shut-off/resume flow	
	Switching flights between arrival streams	
Multiple facility coordination	Coordination between TRACON and associated ARTCCs	Enables time based metering Enables internal departure scheduling Enables runway assignment
	Coordination between upstream and downstream facilities	Enables tiered metering
	Coordination between facilities at same tier	Increased throughput Reduced average delay
	Coordination with facilities outside of system (ATCSCC, ARTCC)	Increased throughput
Runway assignment	Runways assigned to minimize delay	Increased throughput Reduced average delay
	Feeding correct number and mix of aircraft into TRACON according to runway acceptance rates	
Internal departure scheduling	Internal departure release time specification matching demand gaps	Reduced fuel burn Increased throughput Reduced average delay

MODELING AND ANALYSIS APPROACH

Flows at PHL and N90 over 15 days during November 2003 were analyzed in order to arrive at the results presented below. From these two airports, extrapolations to NAS-wide benefits in 2015 were calculated. Comparisons between the baseline system performance and that enhanced by McTMA were conducted using a traffic flow model. The model in use comprises modeling for both demand and capacity of the facility under consideration. From this model the quantitative results were derived.

Demand Modeling

Arrival flows to PHL and the participating N90 airports (JFK, EWR, LGA, TEB) were identified and categorized with input from NASA researchers. Networks of flows into N90 formed the foundation of the model for demand. From historical aircraft position information, statistical models of transition times were constructed and then tested against trajectory-based transition times. The difference

between the two was minimal, providing evidence that the statistical models are reliable.

Capacity Modeling

Data for capacity of the airports under consideration were from the FAA's Aviation System Performance Metrics (ASPM) database. The models here required arrival acceptance rates (AARs) for every airport. These AARs were determined by plotting throughput against demand. Important to note is that throughput increases with demand, until the point of saturation, when it drops sharply. The drop is due in part to workload constraints on the controller, as well airspace safety considerations.

Capacity envelopes were identified for each airport. These envelopes represent the relationship between arrival throughput and departure throughput in a particular time period. Constraints, such as wake vortex separation requirements and controller workload, are also accounted for in these envelopes.

A capacity envelope is presented in percentiles, with the 99th percentile being used as the conservative maximum safe capacity. The 100th percentile is inappropriate because it may include potential violations of safety requirements resulting from controller error.

Baseline Modeling

To represent the current traffic conditions at the airports under review, PHL and N90, a model was constructed containing a miles in trail (MIT) restriction generation component, an MIT spacing component, and a TRACON delay component. These components were designed to reflect the actual operational data for the facilities during November 2003. This information, representing the functioning of PHL and N90 without the McTMA enhancements, was considered the baseline against which the enhanced operations would be compared.

LCCBA Site Selection

In enacting the transition from Single-Center TMA (TMA-SC) to McTMA, the process can best be viewed as adding functions to an already existing structure. McTMA was designed under the constraint that it only work as additions to the TMA-SC system, so the move from TMA-SC to McTMA can be achieved through software upgrades at existing TMA-SC sites. Since McTMA thus includes all functions of TMA-SC as a subset, when TMA-SC receives software upgrades, McTMA is re-synchronized to include those upgrades. Therefore, the move from TMA-SC to McTMA incurs minimal cost, and results in little or no impact on the local facility. When the FAA decides to expand a TMA-SC system, the action merges the additional features of the McTMA release with current TMA-SC systems, creating a "Version 4.0" of TMA-SC. The choice to utilize the McTMA functions is then left to local decision-makers.

Currently, TMA-SC is used at ZMA (Miami), ZHU (Houston), ZFW (Fort Worth), ZDV (Denver), ZMP (Minneapolis), ZTL (Atlanta), ZOA (Oakland), and ZLA (Los Angeles). At the time of writing the report, future sites include ZAU (Chicago) and ZBW (Boston), and planned installation at ZAB (Albuquerque), ZME (Memphis), and ZSE (Seattle). Test locations for TMA-SC include ZBW (Boston), ZNY (New York), ZOB (Cleveland), and ZDC (Washington), configured for cooperative time-based metering to PHL (Philadelphia).

Due to airspace complexity and the need for cooperation among multiple facilities, some airports cannot realize metering benefits from TMA-SC without using the McTMA features. These include: PHL (Philadelphia), the New York TRACON (N90) airports (Kennedy JFK, LaGuardia LGA, Newark EWR, and Teterboro TEB), and the Potomac TRACON (PCT) airports (Baltimore BWI, Dulles IAD, and National DCA). These facilities would not realize any benefits until Version 4 of TMA-SC is made available. Due to the undesirable problems that arise in having multiple versions in service, Version 4.0 would have to be installed at all existing TMA-SC sites before these airports begin seeing benefits.

For purposes of this LCCBA, it is assumed that McTMA will be deployed at the following sites:

- PHL: ZNY, ZDC, ZOB, ZBW (a NASA demonstration site)
- N90: ZNY, ZDC, ZOB, ZBW
- PCT: ZDC, ZNY, ZOB, ZBW, ZID, ZTL (Atlanta).

LCCBA Site Deployment Schedule

Based on the patterns observed in Free Flight Phase 1, and using a site deployment scheduling methodology used in previous studies, the following milestones were used in the schedule: Technology Readiness Level (TRL) 6 completion, Initial Daily Use (IDU), Planned Capability Available (PCA), and Installation.

The planned deployment schedule is shown in Table 4-2.

Table 4-2. McTMA Deployment Schedule

Site	Installation	IDU	PCA
PHL/ZNY, ZDC, ZOB, ZBW	Dec 2004	Jun 2006	Jan 2007
N90/ZNY, ZDC, ZOB, ZBW	Dec 2005	Jun 2007	Jan 2008
PCT/ZDC, ZNY, ZOB, ZBW, ZID, ZTL	Jun 2006	Dec 2007	Jul 2008

Cost Assessment

In this study, the life-cycle cost (LCC) assessment methodology considers three cost characteristics: consideration of all cost types (coverage), establishing timing of these costs (LCC phase), and quantification of costs (estimation). This results in the use of a three-dimensional matrix, with coverage of costs, cost estimation, and LCC phase as the three axes. This methodology is similar to that used in all ASRC LCCBA. The three branches of characteristics were evaluated across the projected life cycle of McTMA to arrive at the results presented later.

Benefits Assessment

To arrive at the life-cycle benefits of McTMA, the study estimates the single-year McTMA benefits for five Northeast airports (JFK, LGA, EWR, TEB, PHL) for 2003, 2010, 2015, and 2025. Using the current traffic flow patterns, and taking into account the enhancements made by implementing McTMA, the benefit mechanisms were modeled and analyzed. The traffic flow model included system demand and capacity constraints, which were entered into metering algorithms that represented the baseline and McTMA operations. Output from the model was adjusted according to an error model that took into account deviations from the desired output due to human and other errors.

Quantitative metrics can be used to measure and compare the performance of McTMA and the baseline system. The traffic flow model thus allows for the benefits to be derived in terms of delay, throughput, and fuel burn. Technical performance was then converted to economic metrics, and then the benefits of McTMA were estimated.

Total benefits over the life of the tool were estimated based on assessments conducted by Titan Systems Corporation for NASA in 2004. From this, two extrapolations were used in this study, and are referred to as Extrapolation 1 and Extrapolation 2. Both were based on the results from the Titan study that derived single-year benefits for the PHL and New York TRACON airports. However, each extrapolation used a different method to arrive at potential benefits for the PCT airports.

Extrapolation 1 uses parameters that are slightly more optimistic. Extrapolation 2 uses parameters that are slight more conservative. The authors are clear to note that the life-cycle benefit results under these two scenarios may be inflated. This is due to demand forecasts not adequately accounting for facility capacity constraints.

RESULTS, FINDINGS, AND CONCLUSIONS

The findings presented here are the results of data analysis conducted for the two facilities listed above—PHL and N90 (five airports in all)—and also include an extension of those results to present NAS-wide benefits in 2015. The study groups the quantifiable benefits into four major categories, which will be addressed here in turn: delay savings, throughput increase, fuel burn savings, and metering duration. Finally, the economic benefits are presented.

It is important to note that the study finds the following results to be conservative estimates. This is because only a subset of McTMA functions were studied, an incomplete set of benefit mechanisms were analyzed, assumptions about McTMA functioning were purposely conservative themselves, and because some dynamic aspects of McTMA metering were not modeled explicitly.

Delay Savings

A baseline delay was calculated for each arriving flight at each of the five airports, and was then compared to the simulated arrival delay under McTMA. The delays were calculated by using a flight's modeled time of arrival less its ETA, as shown in Table 4-3.

Table 4-3. Baseline and McTMA Delay Per Flight

Airport	Baseline		McTMA Increased capacity	
	Average delay [min/flt]	Average number of flights metered [flts/day]	Average delay [min/flt]	Average number of flights metered [flts/day]
PHL	10.293	195	5.357	145
LGA	8.072	190	4.192	193
EWR	8.394	124	2.773	107
JFK	10.276	41	4.922	41
TEB	4.834	21	1.976	15

Assuming that the increase in capacity made possible by McTMA is utilized, Table 4-4 presents the yearly delay savings in minutes possible.

Table 4-4. McTMA Delay Savings Per Year (2003) Assuming an Increase in Capacity Under McTMA

Airport	Yearly McTMA delay savings over baseline operations (2003) [min]
PHL	395,000
LGA	267,000
EWR	263,000
JFK	51,000
TEB	10,000

If no capacity increase is assumed, then the yearly delay savings are as shown in Table 4-5.

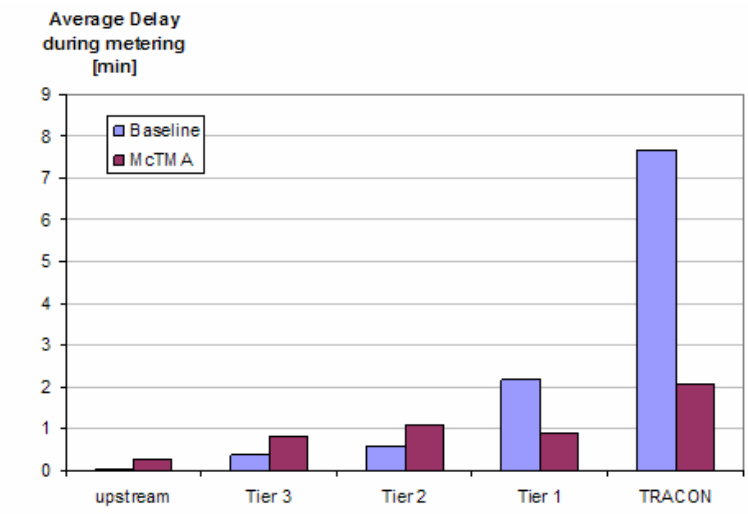
Table 4-5. McTMA Delay Savings Per Year (2003) Assuming No Increase in Capacity

Airport	Yearly McTMA delay savings over baseline operations (2003) [min]
PHL	24,000
LGA	20,000
EWR	22,000
JFK	17,000
TEB	0

In the previous two tables, the lower savings for JFK and TEB reflect the lower amounts of traffic at these airports, relative to the other airports studied.

Following are the results in delay savings over the relevant tiers (Figure 4-1). Important to note here is the more even distribution of delays over the tiers. Delay abilities in the McTMA model push delays upstream when no more delay can be absorbed between any meter fix pair without holding.

Figure 4-1. Average Delay



Throughput Increase

Here again, the results are presented for conditions both with and without capacity increases. Additionally, the results presented are not increases in applied capacity, but rather are averages of throughput increases and improved efficiency in capacity usage. This is because the time period measured includes gaps of idle time in demand. Tables 4-6 and 4-7 demonstrate the results.

Table 4-6. Increases in Throughput During McTMA Metering (2003) Assuming an Increase in Capacity

Airport	Increase in throughput during McTMA metering periods 2003 [%]
PHL	4.96
LGA	2.10
EWR	2.61
JFK	2.87
TEB	0.00

Table 4-7. Increases in Throughput During McTMA Metering (2003) Assuming No Increase in Capacity

Airport	Increase in throughput during McTMA metering periods 2003 [%]
PHL	2.41
LGA	1.31
EWR	2.25
JFK	2.56
TEB	0.00

The significant change in the PHL value from the first to second table is due, according the study, to the banking structure operated at PHL. In this situation, the marginal benefit of capacity increase is higher.

Fuel Burn Savings

As above, the results here are presented both with and without capacity increases (Tables 4-8 and 4-9). The savings were calculated as the amount of delay time absorbed within each tier of the arrival network multiplied by an average burn rate according to given aircraft and flight path characteristics.

Table 4-8. Average Fuel Burn Savings Per Year (2003) Assuming An Increase in Capacity

Airport	Average fuel burn savings 2003 [lbs]
PHL	19,005,000
LGA	15,266,000
EWR	15,873,000
JFK	5,741,000
TEB	520,000

Table 4-9. Average Fuel Burn Savings Per Year (2003) Assuming No Increase in Capacity

Airport	Average fuel burn savings 2003 [lbs]
PHL	2,850,000
LGA	2,613,000
EWR	3,066,000
JFK	3,041,000
TEB	33,000

Duration of Metering

McTMA metering was implemented when airport demand exceeds runway capacity. This demand is measured over 15-minute intervals, since the ASPM database uses this as its resolution in capacity measurement. Table 4-10 presents the duration of metering under McTMA.

Table 4-10. Duration of McTMA Metering

Airport	Mean McTMA metering period duration [min]	Maximum McTMA metering period duration [min]	Minimum McTMA metering period duration [min]
PHL	52	345	30
LGA	109	600	30
EWR	66	345	30
JFK	59	165	30
TEB	42	105	30

Economic Benefits

The following benefits are the yearly savings resulting from the combined savings of fuel burn improvements and delay reductions. Yearly estimates are derived from daily savings calculations and projections for all times when demand exceeds capacity.

All benefits from the implementation of McTMA are a function of the capacity at a facility. The greater the capacity utilization, the greater the resulting benefits. Figure 4-2 presents the increase in savings in operating costs as capacity (throughput) is increased.

Figure 4-2. Growth of Operations Cost Savings by Capacity Increase

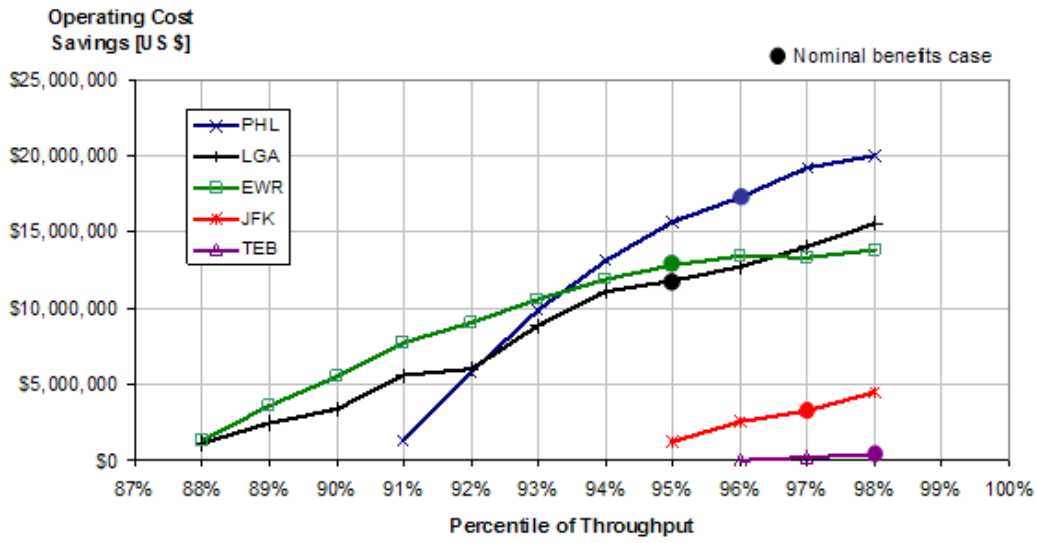


Table 4-11 presents the increase in operating profit assuming a capacity increase.

Table 4-11. Yearly Increase in Operating Profit Due to McTMA (2003) Assuming An Increase in Capacity

Airport	2003 yearly savings [US$/year]
PHL	17,275,000
LGA	11,810,000
EWR	12,817,000
JFK	3,289,000
TEB	383,000

Table 4-12 presents results that assume no capacity increase, representing the lowest bound on McTMA benefits.

Table 4-12. Yearly Increase in Operating Profit Due to McTMA (2003) Assuming No Increase in Capacity

Airport	2003 yearly savings [$/year]
PHL	1,302,000
LGA	1,141,000
EWR	1,343,000
JFK	1,268,000
TEB	4,000

Extrapolation

OTHER FACILITIES

SAIC provided the authors of the study with a number of potential McTMA sites that fit certain criteria SAIC had developed. These criteria included: facility operational requirements, ARTCC/TRACON boundaries, airspace complexity, airport capacity/delay, and weather phenomena. From these characteristics, the study extrapolates average facility benefits using the methodology used to derive the results from PHL and N90 as a starting point.

Since no common metrics exist for all of the above characteristics, and developing such was beyond the scope of the study, the authors chose to focus on airport capacity and relative demand. The model developed is based on queuing dynamics relating benefits (delay savings) to: (1) the total number of arrival operations at an airport per day (*ArrOps*, directly representing demand); (2) the percentage of the year for which arrival demand exceeds reported arrival capacity ($P_{D>C}$, representing when McTMA will be operated, as it is to be operated when demand exceeds capacity); and (3) the utilization of the airport (*Util*, representing how close to available capacity the airport operates). The model parameters were selected such that they may be calculated from available data sources such as Aviation System Performance Metrics (ASPM), and was calibrated against the five airports analyzed to determine the model coefficients. Specifically, arrival demand is obtained from the ARRDEMAND field in the database, reported arrival capacity from the AAR field, and number of arrival operations (or throughput) from the EFFARR field. Utilization is calculated from the average and 99th percentile of the EFFARR field over a year. This model is shown in the equation below.

$$Benefits = 19{,}366 \times \left[\frac{ArrOps_{perday}}{1-(0.0213)(P_{D>C})(Util)} \right]$$

An example using the above model was shown to predict the benefits at LGA with acceptable results (8.1% error). Note that the above equation will yield benefits in year 2003 dollar values; it needs to be modified by the GDP deflator to get values in terms of year 2004 dollars.

To arrive at the potential McTMA benefits at Potomac TRACON (PCT), ASRC Aerospace computed McTMA benefits for the 3 major PCT airports (IAD, BWI, and DCA) for the year 2003 using this model. The parameters for each airport were calculated from FAA ASPM database, and summarized in Table 4-13 together with the results.

Table 4-13. PCT airports 2003 single-year TMA-MC benefit extrapolation

Airport	ArrOps	PD>C	Util	Benefit (Year 2004 $M)
BWI	370.2	2.69	0.39	$7,425,609
DCA	345.1	8.48	0.42	$7,324,754
IAD	493.4	9.34	0.23	$10,146,489
PCT				$24,896,853

FUTURE YEARS

To estimate the benefits of future years at PHL and N90 airports, the authors relied on figures for increases in demand at each of the five airports under consideration as provided by the FAA-APO Terminal Area Forecast (TAF). Note that the TAF only extrapolates to 2020, so demand for 2025 was extrapolated linearly from that given for 2020. Projected increases in demand for the five airports studied are presented in Table 4-14.

Table 4-14. Forecasted Demand Increases

Airport	Forecasted increase in demand from 2003 (%)		
	2010	2015	2025
PHL	25.0	37.8	63.4
LGA	7.7	7.7	7.7
EWR	28.6	42.5	70.2
JFK	24.4	41.9	76.7
TEB	14.3	24.5	44.9

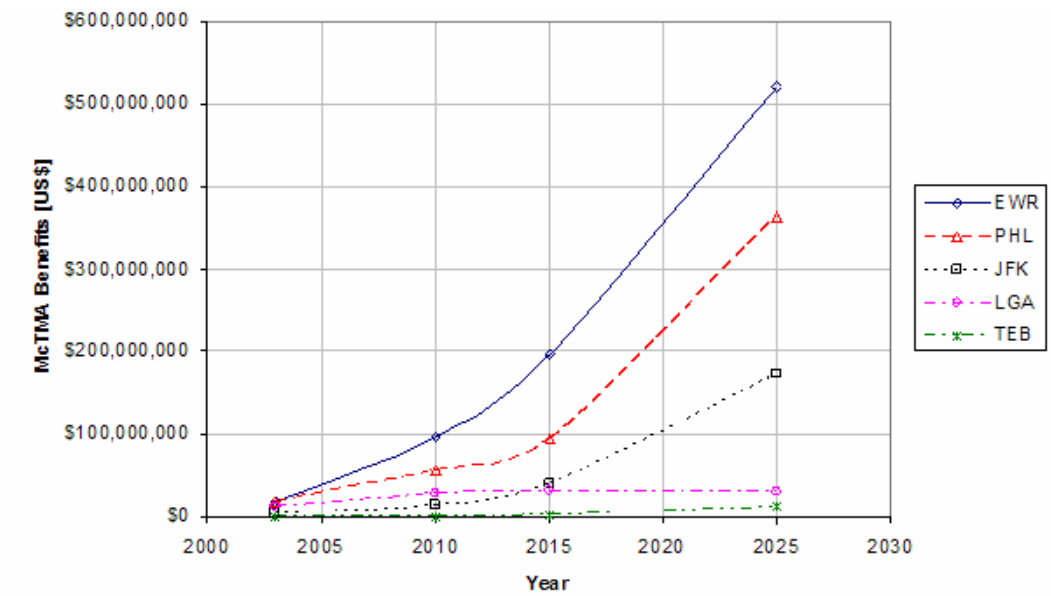
From these projected demand levels, the following increases in operating profits and growth in McTMA benefits resulted (Table 4-15).

Table 4-15. Extrapolated Increases in Operating Profit Due to McTMA

Airport	Yearly savings (2003 US $/year)			
	2003	2010	2015	2025
PHL	17,275,000	56,538,000	94,779,000	363,808,000
LGA	11,810,000	28,569,000	29,480,000	29,409,000
EWR	12,817,000	96,655,000	196,430,000	520,122,000
JFK	3,289,000	14,595,000	40,253,000	172,494,000
TEB	383,000	605,000	1,635,000	12,922,000

Figure 4-3 illustrates the growth over time of the benefits associated with McTMA.

Figure 4-3. Projected Benefits Based on Traffic Demand Growth



Through examination of the benefit predictions for the PHL and N90 TRACONs and their corresponding traffic demands, it is apparent that there is a non-linear, exponential relationship between demand and potential McTMA benefit. Least squares regression was performed and produced two equations describing this relationship for PHL and N90, respectively. They are:

$$PB_t^{PHL} = 7{,}312{,}099 + 54{,}866 \times e^{(Op_t^{PHL} \times 1.20 \times 10^{-5})}$$

where:

PB_t^{PHL} is the potential benefit of McTMA at PHL in year t in year 2004 $

Op_t^{PHL} is the total number of operations of PHL in year t according to the TAF

$$PB_t^{N90} = -62{,}993{,}997 + 1{,}030{,}234 \times e^{(Op_t^{N90} \times 3.45 \times 10^{-6})}$$

where:

PB_t^{N90} is the potential benefit of McTMA at N90 in year t in year 2004 dollars

Op_t^{N90} is the total number of operations in N90 in year t according to the TAF

These regression results represent the data well, with R^2 values approaching 1.

To forecast future McTMA potential benefits at PCT, ASRC Aerospace used an analogy between PCT and N90, and developed relationships between benefit and demand at PCT. These relationships are:

1. The PCT benefit-demand equation is that of N90's with the origin moved to match the 2003 PCT benefit,

2. The PCT benefit-demand equation is that of N90's with the baseline moved to match the 2003 PCT benefit.

Between them, Option 2 is conservative while Option 1 may be optimistic. It is concluded that although the potential McTMA benefit at PCT is between the two, it should be closer to that predicted by Option 1, given that the potential benefits estimated for N90 are obtainable. The equation describing Option 1 is given below:

$$PB_t^{PCT} = (-62{,}993{,}997 - 1{,}766{,}079) + 1{,}030{,}234 \times e^{[(Op_t^{PCT} + 379{,}690) \times 3.45 \times 10^{-6}]}$$

Where:

PB_t^{PCT} is the potential benefit of McTMA at PCT in year t in year 2004 $

Op_t^{PCT} is the total number of operations of PCT in year t according to the TAF

While that for Option 2 is:

$$PB_t^{PCT} = (-62{,}993{,}997 + 63{,}702{,}879) + 1{,}030{,}234 \times e^{(Op_t^{PCT} \times 3.45 \times 10^{-6})}$$

Life-Cycle Cost Benefit Assessment Results

The following results cover those derived in the McTMA LCCBA, which used two major cases studies: the 20 year ESL, and the 10 year ESL. The costs and benefits are given separate sections. Additionally, the benefits for PCT are analyzed individually, as the results for that facility represent the study's greatest uncertainties.

Important to note is that the results for the benefits are likely to be slightly too high. This is because the demand increase forecast used in the study was not entirely feasible, given the facility capacity applied. The authors note that in previous studies, as well, the current demand forecasts do not adequately account for capacity constraints.

Life-Cycle Cost

Table 4-16 presents the life-cycle cost results. The numbers reflect the use of a 7 percent annual discount rate, and assume that costs are spread evenly over the year.

Table 4-16. McTMA Life-Cycle Cost Results
(In Millions of 2004 Dollars)

Scenario	Life-cycle cost ($M 2004, before discounting)	Life-cycle cost present value ($M 2004, after discounting)
20-year ESL	$192.2	$117.2
10-year ESL	$130.3	$97.9

Figures 4-4 and 4-5 show both the annual and cumulative costs before discounting.

Figure 4-4. Annual and Cumulative Costs of 20-Year ESL Case, No Discounting

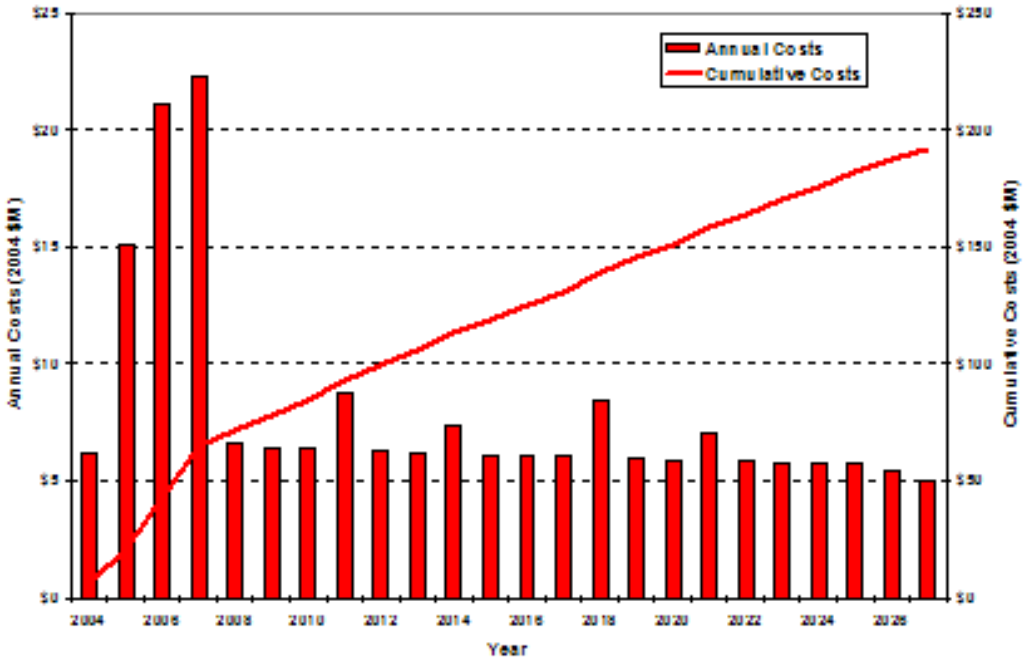
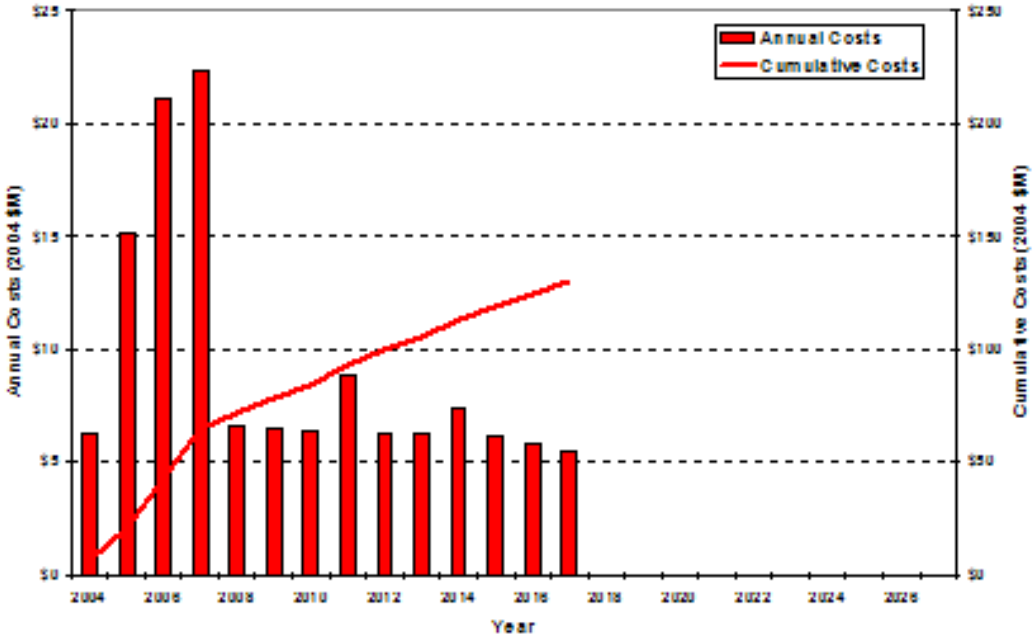


Figure 4-5. Annual and Cumulative Costs of 10-Year ESL Case, No Discounting



Figures 4-6 and 4-7 break the costs into their relevant components.

Figure 4-6. Breakdown of 20-Year ESL Life-Cycle Costs After Discounting

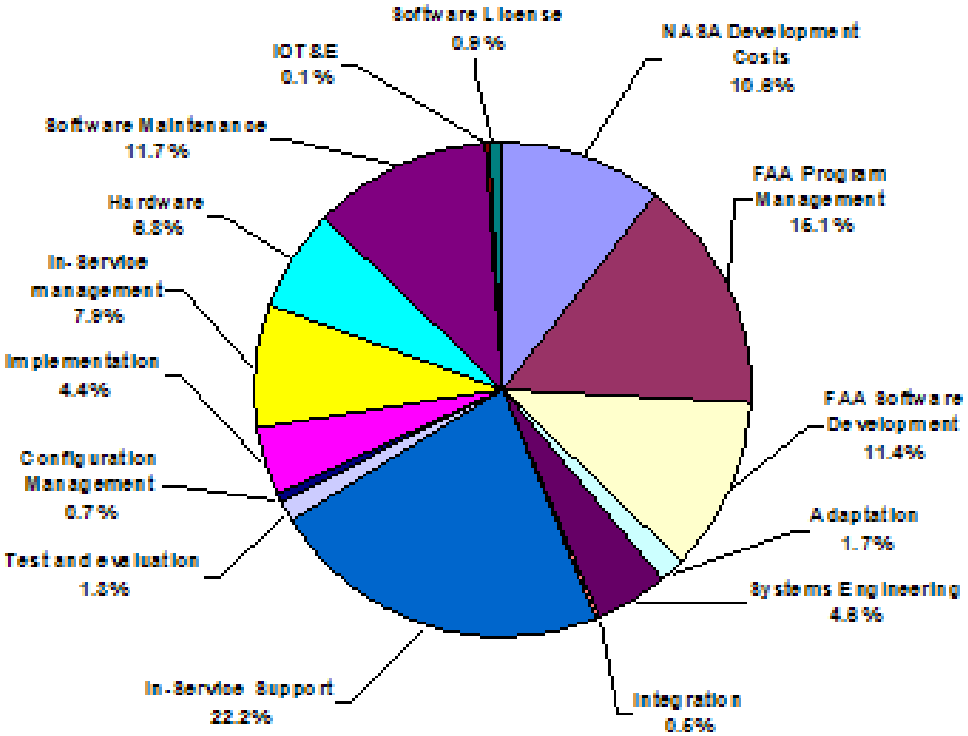
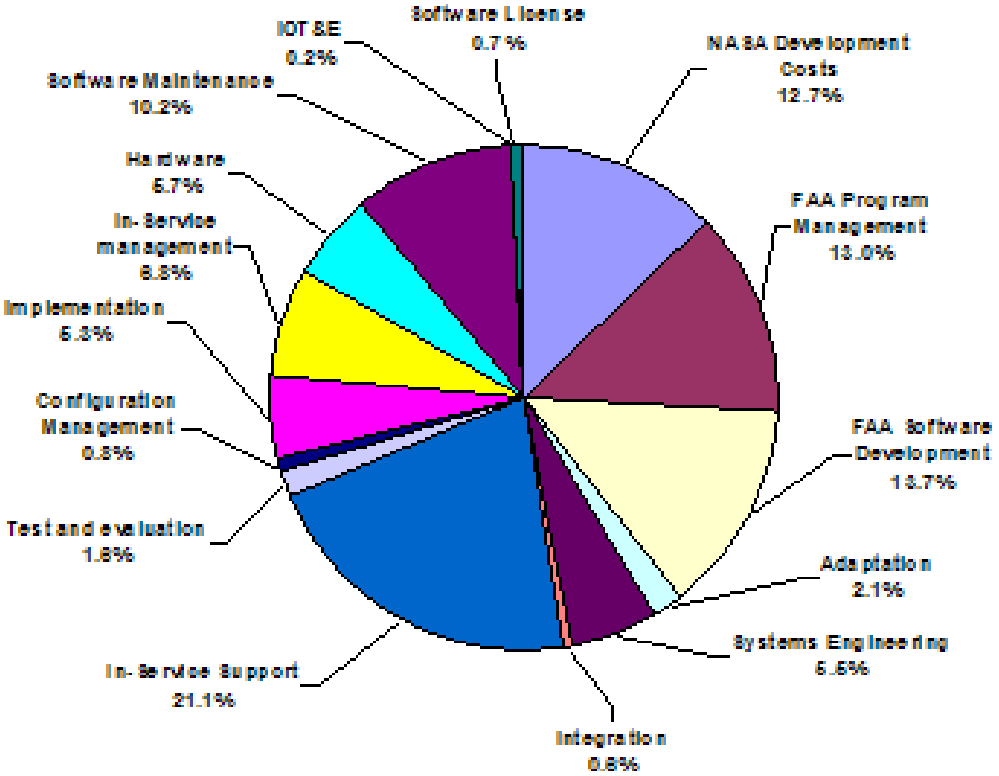


Figure 4-7. Breakdown of 10-Year ESL Life-Cycle Costs After Discounting



From the previous two graphs, it can be seen that the primary cost drivers are in-service support costs, the FAA management program, and FAA software development.

Life-Cycle Benefits

Values in Table 4-17 represent the life-cycle benefits for both the 20- and 10-year ESL cases. They were calculated in the same way as the values presented above in Table 4-16. Two benefit extrapolation scenarios are considered: Extrapolation 1 with slightly optimistic PCT benefits predicted by Option 1, and Extrapolation 2 with conservative PCT benefits predicted by Option 2 (see the Extrapolation section).

Table 4-17. McTMA Life-Cycle Benefit Results (In Millions of 2004 Dollars)

Scenario		Life-cycle benefit ($M 2004, before discounting)	Life-cycle benefit PV ($M 2004, after discounting)
20-year ESL	Extrapolation 1	$15,814.3	$5,762.3
	Extrapolation 2	$11,226.1	$4,224.8
10-year ESL	Extrapolation 1	$3,718.0	$2,156.1
	Extrapolation 2	$2,777.6	$1,649.0

Figures 4-8 and 4-9 show both the annual and cumulative benefits before discounting. It should be noted that these use the optimistic predictions for PCT.

Figure 4-8. Optimistic Benefits of the 20-Year ESL Case Before Discounting

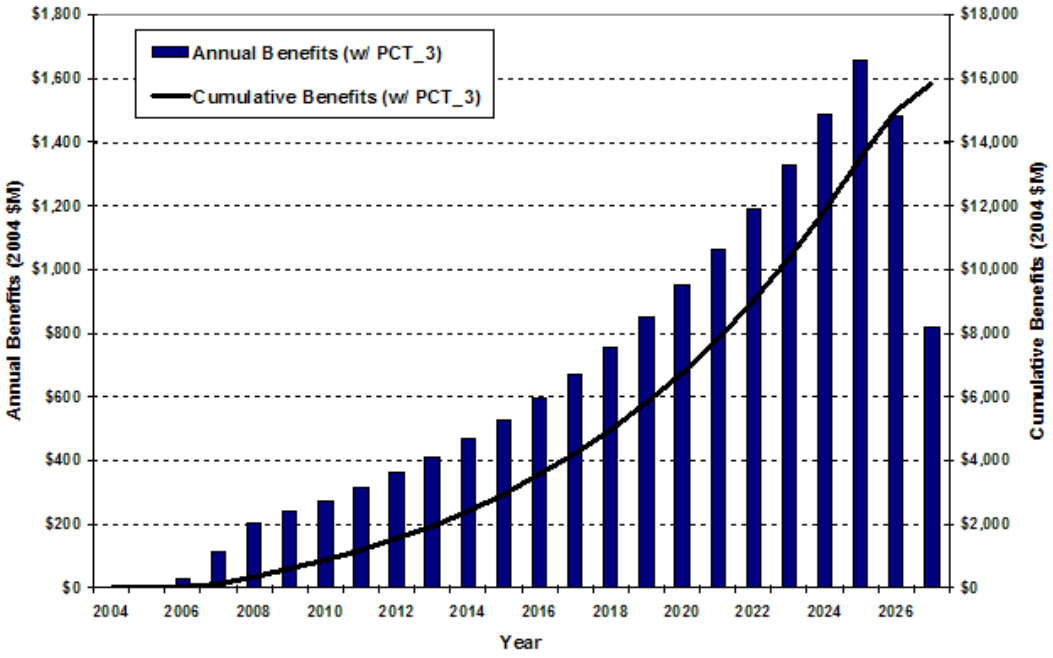
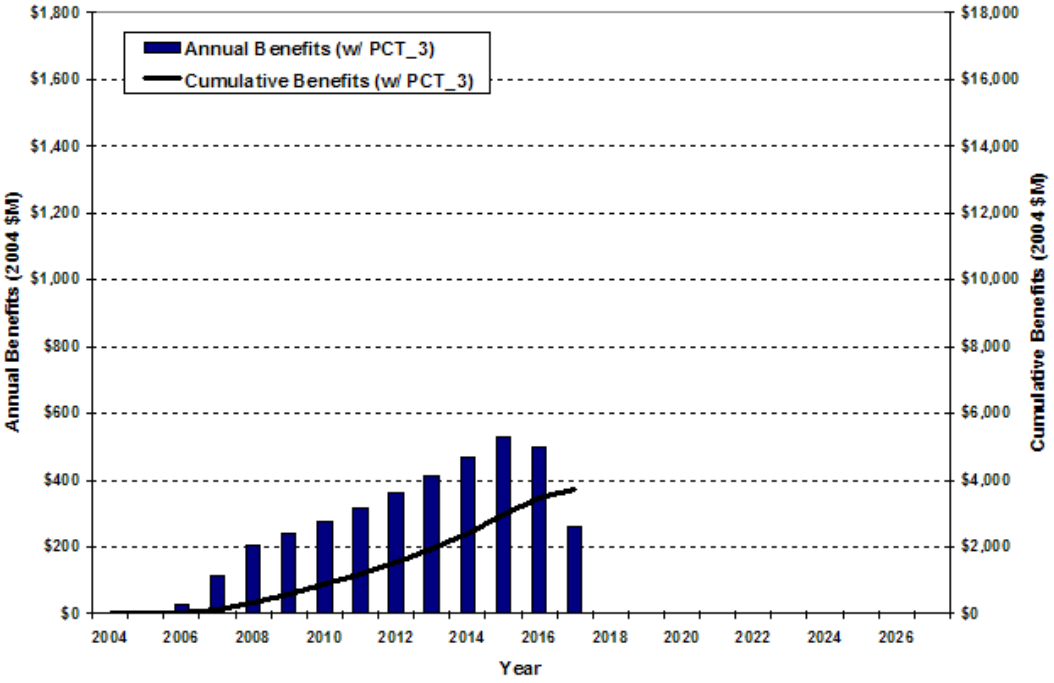


Figure 4-9. Optimistic Benefits of the 10-Year ESL Case Before Discounting



Figures 4-10 and 4-11 represent the same information, but under more conservative assumptions about the benefits for PCT.

Figure 4-10. Conservative Benefits of the 20-Year ESL Case Before Discounting

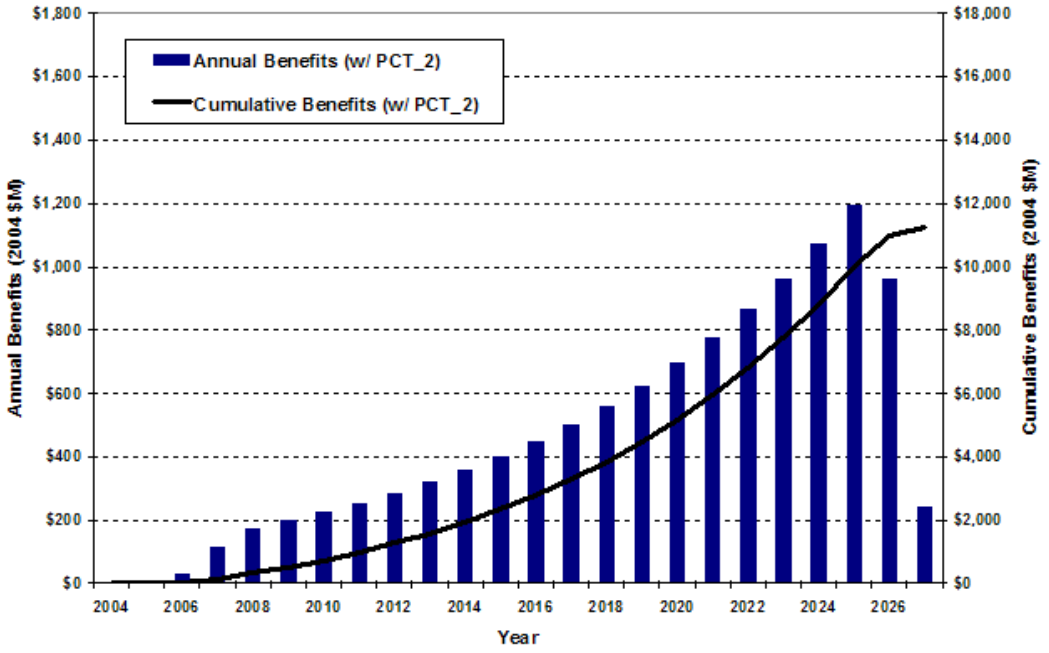
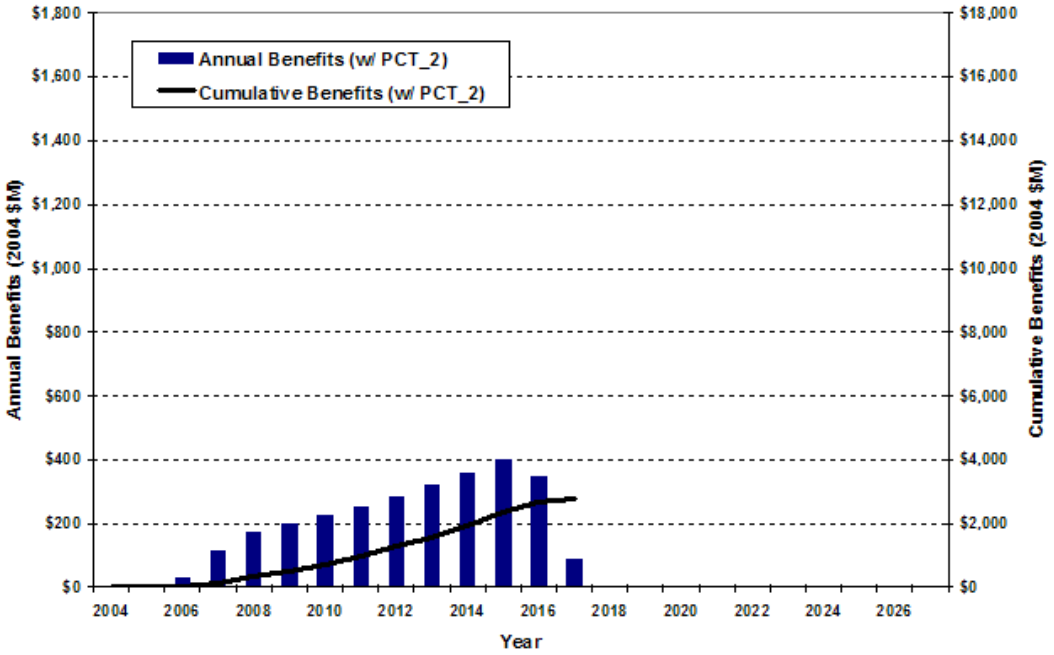


Figure 4-11. Conservative Benefits of the 10-Year ESL Case Before Discounting



The number of sites in operation and the annual benefits are in direct correlation so that benefits rise and fall in line with the number of sites. When the number of sites remains constant, however, annual benefits begin to grow at an increasing rate with future growth in demand, while annual operations increase linearly according to the FAA's terminal area forecast.

Life-Cycle Cost/Benefit Assessment

Table 4-18 presents the information obtained for the key metrics in the cost/benefits assessment.

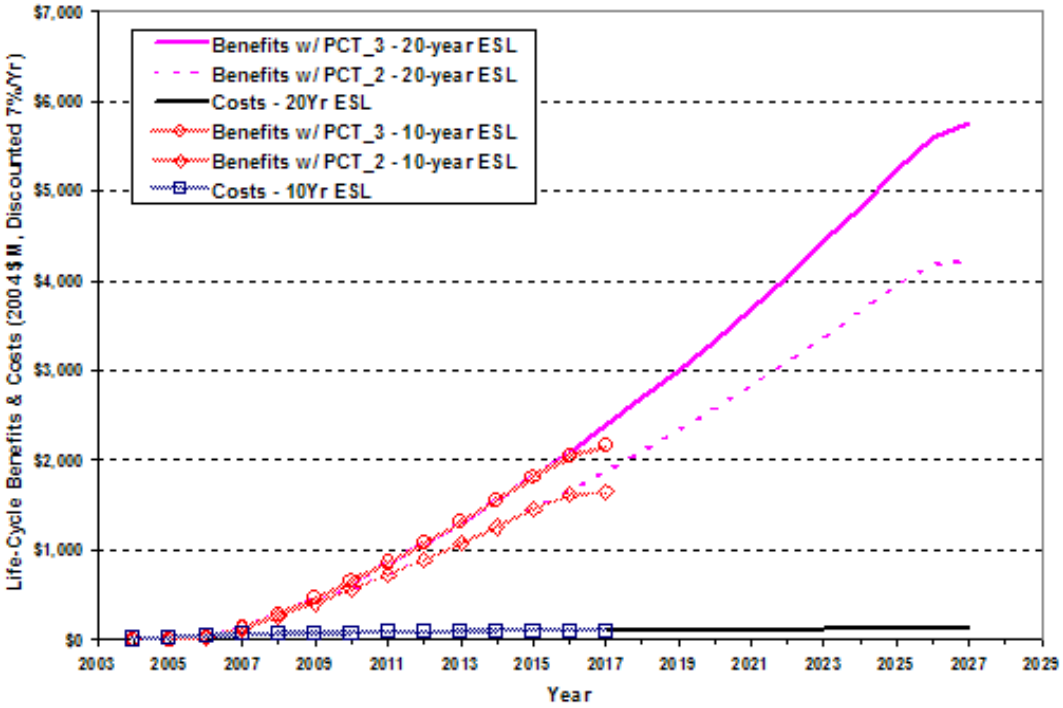
Table 4-18. McTMA Life-Cycle Cost/Benefit Assessment Results (In Millions of 2004 Dollars)

Scenario		Discounted benefits ($M 2004)	Discounted costs ($M 2004)	B/C Ratio	NPV ($M 2004)	BEP
20-year ESL	Extrapolation 1	$5,762.3	$117.2	49	$5,645.1	2007
	Extrapolation 2	$4,224.8		36	$4,107.7	2007
10-year ESL	Extrapolation 1	$2,156.1	$97.9	22	$2,058.2	2007
	Extrapolation 2	$1,649.0		17	$1,551.1	2007

The high B/C ratios and NPVs indicate there is a great deal of potential profit to be made from using McTMA.

Figure 4-12 represents the discounted life-cycle costs and benefits.

Figure 4-12. Discounted Life-Cycle Costs and Benefits



Additionally, a sensitivity analysis was performed. This was motivated by the fact that McTMA costs are on a different scale than the potential benefits. To address this, the authors analyzed the benefits under the assumption that they had underestimated McTMA costs by a factor of two. The results from this are given in Table 4-19.

Table 4-19. McTMA Life-Cycle Cost/Benefit Assessment Sensitivity to Life-Cycle Cost

Scenario		Discounted benefits ($M 2004)	Discounted costs ($M 2004)	B/C ratio	NPV ($M 2004)	BEP
20-year ESL	Extrapolation 1	$5,762.3	$234.3	25	$5,528.0	2007
	Extrapolation 2	$4,224.8		18	$3,990.5	2007
10-year ESL	Extrapolation 1	$2,156.1	$195.9	11	$1,960.2	2007
	Extrapolation 2	$1,649.0		8	$1,453.1	2007

PCT Potential Benefits Analysis Caveats

As previously mentioned, the forecasted level of demand is potentially inaccurate, given the current capacity levels applied under current or McTMA operations. Also, because these estimates use the maximum safe capacity that McTMA may use at each airport, the results presented before this may be theoretical upper bounds on benefits.

CONCLUSIONS

Overall, McTMA demonstrated considerable improvements over the current system. When taking capacity increases into account, each of the five airports studied would realize significant increases in operating profit, ranging from $383,000 for the airport with the lowest demand (TEB) to $17,275,000 for the airport with the highest (PHL). In terms of delay savings, the range went from 10,000 minutes per year at TEB to 395,000 minutes at PHL. With the exception of TEB—where the demand is considerably lower, and thus the marginal benefits lower—the airports would realize savings even with the increases in capacity.

In considering other facilities, the study reported an average annual savings of $16,791,000 (in 2003 dollars). When the study was expanded NAS-wide for 2015, the increases in operating profits matched the increases in demand (again in 2003 dollars), with $363,808,000 being the 2025 yearly increase prediction for PHL, and $12,922,000 for TEB.

In relation to the LCCBA, it is critical to understand that the McTMA system is an expansion of the TMA-SC system that is already in place at eight facilities, and as such consists entirely of additions to that system, and does not exist as a separate tool. This life-cycle cost/benefit assessment found, in both its 20-year ESL and 10-year ESL cases, that the potential benefits far exceed the anticipated costs.

During the study, the most important cost drivers were found to be training and training support costs—between 21 and 22 percent in each case—in both the conservative and optimistic assumptions about PCT growth.

Given a 20-year ESL, airspace users could expect benefits of $11.2 billion (in 2004 dollars) over the life the DST, even using the conservative growth estimates for PCT. In comparison, the costs are placed at $192.2 million (in 2004 dollars) over the life of the tool. This results in a net present value of nearly $4.1 billion in 2004 dollars, giving a B/C ratio of 36. Using more optimistic assumptions about growth for PCT, the net present value climbs to $5.6 billion in 2004 dollars, giving a B/C ration of 49. In both instances, the breakeven point comes in 2007, the second year of operation for NASA’s demonstration site at PHL.

The authors end by noting that the assessment supports the conclusion that McTMA will be a highly beneficial decision support tool.

Chapter 5
Regional Metering (RM)—Summary of Single-Year NAS-Wide Benefits and Life-Cycle Cost/Benefit Assessments

INTRODUCTION

Regional Metering (RM) is at the TRL-4 stage of prototype development and research. The RM capability is envisioned as part of the Center TRACON Automation System (CTAS) to enhance the Single and Multi-Center Traffic Management Advisor (TMA-SC/MC) and complement other traffic flow management (TFM) tools for congested airspace.

Currently, procedures for dealing with such congestion involve holding aircraft at center or sector boundaries and using miles-in-trail (MIT) restrictions. These initiatives are planned and executed with little or no automation assistance, and are inherently an inefficient approach to solving congestion problems. RM can be applied on a much finer scale, thus allocating delay to aircraft over a wider spatial area with a greater degree of equity. RM will provide traffic managers with a tool to efficiently plan, coordinate, and implement metering restrictions between centers. The downstream centers will be able to identify congestion early and formulate a tailored set of time-based restrictions to smooth out the incoming flow. The upstream centers will be able to take those restrictions and distribute delays efficiently while aircraft are transiting through their airspace.

This summary is based on the following reports:

> *Single-Year, NAS-Wide Benefits Assessment of Regional Metering AATT Decision Support Tool,* Dan Rosman, RTO-71 report to the AATT office, July 2003.
>
> *Initial Life-Cycle Cost/Benefit Assessment of Regional Metering (RM),* JianZhong Jay Wang, RTO-78 report to AATT Office, May 2004.

FUNCTIONS AND BENEFIT MECHANISMS

The primary mission of the RM capability is to replace en route miles-in-trail (MIT) operations with time-based metering (TBM), enhancing TMA-SC/MC's ability to address three operational needs:

- First, RM will effectively extend arrival metering beyond the existing range of TMA-SC/MC, thus increasing "delayability" of flights beyond what has been possible with TMA-SC/MC. RM will allow downstream en route Air Route Traffic Control Centers (ARTCCs, or centers) with traffic flow bottlenecks to pass flow restrictions to upstream centers. By doing so, RM extends the availability of time-based metering to better address transition airspace problems caused by terminal-area congestion.

- Second, RM introduces TBM for arrival traffic into many airports that do not warrant full TMA-SC/MC implementation.

- Third, RM will facilitate TBM to address constrained en route airspace problems that typically arise from a combination of traffic volume and limited sector capacity due to weather, equipment outages, or unavailability of special use airspace.

In addition to these three key enhancements, RM will enable traffic managers to better visualize regional flows and demand between upstream and downstream centers.

The following benefit mechanisms have been identified and quantified for RM:

- Time-based metering
  - En route sector TBM
  - Airport arrival TBM
- Independent routing
- Collaborative substitution.

SINGLE-YEAR BENEFITS ASSESSMENT

TBM is more effective than MIT at maximizing the flow rate during constrained operations. By dynamically switching from one stream to another, the flow rate can be maintained during situations when the capacity in one stream is temporarily reduced. Because MIT restrictions require a fixed distance interval between flights, it is not always possible to utilize every arrival slot that is available. In the case of TBM, meter fix times can be assigned more flexibly to meet the Airport Acceptance Rate (AAR) with the highest level of accuracy and minimum level of

unnecessary delay. The quantitative benefit of TBM arises from the delay savings and the improvement in delay equity among the delayed flights. The reported benefits are further decomposed to the ones due to the en route sector TBM and airport arrival TBM.

Current MIT restrictions require controllers to space flights relative to each other. This is easiest to do when they are in trail of each other. In certain areas such as the northeast, this means that flights are queued up considerably in advance of the actual boundary crossing. With RM, flights will no longer have to form a single queue to allow the flow to be metered. By avoiding being routed into a single stream of traffic, they will be able to fly shorter distances, resulting in fuel savings.

The collaborative substitution of the RM allows airlines to decide which planes to delay en route. The quantitative benefit of collaborative substitution arises from increased on-time performance, and non-linear cost of flight delay. A flight is defined as on-time if its arrival time is within 15 minutes of its scheduled arrival time.

The RM benefit assessment is based on traffic simulation at 20 selected sectors and 70 selected airports: one with MIT and another with RM. The flights through the selected en route sectors and airports capture a total of about 50 percent of the flights in the NAS. The NAS-wide benefits in 2000 are based on the extrapolation of results of detailed studies of the selected traffic in two days, one of good weather and one bad weather. The extrapolation is based on the recorded traffic and MIT restriction statistics NAS-wide for every day in 2000.

The NAS-wide benefits in 2015 are based on the same extrapolation scheme used for 2000. The models are run for the same identified en route sectors and airports with about a 33 percent increase of traffic between 2000 and 2015. The en route capacity, as in the base case, is assumed to increase 20 percent between 2000 and 2015.

The annual benefits, for the time-based metering and independent routing, are summarized in Table 5-1, for year 2000 and 2015. Note that the 2000 as well as 2015 economic savings are based on out-dated FAA TAF published in April, 2002, which has inflated future traffic forecast. In other words, RTO-71 overestimated the potential RM single-year benefits. These single-year benefits are adjusted by ASRC Aerospace to more current FAA operations data according to the FAA TAF published in July, 2003, before the extrapolation of RM life-cycle benefits.

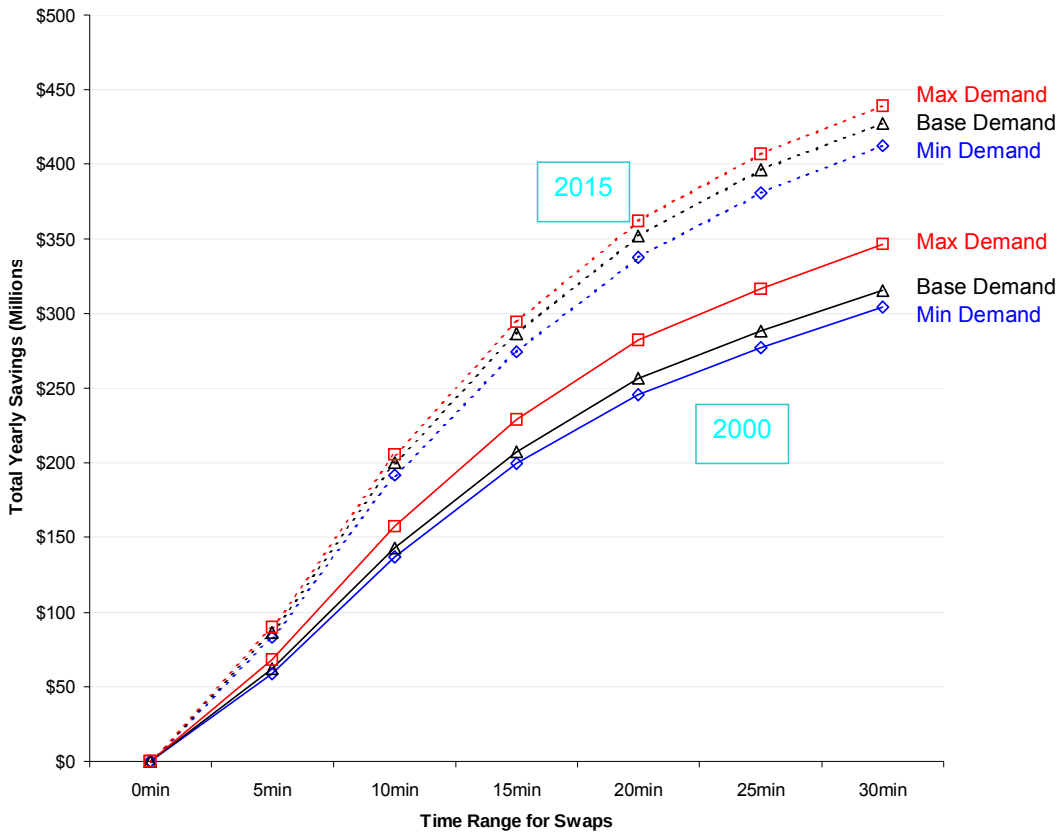
Table 5-1. Single-Year RM Benefit Assessment Results With Corresponding Traffic Demands

Benefit Mechanism	Benefit ($M 2000)			
	2000 base demand	2015 min demand	2015 base demand	2015 max demand
En route section time-based metering	$65.0	$142.0	$224.6	$379.2
Airport arrival time-based metering	$50.0	$98.7	$154.5	$165.9
Independent routing	$25.7	$56.1	$88.8	$149.9
Total RM benefit	$140.7	$296.8	$467.9	$695.0
Demand (air carrier + commuter operations)	29768154	38081026	39569434	41057842

The columns for minimum and maximum demands in 2015 are for the sensitivity assessment. In fact, the annual benefits are also sensitive to the NAS en route capacities as reported in RTO-71: the benefits can be twice or half of the reported values in the above table, if the en route capacities are increased 10 percent or 30 percent.

The benefit due to aircraft swapping is considered sensitive material pending patent application. The AATT office should make the appropriate decision about how this information is distributed. Collaborative aircraft swapping will improve the on-time performance, and based on the non-linear delay cost, the dollar amount savings of the swapped flights is summarized by Figure 5-1 (Figure 43 in RTO-43 report).

Figure 5-1. Average Total Savings for Each Demand Case



Other benefit mechanisms have been identified, but not quantified, which are summarized by Table 5-2.

Table 5-2. Summary of Qualitative Benefit Mechanisms

Benefit mechanism	Projected impact
Visualization	Allow traffic management specialists to look at the same tactical TFM picture across upstream and downstream centers and enhance their ability to better solve regional and local traffic flow problems with less workload and resulting in delay savings.
Workload distribution	Result in less overall delay in high workload sections as well as a more equitable distribution of delay over a wider ranging area. Reduce workload in congested airspace and better distribute workload to upstream sectors.
Custom TFM solution	Minimize the disruption to en route flights by addressing just the impacted area, instead of performing a larger scope solution. Delay savings in terms of average reduction in delay per flight.
Reduction in scope of national initiatives	Give local facilities the ability to better manage dynamic congestion problems within their airspace. Allow strategy planners to reduce the number of flights impacted during national initiatives resulting in delay savings.

LIFE-CYCLE COST/BENEFIT ASSESSMENT

Methodology

The life-cycle cost/benefit assessment (LCCBA) methodology was first developed for a previous assessment of seven AATT DSTs performed in 2001, which has been since revised several times and used in LCCBA studies of MC-TMA and EDP. The methodology includes site selection analysis, site deployment schedule development, cost and benefit assessment models, and the life-cycle cost/benefit assessment. The site selection analysis provides a prioritized list of deployment sites. A site development schedule is developed using this ordered list and the site deployment scheduling methodology. Given the schedule of deployment at the various sites, DST annual costs and benefits are assessed. The costs and benefits are combined in a life-cycle cost/benefit analysis.

Three deployment scenarios of RM are considered. The base case is the national deployment at all 20 centers within the continental United States (in deployment order, they are: ZOB, ZDC, ZOA, ZBW, ZNY, ZAU, ZID, ZTL, ZMP, ZLC, ZSE, ZLA, ZKC, ZJX, ZHU, ZME, ZFW, ZAB, ZDV, and ZMA) while the other cases are alternative limited deployments of the eight most probable sites (Centers).

Site selections and their deployment order were decided based on input from NASA's RM developers and a single-year, NAS-wide RM benefit study performed in TO-71. Deployment order is either driven by the center-by-center RM potential benefits breakdown from the TO-71, or by a "single-cluster" logic. The deployment site order for the first alternative, denoted "RM-8 sites (TO-71)", is: ZOB, ZDC, ZOA, ZBW, ZNY, ZAU, ZID, and ZTL. The deployment site order for the first alternative, denoted "RM-8 sites (Cluster)", is: ZOB, ZAU, ZID, ZDC, ZTL, ZME, ZKC, and ZMP. See Figures 5-2 and 5-3 for graphical representations of all the deployment scenarios. In Figure 5-2, the first eight sites depict the limited deployment case.

Given the schedule of deployment at the various sites, DST annual costs and benefits are assessed. The costs and benefits are combined in a life-cycle cost/benefit analysis. Three key economic metrics (net present value, benefit-to-cost ratio, and breakeven point) are assessed.

Figure 5-2. Limited and NAS-Wide RM Deployment With TO-71 Logic

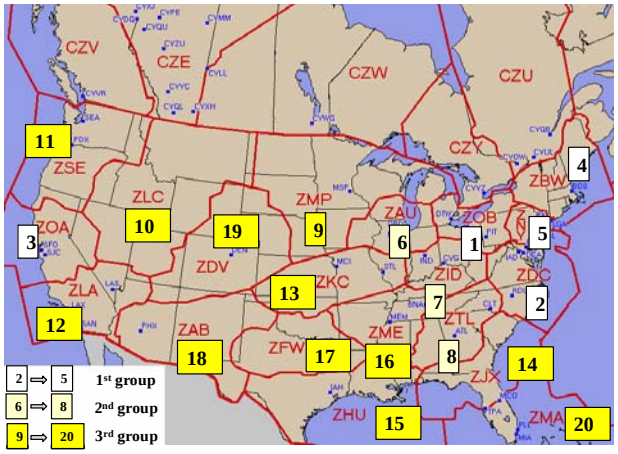
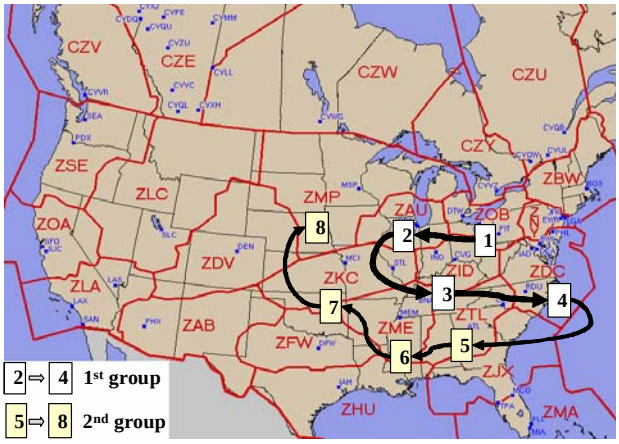


Figure 5-3. Limited RM Deployment Order With Cluster Logic



Life-Cycle Cost Estimation

The life cycle cost (LCC) assessment methodology addresses the three key cost characteristics: consideration of all cost types (coverage); establishing timing of these costs (LCC phase); and quantification of these costs (estimation). It can be represented by a three-dimensional space where the axes represent coverage, estimation, and LCC phase, similar to previous cost-benefit analyses.

Special attention has been paid to estimate only the incremental costs of RM on top of TMA-SC/MC. It was assumed that prior to the deployment of RM, TMA-SC will be in operational use at the eight existing FFP1 TMA sites as well as the 3 proposed FFP2 sites. In addition it was also assumed that MC-TMA will pre-exist in the eight sites that the initial LCCBA of MC-TMA study considered to be the limited deployment scenario for MC-TMA. This matches the benefit assessment by TO-71.

Table 5-3 shows life-cycle costs for the three RM deployment scenarios, before and after discounting. Figure 5-4 depicts the annual (calendar year) and cumulative costs before discounting for the RM-20 site case, while Figure 5-5 shows the breakdown of the costs after discounting. Both figures are representative of all deployment scenarios considered.

Annual costs start with the initial research, engineering, and development (RE&D) costs, increase during deployment, then level off, with generally decreasing costs afterward, but with occasional peaks representing hardware refresh costs. The leveling off of the annual costs starts when the project enters the sustainment phase. At the end of their economic service life, RM is removed from service starting with the NASA demonstration site. During this period the annual cost decrease also reflects the reduced number of operational sites. Software maintenance, NASA development, and FAA software development are the top three cost drivers for all three deployment scenarios.

Table 5-3. RM Life-Cycle Cost Results

Scenario	Life-cycle cost ($M 2004, before discounting)	Life-cycle cost present value ($M 2004, after discounting
RM-20 site	232.6	93.0
RM-8 site (TO-71)	141.0	70.2
RM-8 site (Cluster)	141.2	71.6

Figure 5-4. Annual and Cumulative Costs of the RM-20 Site Case (Before Discounting)

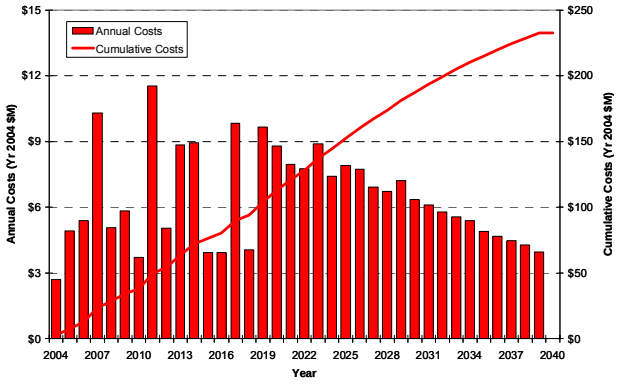
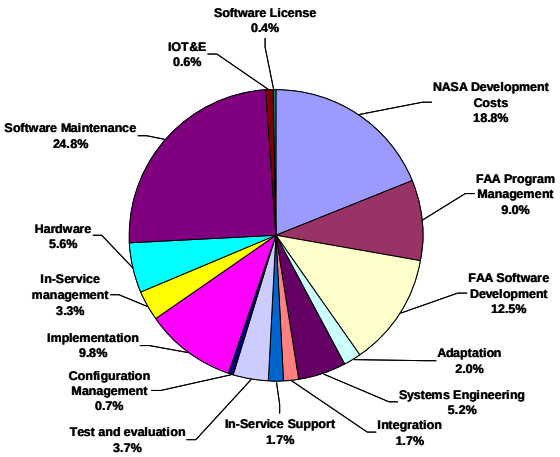


Figure 5-5. Breakdown of RM-20 Site Life-Cycle Costs (After Discounting)



Life-Cycle Benefit Estimate

Life-cycle benefit estimation is based on the RM deployment scenarios. Furthermore, the benefit is also a function of the traffic level, which can be estimated either as a piece-wise linear interpolation, or as an exponential interpolation, of the point estimation in Table 5-1.[1] Note that the point estimation in Table 5-1 are adjusted to more current FAA operations data for according to the FAA TAF before this process.

The life-cycle benefit results for all three scenarios are presented in Table 5-4. Figures 5-6 and 5-7 show the piece-wise linearly, and exponentially extrapolated annual[2] and cumulative benefits before discounting for the 20-site, full deployment scenario. Figures for other cases are similar.

[1] Since Table 5-1 does not include the benefit from collaborative swapping as shown in Figure 5-1, the benefit estimates are conservative.

[2] Calendar year.

Table 5-4. RM Life-Cycle Benefit Results

Scenario		Life-cycle benefit ($M 2004, before discounting)	Life-cycle benefit PV ($M 2004, after discounting)
RM-20 site	Linear benefits growth	14,122.4	3,690.1
	Exponential benefits growth	22,315.0	4,880.6
RM-8 site (TO-71)	Linear benefits growth	8,768.9	2,571.5
	Exponential benefits growth	10,937.9	2,890.5
RM-8 site (Cluster)	Linear benefits growth	6,093.9	1,800.0
	Exponential benefits growth	7,587.3	2,015.4

Figure 5-6.Linear Benefits of the RM-20 Site Case (Before Discounting)

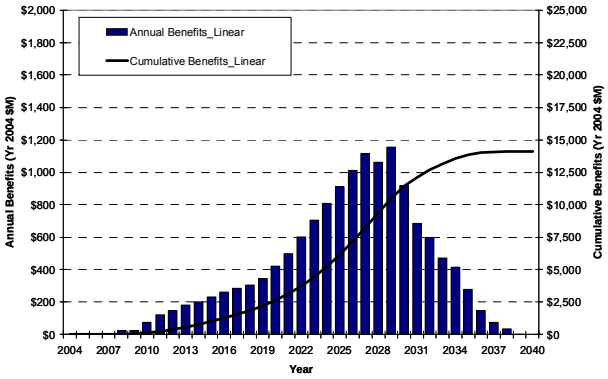
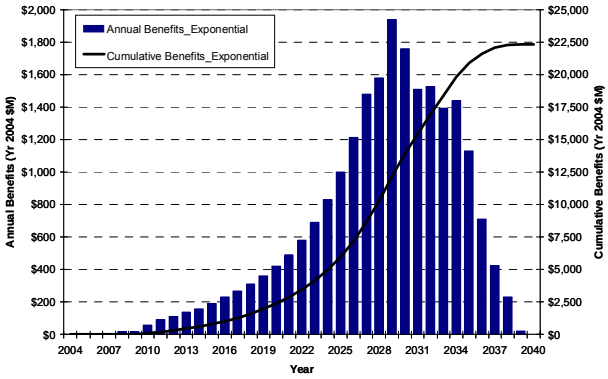


Figure 5-7. Exponential Benefits of the RM-20 Site Case (Before Discounting)



The annual benefits generally rise and fall with the number of sites in operation. When the number of sites remains constant, benefits continue to escalate with time. This is because benefits grow with annual operations.

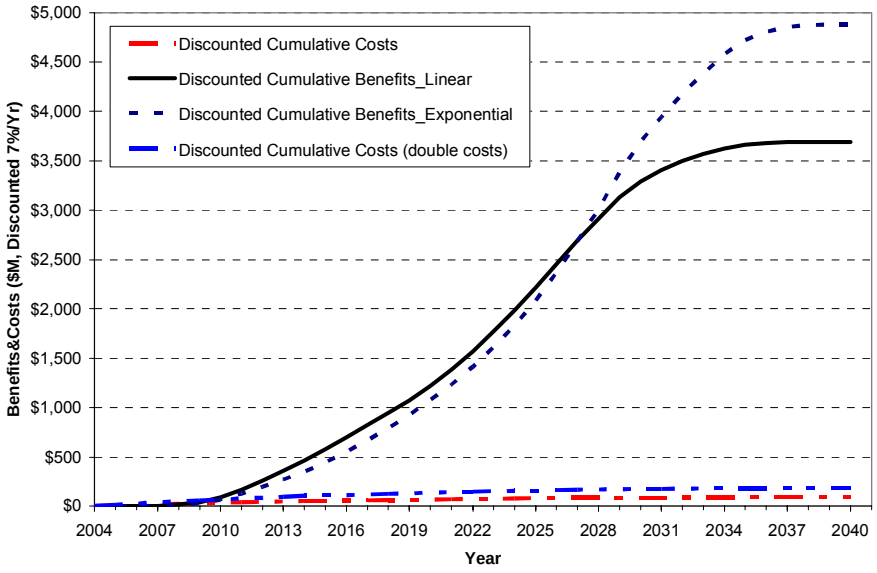
Life Cycle Cost/Benefit Assessment

Table 5-5 shows economic metrics—net present value (NPV), benefit-to-cost (B/C) ratio, and breakeven point (BEP)—for all deployment cases. The B/C ratios range from 25 for the RM-8 site (cluster) case to 52 for the RM-20 site case. The very high B/C ratios and NPVs indicate that Regional Metering is potentially a very valuable DST and a good use of public funds. Figure 5-8 is a graphical representation of the discounted life-cycle costs and benefits for the RM-20 site case.

Table 5-5. RM Life-Cycle Cost/Benefit Assessment Results

Scenario		Discounted benefits ($M 2004)	Discounted costs ($M 2004)	B/C ratio	NPV ($M 2004)	BEP
20-site	Linear benefits growth	3,690.1	$93.0	39.67	3,597.0	2009
	Exponential benefits growth	4,880.6		52.47	4,787.6	2010
8-site (TO-71)	Linear benefits growth	2,571.5	$70.2	36.61	2,501.2	2009
	Exponential benefits growth	2,890.5		41.15	2,820.2	2009
8-site (Cluster)	Linear benefits growth	1,800.0	$71.6	25.15	1,728.4	2009
	Exponential benefits growth	2,015.4		28.15	1,943.8	2010

Figure 5-8. Life-Cycle Cost/Benefits for the RM-20 Site Case and Sensitivity to Potential Costs



Estimated potential RM costs are not of the same magnitude as the estimated potential benefits. A sensitivity analysis shows that if the potential costs have been underestimated by as much as a factor of two, only a 2 percent to 4 percent drop will be seen in the NPVs. The life-cycle cost/benefit results of this sensitivity case for the RM-20 sites scenario are depicted in Figure 5-8.

This study concludes that RM would be a low-cost, high-return DST capability. This owes much to the fact that RM is being developed as an enhancement to TMA-SC/MC. Many of the costs would have been covered by TMA-SC/MC by the time RM is under deployment, with a vast potential for benefits (for example, time-based metering in the en route airspace, and in terminal airspace at airports without TMA installations) that TMA-SC/MC, alone, would not realize.

Chapter 6
Traffic Flow Management (TFM) R&D—Summary of Single-Year NAS-Wide Benefits and Life-Cycle Cost/Benefit Assessments

INTRODUCTION

Traffic Flow Management (TFM) is a collaborative decision-making process involving the FAA and airlines when the National Airspace System (NAS) is constrained due to inclement weather, traffic congestion, and other conditions. While attempting to maintain air traffic demand below capacity at airports and in the air, TFM will slow down or stop traffic, or redirect the traffic to a different area. TFM mainly includes the following programs: Ground Delay Program (GDP), Ground Stop (GS), Miles in Trail (MIT), rerouting, departure spacing program, and holding.

Strategic TFM programs are managed by the Air Traffic Control System Command Center (ATCSCC), while tactical programs are managed by the ARTCC, TRACONs, and control towers. Limitations of the current TFM process and procedures can be summarized as follows:

- There is *limited integration* of FAA decisions on different TFM initiatives. This may be improved with increased integration, such as taking into account the resulting congestion while making rerouting decisions.

- There is a *limited ability to predict NAS problems and assess solutions* accurately, leading to overly conservative restrictions. Given the available accuracy in weather prediction, traffic managers lack sufficient ability to predict the effect of their actions.

- There is *limited cooperation between the FAA and the airlines* in making traffic flow management decisions. There is also a need for common situational information and integrated—rather then conflicting—solutions between the FAA and the airlines, and among different airlines.

NASA's Advanced Air Transportation Technologies (AATT) project is developing TFM research and development tools as extensions of the Future Air Traffic Management Concepts Evaluation Tool (FACET). FACET provides an environment for modeling, developing, and evaluating improved concepts for system-wide operations over the NAS prior to operational use. TFM R&D will extend the modeling and simulation capabilities of FACET to provide planning and

evaluation tools to enable more efficient NAS operations by removing unnecessary restrictions. TFM R&D tools are intended to support the internal and collaborative decision-making processes of the FAA and airline personnel with regard to traffic flow management. Adaptation of FACET to meet the needs and requirements of the ATCSCC and other FAA facilities is referred to as the System-Wide Evaluation and Planning Tool (SWEPT). Adaptation of FACET to satisfy the needs and requirements of the Airline Operation Center (AOC) is called FACET-AOC.

This summary is based on the RTO-78 report to the AATT office: *Single-Year, NAS-Wide Benefits Assessment of TFM R&D,* November 2003, whose objective was to provide an initial assessment of the potential NAS-wide benefits of TFM R&D tools for a recent year and for 2015. This chapter also documents the life-cycle cost/benefit assessment (LCCBA) of TFM R&D. The LCCBA summary is based on the report for the ASRC Aerospace Corporation. The full citation is as follows:

> *Life-Cycle Cost/Benefit Assessment of Traffic Flow Management Research and Development (TFM R&D).* Jianzhong Jay Wang. Contract NAS2-03145. Task Order 480021. ASRC Aerospace Corporation, NASA Ames Research Center, Moffett Field, CA 94035.

FUNCTIONS AND BENEFIT MECHANISMS

TFM R&D (SWEPT and FACET-AOC) functions are to:

- Collect and share information
- Predict future behavior
- Identify problems
- Generate alternative solutions
- Evaluate alternatives and select appropriate solutions
- Monitor and evaluate system performance.

The RTO-78 report concentrated its analysis modeling and benefit assessment on the application of SWEPT and FACET-AOC to the following three problems:

- SWEPT decision support in solving Flow Constraint Area (FCA) problems
- SWEPT decision support in solving airspace design and resectorization problems

- FACET-AOC decision support in airline response to congestion, particularly preemptive actions by the airlines.

Associated with each of the functions of TFM are several mechanisms that result in common benefits. Table 6-1 presents these.

Table 6-1. Functions and Related Benefit Mechanisms

TFM functions	Benefit mechanisms	Benefits
FAA comparison between reroutes (without metering)	Shorter routes	Increased throughput Reduced arrival delay Reduced en route delay
	More distributed and balanced route loading	
	More accurate selection of impacted flights	
	Accounting for FCA uncertainty	
	More accurate duration	
Integrated TFM in solving FCA problems	Enables: FAA Comparison	As above
	Improved metering	Increased throughput Fuel saving
	Improved holding on ground	Fuel saving Reduced en route delay
	Improved rerouting around overloaded sectors	Increased throughput Reduced en route delay Reduced arrival delay
Collaborative rerouting around FCA	Less deviation from airline-preferred route	Increased through put Reduced arrival delay Reduced en route delay
	More distributed and balanced route loading	
SWEPT: solving airspace design problems	Balanced distribution of traffic over sectors	Reduced arrival delay Reduced en route delay
	Better coordination (fewer hand-offs)	
	Reduced airspace complexity	
	Improved flow interaction	
FACET-AOC: preemptive airline response to NAS constraints	Enables Collaborative rerouting around FCA	As above
	Airline to re-file alternate route	Increased throughput Reduced arrival delay Reduced en route delay
	Airline delay departure time	Increased throughput Reduced arrival delay Reduced en route delay Reduced arrival delay of high-priority flights
	Airline cancel flight	

MODELING AND ANALYSIS APPROACH

General Modeling Methodology

The analysis methodology starts with the identification of benefit mechanisms, followed by a comparison of baseline and TFM R&D traffic levels. Finally, the enabled traffic is converted to economic values, and extrapolated to future years.

The benefit mechanism analysis involves the following steps:

1. Assess the current NAS operations and flow management procedures, identifying their constraints and limitations

2. Assess TFM R&D functionality

3. Identify the benefits of each TFM R&D function by applying the function to alleviate the identified system constraints and limitations. This includes mapping separate benefit mechanisms for each function according to the constraints on current operations.

When comparing operations in the current NAS to those with TFM R&D, real traffic and weather data are used as recorded in the Enhanced Traffic Management System (ETMS), while aircraft operations are based on the simulation of SWEPT and FACET-AOC. The reason to use simulation even for current NAS operations, as opposed to the traffic recording, is because the traffic recording has maneuvers for reasons other than TFM. It is thus a more equitable comparison if both results are from simulations.

Modeling TFM R&D Benefit in Solving Flow Constraint Area (FCA)

An FCA is an area of the NAS that may constrain the flow of air traffic. SWEPT may assist in solving rerouting around an FCA in either real time or offline modes of operation.

In the offline mode, SWEPT assists using historical analysis of FCA problems in the redesign of current TFM initiatives, such as the development of new reroutes for the National Playbook and the development of time-based metering. The new TFM alternatives could then be implemented in rerouting around an FCA using SWEPT in real time. The offline mode of SWEPT thus increases and improves alternative solutions available for the real-time mode, based on historical analysis. Benefit mechanism identification and modeling are focused conservatively on the real-time mode in the RTO-78 report.

By applying SWEPT functions to alleviate limitations in the current TFM procedures, three primary benefit mechanisms will be considered for rerouting around an FCA in real time:

- SWEPT will improve rerouting by enabling the Command Center to test and simulate different reroutes and reroute modifications, from a set of FAA reroute alternatives such as the playbook.
- SWEPT will improve rerouting by enabling an integrated TFM approach integrating rerouting with temporal metering decisions.
- SWEPT will improve rerouting through enabling collaboration with airlines, allowing the airlines to suggest and request to replace the FAA reroute selection with their preferred reroutes to avoid the FCA.

Modeling the Benefit of Reroute

Through its simulation engine, SWEPT provides a tool for reroute assessment and more flexible reroute selection.

The benefit mechanisms include selecting shorter reroutes, a more balanced loading of flights among reroutes, a more accurate identification of the set of flights that need to be rerouted, and a more accurate duration of reroute application. With a prediction of FCA progress, which SWEPT is expected to include, reroute selection may be optimized accounting for the uncertainty in the FCA progress over time. The need for holding and MIT restrictions to mitigate the congestion caused by a playbook reroute is thus reduced. A result of this is reduced en route delay. Because this response does not delay the departure of the flight any later than originally scheduled, en route delay is reduced without increasing ground delay. Thus, arrival delay, which includes en route delay and ground delay, is also reduced.

Modeling the Benefit of Integrated TFM

SWEPT enables the integration of a number of TFM responses to congestion. RTO-78 adopts a three-tiered approach to solving the FCA problem. Tier one is a global reroute to avoid the FCA spatially. A result of this reroute is a high volume of traffic passing through new sectors, which can cause congestion in these sectors due to existing traffic already passing through them. Temporal restrictions therefore form the second tier, with the function of metering the increased traffic flow in these congested sectors. Local reroutes form the third tier in assisting the temporal restrictions in preventing any remaining sector overload. Local reroutes refer to the tactical rerouting of selected flights around a congested sector, and constitutes an offloading of these flights to adjacent sectors that may have lower loads.

The integration of these TFM responses allows making the rerouting and associated temporal metering decisions for each flight based on the combined effects of both types of restrictions: rerouting and metering. This results in improved effectiveness of each of the responses as they are applied in accordance with each other, and not independently.

Modeling FAA and Airline Collaborative Rerouting

In addition to assessing different FAA reroutes, a collaborative rerouting scheme is enabled by SWEPT whereby the airlines may be able to suggest and be granted reroutes closer to their preferences. Using SWEPT for collaborative rerouting around an FCA, where reroutes are allocated through collaborative decision making (CDM) with the airlines, results in a number of benefits as described below.

Collaborative rerouting around an FCA will reduce flight deviation from airline preferred routes, as airlines are able to choose reroutes according to their own priorities. This leads to shorter routes as long as the airline preferred routes are shorter than the FAA selected reroutes. Shorter routes lead to benefits in terms of increased throughput and reduced en route and arrival delays.

Collaborative rerouting also enables a more distributed and balanced loading of flights on reroutes, as fewer flights will follow the congested reroute selected by the FAA. This will result in a reduction in en route congestion and a corresponding reduction in the need for mitigating congestion through temporal restrictions.

Modeling TFM R&D Benefit in Airspace Dynamic Resectorization

To improve operation of the NAS, sectors can be redesigned dynamically to cope with traffic congestion, equipment outages, weather, special use airspace, airport configuration changes, and the like. If done properly, dynamic resectorization can result in a more balanced distribution of traffic over the sectors; improved coordination between controllers, as the sectors are redesigned to reduce the number of hand-offs required; reduced airspace complexity; and improved interaction among the traffic flows.

Benefits of resectorization include separating two streams between two controllers; redesigning sector boundaries to avoid streams exiting and then re-entering a sector; and switching fixes such that flows do not intersect. Each of the benefit mechanisms described above results in avoidance of a particularly high workload in the sectors in question. Avoidance of high workloads reduces the need for en route holding and MIT. En route holding and MIT are also reduced directly by improved flow interaction and more balanced distribution of traffic. This further results in reduced en route delay and reduced arrival delay, since ground delay is not increased.

Modeling the Benefit Mechanisms of Preemptive Airline Collaboration

Preemptive collaboration analyzed in this study is initiated by the airlines in response to a NAS constraint, enabled by FACET-AOC, prior to any FAA TFM to deal with the constraint.

The main preemptive airline actions in response to NAS constraints are the following:

- The re-filing of an aircraft's flight plan on an alternate route
- The delay of a departure by the airline
- The cancellation of a flight by the airline.

All three preemptive actions by the airlines would result in less traffic being impacted by the constraint, and thus less congestion at the constraint. This would require less severe TFM initiatives to be put in place by the FAA to deal with the constraint. This may include, for example, reduced en route holding, reduced MIT restrictions, and less need for a playbook reroute to be applied. A reduction in restrictions would result in a reduction in en route delay and arrival delays. These reductions benefit all traffic and not just the flights that were acted upon by the airlines. A reduction in restrictions also results in an increase in system throughput as demand pressure is maintained at destination airports.

Modeling preemptive airline action is achieved by introducing airline responses to the FCA prior to the FAA's TFM initiative (a playbook reroute). The rest of the model is identical to the baseline case of a playbook reroute followed by required metering.

Traffic Sample

The following are the five playbook reroutes and the dates used in the analysis:

- CAN_1_EAST on June 11, 2003
- VUZ on September 15, 2002
- FAM on August 16, 2002
- IAH_EAST on August 16, 2002
- DFW_EAST on September 19, 2002

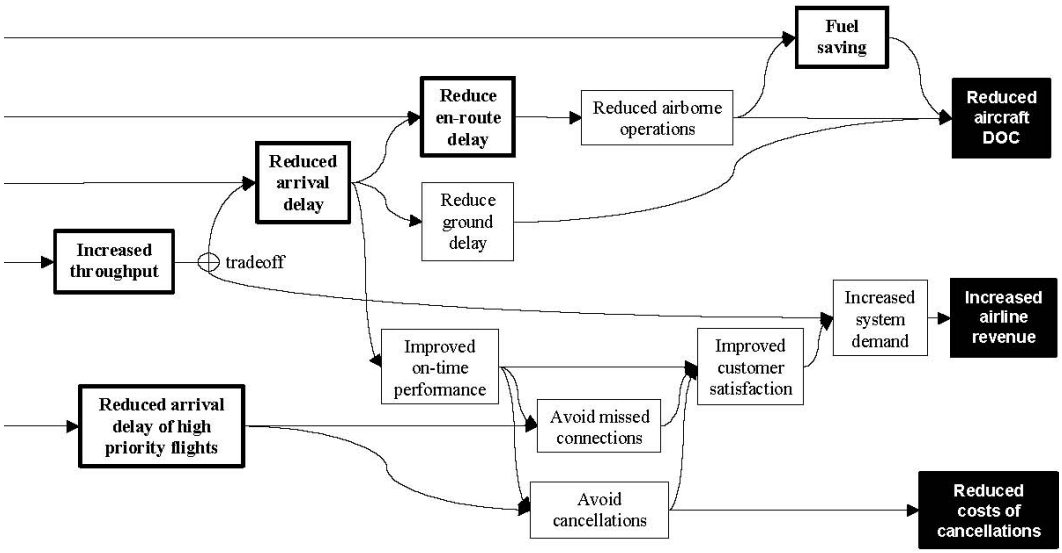
The first three playbook reroutes are transcontinental, while the fourth and fifth are airport closures. Weather is the reason to initiate the rerouting of flights, although it was only for a certain period in each day selected. For the benefit

assessment due to dynamic airspace resectorization, only the three transcontinental playbook reroutes are analyzed.

Methodology of Economic Benefit Estimate

Economic benefits come from fuel savings, reduced en route delay, reduced arrival delay, increased throughput, and reduced arrival delay of high priority flights. The analysis flow chart is shown in Figure 6-1.

Figure 6-1. Direct Economic Benefits



Extrapolation to Yearly Benefits

Yearly economic benefits are estimated by extrapolating the benefits of each type in a year. The number of playbook reroutes each year was estimated from two periods in 2003, July and September. July, a summer month, is a period when severe weather is generally more common, and the number of playbook reroutes is thus higher. In September, severe weather is less common, which is more typical of the rest of the year. The number of playbook reroutes, per month, is correspondingly lower.

Extrapolating the results for July to the whole summer (June to August), and the results for September to the rest of year (September to May), the average number of playbook reroutes of each type implemented per year was estimated as follows:

- Transcontinental: 317 reroutes per year
- Airway Closure: 108 reroutes per year
- Airport Closure: 905 reroutes per year

- South to Northeast: 49 reroutes per year
- Non-playbook: 335 reroutes per year
- Other Reroutes: 1379 reroutes per year.

Since only two types of reroutes were modeled for transcontinental playbook reroutes (CAN_1_EAST, FAM and VUZ), and airport closure playbook reroutes (DFW_EAST and IAH_EAST), the other types of playbook reroutes are first mapped into these two types. Airway closure playbook reroutes and South to Northeast playbook reroutes are similar in nature to transcontinental reroutes, so the benefits of TFM R&D to these reroutes is likely to be similar to the benefits to transcontinental reroutes. Airway and South to Northeast playbook reroutes can thus be assumed to be grouped with transcontinental reroutes, increasing the total number of such reroutes to 474 per year.

Non-playbook reroutes and other reroutes implemented by the FAA differ significantly from transcontinental and airport closure playbook reroutes. Because the benefits of TFM R&D have not been assessed for such tactical reroutes, the benefits of these reroutes cannot be included in the analysis. The results presented below are thus conservative.

Extrapolation to Future Years

For 2015, the benefits assessment follows the same methodology as for 2002, except that the traffic is a forecast. Increases in demand relative to 2002 levels are forecast by the FAA Terminal Area Forecast (TAF) released in June 2003. Both the baseline and the improvement scenarios were simulated under the increased demand.

Demand was increased by adding flight plans to the simulation input files. Flight plans were added such that the departure rate from each airport is increased to the level predicted by the TAF forecast of each airport. Departures from each airport were added by selecting a flight plan randomly and duplicating it. The demand was increased in each hour of the day separately to maintain the dynamics of the original schedule over time.

Modeling parameters were not adjusted to reflect any possible technological improvements. Such adjustments to modeling parameters could include increased sector capacities to reflect improved technologies, addition of runways, navigational aids, and decision support tools.

The benefit estimates for the years between 2002 and 2015 are done via interpolation; for the years beyond 2025, they are done via extrapolation. The interpolation and extrapolation can be linear or exponential curves fitting the two years' data.

LCCBA Methodology Overview

The process used to derive results closely follows that used in numerous prior LCCBA studies. The methodology consists of site selection analysis, deployment schedule development, cost and benefit assessment models, and a prioritized list of deployment sites.

LCCBA Site Selection

There were two possible options for deployment of SWEPT, one having the system distributed among some or all ARTCCs, the other being centralized at the ATCSCC. After evaluating the two options, the authors concluded that because of small benefit from using a distributed system, they would consider only the centralized version of deployment. This allows each center to act as a client of the main system, running queries on the server located at the ATCSCC.

User interface changes associated with SWEPT would be implemented as part of periodic upgrades of ETMS client applications that are located at each center, as well as the ATCSCC.

For FACET-AOC, this study assumes only that the system has been deployed at the major passenger airlines. This is due to the fact that most rerouting occurs at the major airlines, thus allowing the study to focus on FACET-AOC's rerouting capabilities. Major airlines are those carriers that see over $1 billion in operating revenue. While this category includes cargo airlines, the authors excluded these from the study because most cargo flights operate at night, and thus do not contribute heavily to airspace congestion. This gives a total of 12 FACET-AOC users in the study.

Under the site selection process, the authors created the two scenarios for development. In the first scenario, a private company like Flight Explorer would take over development and deployment once the DST reaches Technology Readiness Level 6 (TRL 6). Operating in this way would mean that the 12 major airlines would subscribe to services provided by the company. This scenario is indicated as FACET-AOC (FE). In the second scenario, the 12 airlines would be assumed to take responsibility for development and deployment once NASA has concluded its work.

LCCBA Site Deployment Schedule

Milestones used to create a schedule for deployment include: TRL 6 completion, Initial Daily Use (IDU), Planned Capability Available (PCA), and Installation. These were matched to the events occurring in the life cycle benefits and cost process as follows:

- FAA/Flight Explorer/airline program start date is the same as the TRL 6 completion date.

- Technology transfer start date is the same as the TRL 6 completion date. It will last a period of 2 years.
- The FAA's/Flight Explorer's/airline's deployment costs, initial hardware, software development, site adaptation, and so on, would occur during the deployment phase, i.e., from the start of the program to the PCA at the last site.
- The period between last site PCA to end of program will be the sustaining phase where the operation & maintenance (O&M) costs (software maintenance and the like) would occur.
- Benefits at a site will begin at PCA, and end after 20 years.
- The FAA/Flight Explorer/airline program end date is the same year that the last site reaches its 20-year economic service life (ESL).

In terms of process currently underway, TFM R&D is expected to be complete by the end of September 2004. Using previous DST processes as a guide, the time between TRL 4 and 5 is believed to be approximately 1.5 years. The same amount of time is given for moving from TRL 5 to TRL 6. This places the completion of TRL 6 for TFM R&D in September 2007. The following are scheduling assumptions until the PCA at the first site:

- Time between TRL 4 completion to TRL 5 completion: 1.5 years
- Time between TRL 5 completion to TRL 6 completion: 1.5 years
- Time between TRL 6 completion to IDU at the first site: 0.5 years
- Time between IDU to PCA at the first site: 0.5 years
- Time between Installation and IDU at a site: 1.0 years

Because the deployment of FACET-AOC is anticipated to be relatively simple, all airlines are assumed to be deploying it simultaneously. This means that the above assumptions are sufficient for FACET-AOC as well.

Life-Cycle Cost Assessment Methodology

In this study, the life-cycle cost (LCC) assessment methodology considers three cost characteristics: consideration of all cost types (coverage), establishing timing of these costs (LCC phase), and quantification of costs (estimation). This results in the use of a three-dimensional matrix, with Coverage of Costs, Cost Estimation, and LCC Phase as the three axes. This methodology is similar to that used in all ASRC LCCBAs. The three branches of characteristics were evaluated across the projected life cycle of TFM R&D to arrive at the results presented later. Those methods specific to this assessment are presented below.

COVERAGE OF COSTS

A two-level arrangement was used to model the costs for this program: cost elements, and cost factors. Additionally, no site adaptation was required. Due to the study assumptions that SWEPT will be a government acquisition program, and that FACET-AOC will be under the control of a private company, some costs applicable to SWEPT are not applicable to FACET-AOC, and vice versa.

SOFTWARE-RELATED COST ESTIMATION

For cost estimation on TFM R&D software issues, Constructive Cost Model (COCOMO) II was utilized.

For development of software, costs fall into three categories: NASA software development, user software development, and user software maintenance. The inputs for the estimation process are presented in Table 6-2.

Table 6-2. User Software Development Cost Estimation Inputs

		SLOC	Reuse	Learning
SWEPT	New Code	50,000	N/A	N/A
	Old Code	392,236	100%	90%
FACET-AOC (Flight Explorer)	New Code	50,000	N/A	N/A
	Old Code	392,236	95%	100%
FACET-AOC (Airlines)	New Code	50,000	N/A	N/A
	Old Code	392,236	95%	100%

Scale Drivers (SF_i)	1.0775
Effort Multipliers (EM_i)	1.3151
Labor Rate ($/month)	29,759

Note: SLOC = Source Lines of Code.

OTHER COST ESTIMATIONS

Cost factors had to be estimated using an assortment of methods. These included parametric, analogy, and expert judgment, and were based on the analysis done for the TMA-SC Free Flight Phase (FFP) 1 and FFP 2 costs. The equations used for that study were employed, with modifications specific to software development issues, for use in this assessment.

Life-Cycle Benefit Assessment Methodology

Benefits of TFM R&D were originally computed by Titan Systems Corporation for demand levels in years 2003 and 2015. Annual, NAS-wide benefits were derived using a simulation tool in order to compare operations that take advantage of TFM R&D tools to those baseline tools that are currently in use. These benefits

were then converted into economic terms and extrapolated into annual savings based on the number of transcontinental and airport closure playbook reroutes that are implemented each year. Results for 2015 were determined by including growth in demand at a rate determined by the Terminal Area Forecasts in the model. Results of this extrapolation are presented in the following section on results, findings, and conclusions.

RESULTS, FINDINGS, AND CONCLUSIONS

Single-Year, NAS-Wide Benefit Estimate

SUMMARY ECONOMIC BENEFIT ESTIMATES

Table 6-3 shows the summary economic benefits estimated by the RTO-78 study. Note that RTO-78 used slightly inflated air traffic demand data published in July, 2003 by the FAA. These single-year benefits are adjusted by ASRC Aerospace to more current FAA operations data according to the FAA TAF published in March, 2004, before the extrapolation of RM life-cycle benefits. In addition, the FACET-AOC single-year benefits are reduced to reflect savings from deployment of only the 12 major airlines.

Table 6-3. Yearly Economic Benefits of TFM R&D Selected Functions

Analyzed TFM R&D functions	Yearly savings in 2003 ($M 2002)	Yearly savings in 2015 ($M 2002)
SWEPT: Improved rerouting around FCA	$84.253	$186.953
SWEPT: Airspace dynamic resectorization[1]	$14.568	$95.561
FACET-AOC: Preemptive airline collaboration	$97.077	$277.976

The benefit estimates reported in this study are believed to be low-fidelity and conservative due to a number of reasons:

- This study focused on only a subset, namely three, of the possible TFM R&D functions.
- Only a subset of the benefit mechanisms of these three functions was assessed. The benefit mechanisms that were analyzed included:
  - The use of SWEPT for simulating different playbook reroutes and selecting one reroute based on integrated rerouting and metering. These are only one example of possible integration between TFM programs.

[1] Because it was decided that dynamic resectorization using SWEPT is not an achievable goal in the near future, this benefit is not counted towards SWEPT life-cycle benefits.

The reroute with least total delays was selected, where total delays were caused by reroute distance and metering due to congestion.

- The use of SWEPT for allocating and distributing flights over more than one reroute, also integrating rerouting and metering in the allocation decision.
- The use of SWEPT for collaboration with airlines to allocate flights between playbook and customized reroutes.
- The use of SWEPT for changing sector boundaries to distribute and reduce sector overload and reduce the need for metering.
- The use of FACET-AOC for one airline or all airlines re-filing of alternate routes for their flights affected by an FCA to reduce the need for FAA metering.

- Only airport closure and transcontinental reroute scenarios were selected to cover the two most prominent playbook reroute types; no other reroute types nor other TFM restrictions (such as temporal restrictions) were considered.
- This study covered more functions at the expense of more details for each specific function. A number of simplifying assumptions were made, given the wide range of functions covered and the non-constraining fidelity requirements.

LCCBA Results

LIFE-CYCLE COST RESULTS

For the two FACET-AOC scenarios and the single SWEPT scenario, Table 6-4 presents the cost results for the full life-cycle:

Table 6-4. TFM R&D Life-Cycle Cost Results

Scenario	Life-cycle cost ($M 2004, before discounting)	Life-cycle cost present value ($M 2004, after discounting)
SWEPT	$63.2	$34.7
FACET-AOC (FE)	$51.3	$34.3
FACET-AOC (AL)	$503.1	$315.8

Figures 6-2, 6-3, and 6-4 depict the annual and cumulative costs of SWEPT and FACET-AOC (FE and AL) before discounting.

Figure 6-2. Annual and Cumulative Costs of SWEPT (Before Discounting)

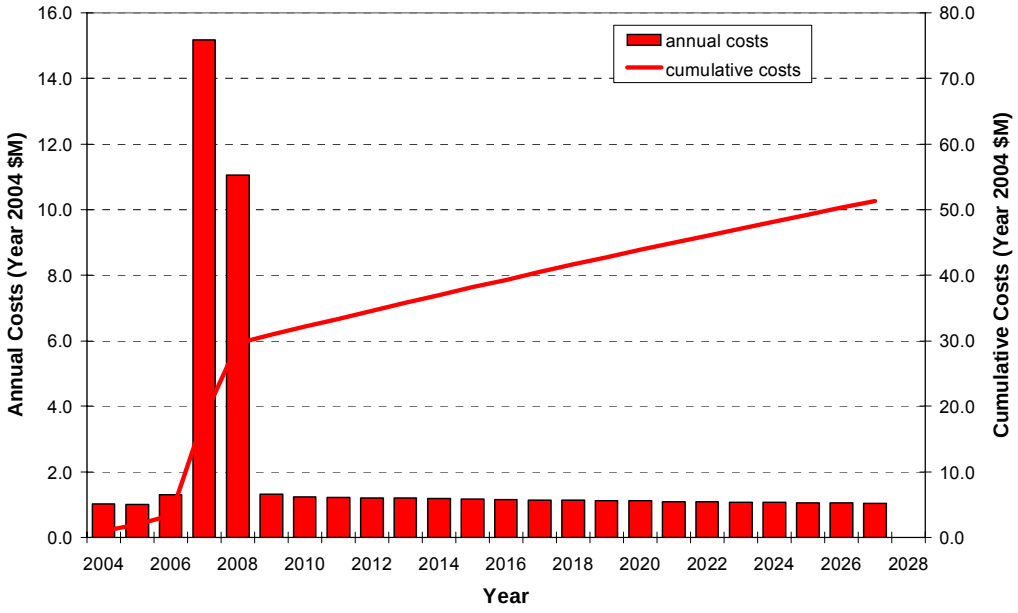


Figure 6-3. Annual and Cumulative Costs of FACET-AOC (FE) (Before Discounting)

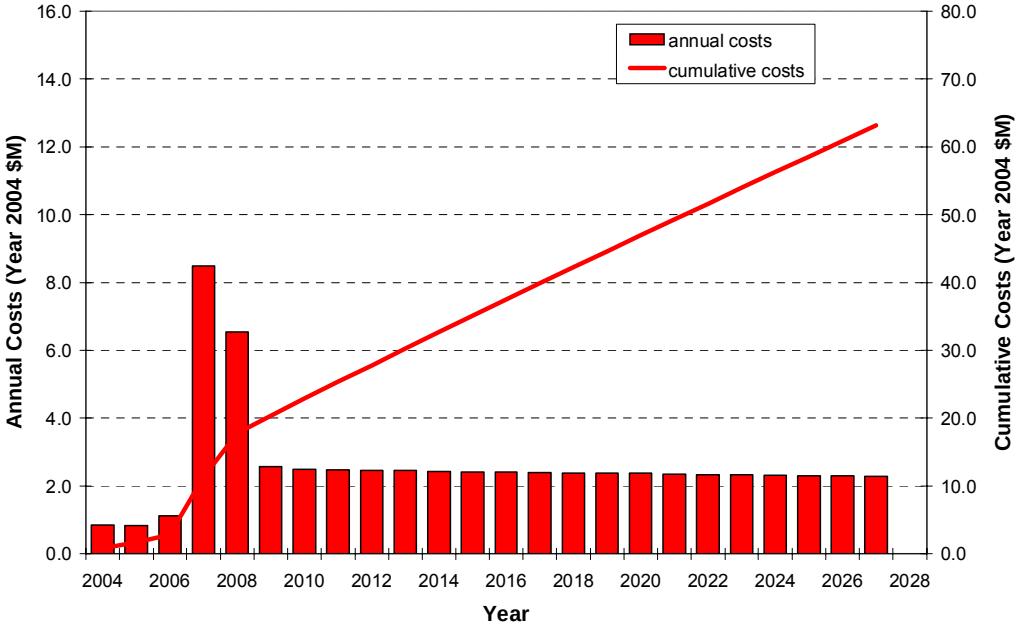
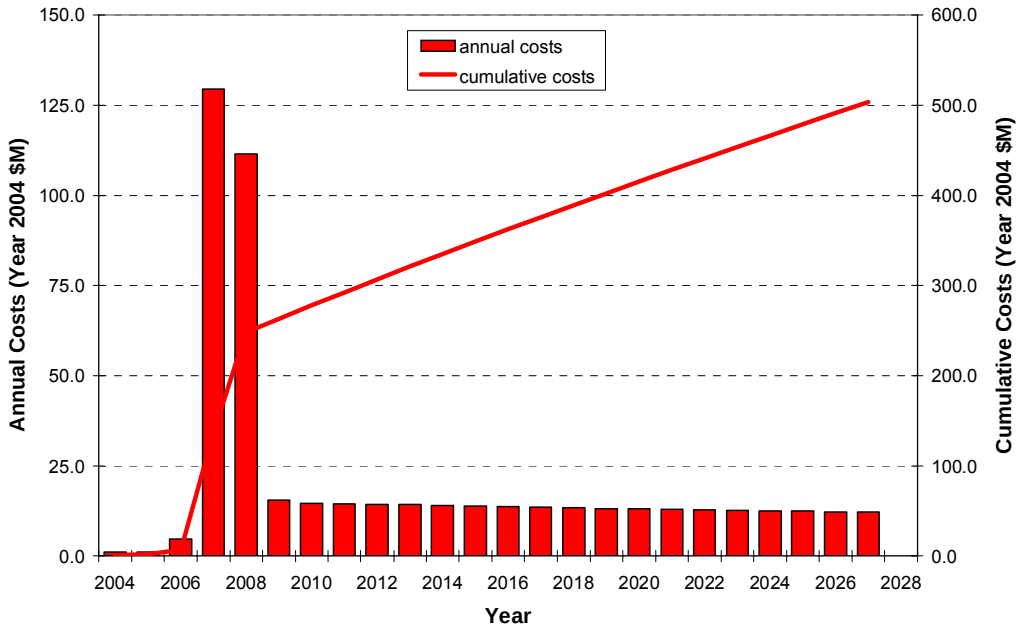


Figure 6-4. Annual and Cumulative Costs of FACET-AOC (AL) (Before Discounting)



Figures 6-5, 6-6, and 6-7 break down the post-discounting life-cycle costs of SWEPT and FACET-AOC (FE and AL).

Figure 6-5. Breakdown of SWEPT Life-Cycle Costs (After Discounting)

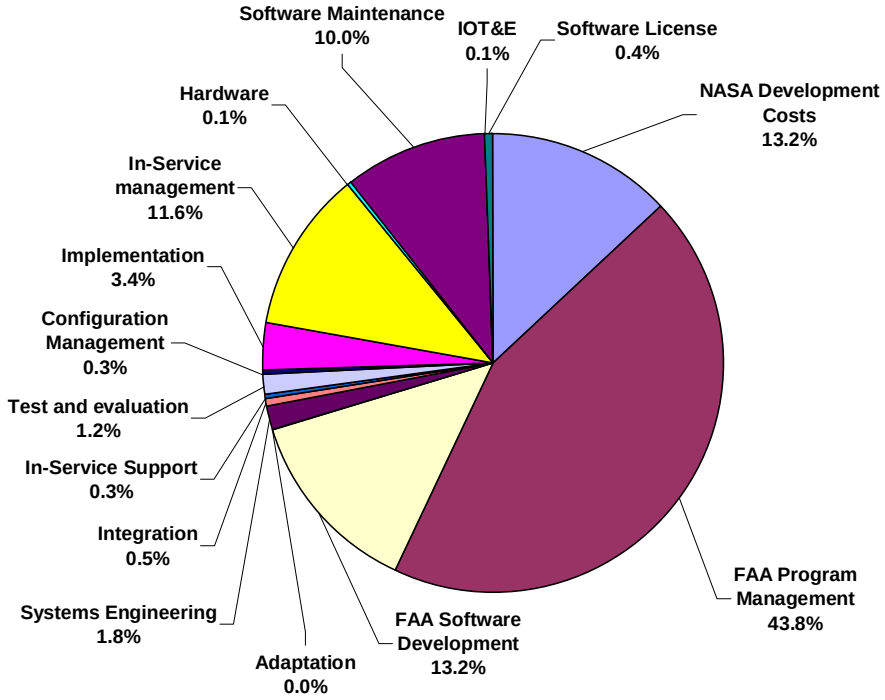


Figure 6-6. Breakdown of FACET-AOC (FE) Life-Cycle Costs (After Discounting)

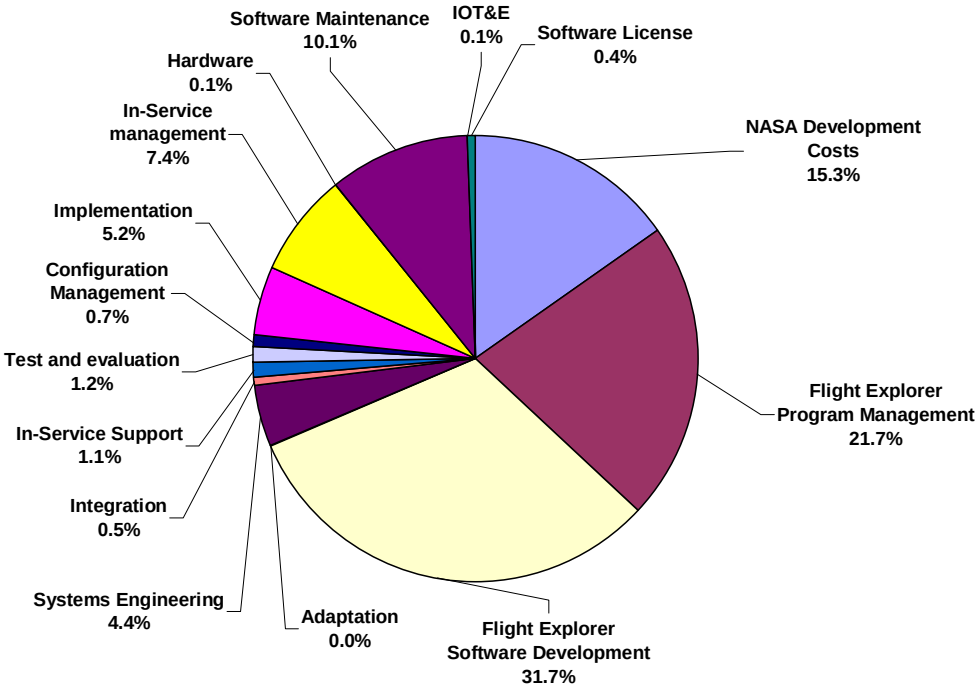
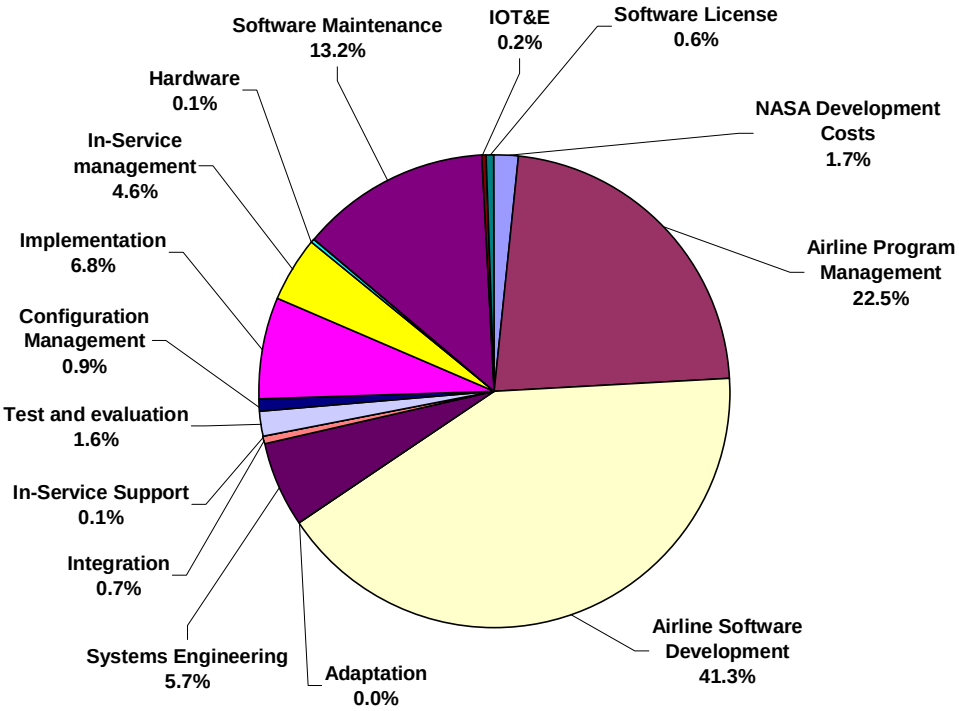


Figure 6-7. Breakdown of FACET-AOC (AL) Life-Cycle Costs (After Discounting)



LIFE-CYCLE BENEFIT RESULTS

The results from the extrapolation of benefits are presented in Table 6-5.

Table 6-5. Benefits Extrapolation

Scenario		Life-cycle benefit ($M 2004, before discounting)	Life-cycle benefit PV ($M 2004, after discounting)
SWEPT	Linear Benefits Growth	3,629.4	1,466.7
	Exponential Benefits Growth	3,819.3	1,487.7
FACET-AOC (FE)	Linear Benefits Growth	4,261.9	1,689.5
	Exponential Benefits Growth	4,645.0	1,738.2
FACET-AOC (AL)	Linear Benefits Growth	4,261.9	1,689.5
	Exponential Benefits Growth	4,645.0	1,738.2

The benefits of SWEPT and FACET-AOC before discounting are presented in Figures 6-8 and 6-9.

Figure 6-8. Linear Benefits of SWEPT (Before Discounting)

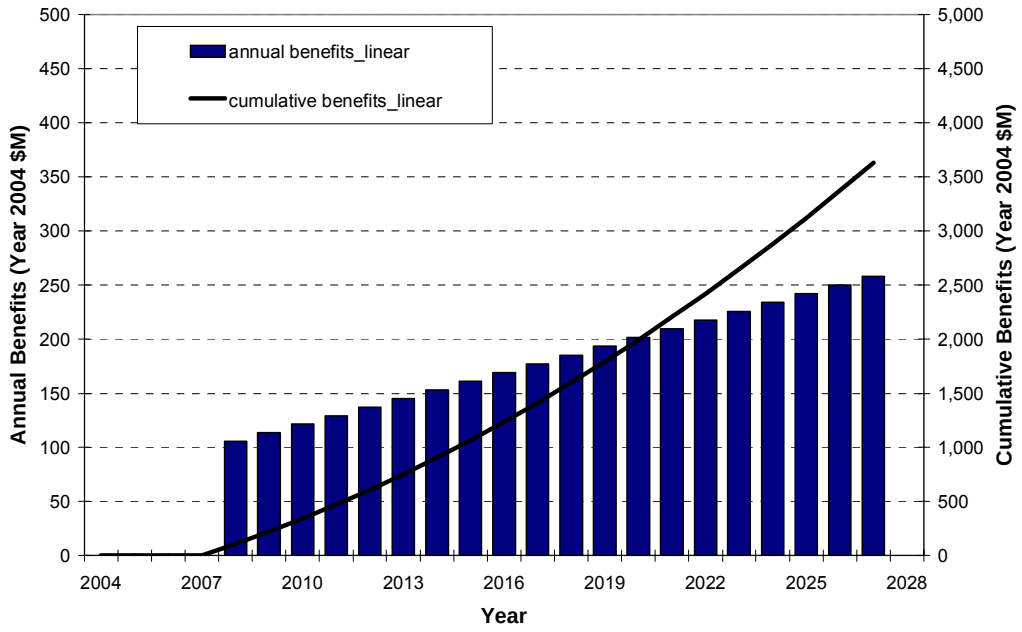
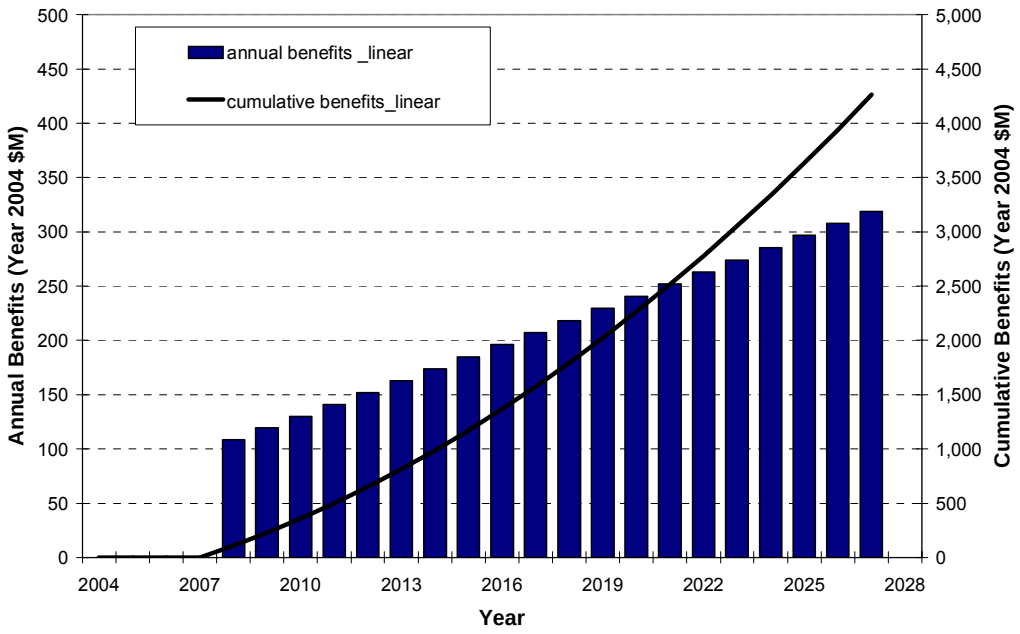


Figure 6-9. Linear Benefits of FACET-AOC (Before Discounting)



The exponential benefits of SWEPT and FACET-AOC are presented in Figures 6-10 and 6-11.

Figure 6-10. Exponential Benefits of SWEPT (Before Discounting)

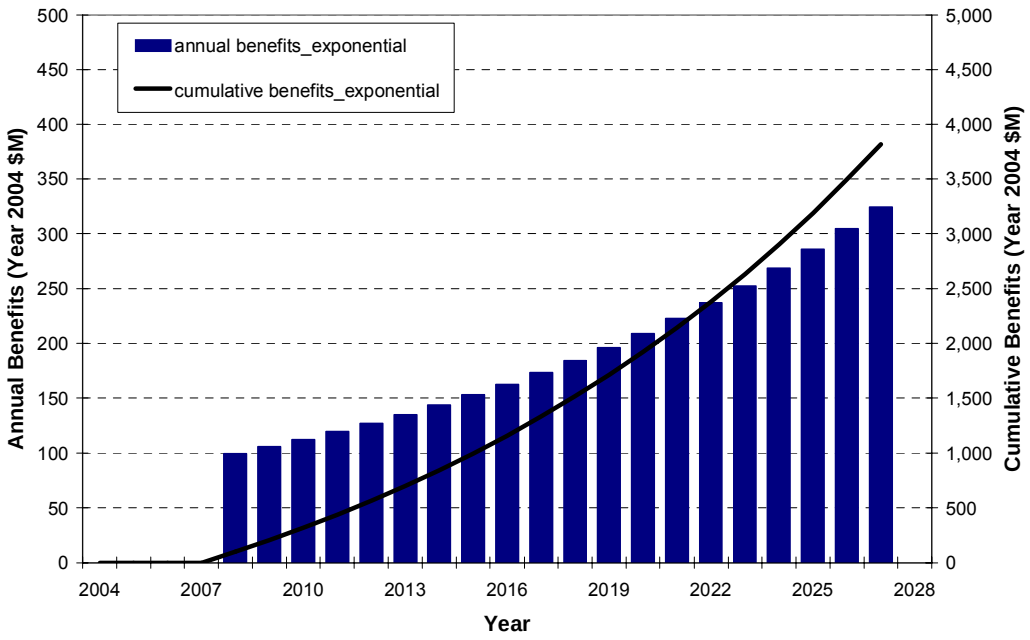
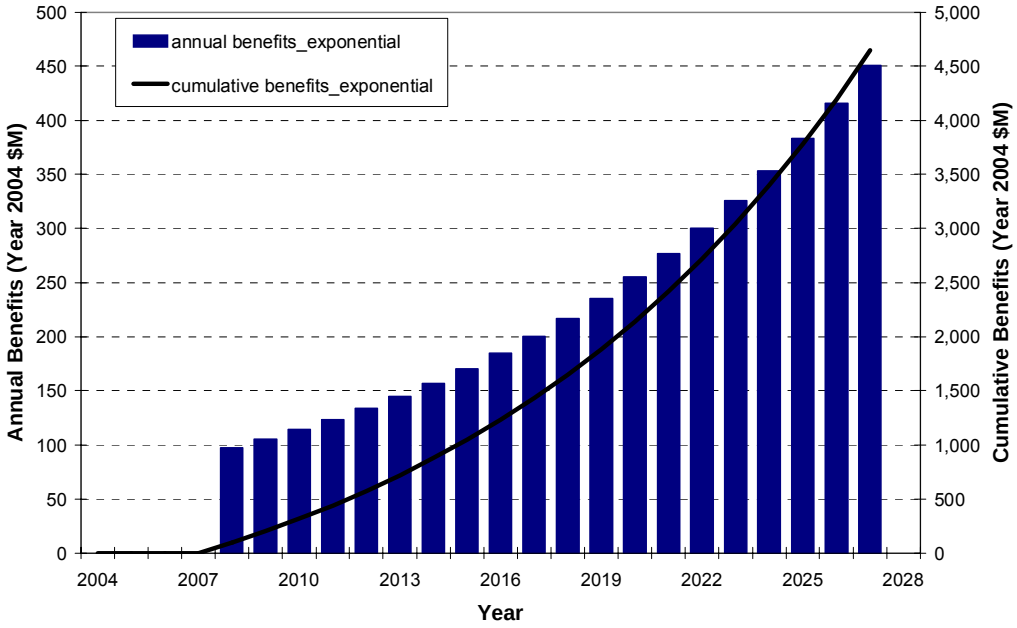


Figure 6-11. Exponential Benefits of FACET-AOC (Before Discounting)



As can be seen from the above, annual benefits grow over time. This is due to the increase in annual operations increasing linearly according to the FAA's forecasts, resulting in a matching pattern in benefits growth.

The Life-Cycle Cost/Benefit Assessment

This assessment was performed for the three scenarios mentioned above (one for SWEPT, and two for FACET-AOC). The results for this study are presented in Table 6-6.

Table 6-6. TFM R&D Life-cycle Cost/Benefit Assessment Results

Scenario		Discounted benefits ($M 2004)	Discounted costs ($M 2004)	B/C Ratio	NPV ($M 2004)	BEP
SWEPT	Linear benefits growth	1,466.7	$34.7	42.31	1,432.0	2008
	Exponential benefits growth	1,487.7		42.91	1,453.0	2008
FACET-AOC (FE)	Linear benefits growth	1,689.5	$34.3	49.28	1,655.2	2008
	Exponential benefits growth	1,738.2		50.70	1,703.9	2008
FACET-AOC (AL)	Linear benefits growth	1,689.5	$315.8	5.35	1,373.7	2010
	Exponential benefits growth	1,738.2		5.50	1,422.4	2010

CONCLUSION

Traffic Flow Management R&D has the potential to be a very highly profitable tool. The B/C ratios for SWEPT are between 42 and 43; for FACET-AOC (FE), between 49 and 51; and for FACET-AOC (AL), 5 and 6. These results, together with high net present values, mark the possibility of high returns for the tool. Additionally, the breakeven points for TFM R&D tools come very early. In one case, for FACET-AOC (FE), the breakeven point is in the same year it begins operation.

Chapter 7
Traffic Flow Automation System (TFAS)—Summary of Single-Year NAS-Wide Benefits Assessment

INTRODUCTION

The FAA's System Command Center currently uses Enhanced Traffic Management System (ETMS)-based Monitor-Alert and Sector-Overloading tools to manage National Air Traffic Flow Control. The Traffic Flow Automation System (TFAS) is being developed by NASA with the aim of improving the reliability of these tools.

This chapter summarizes the report produced to assess the value of TFAS by its ability to reduce of the number of Missed Monitor Alerts (MMAs) and False Monitor Alerts (FMAs). Assessment of the potential benefits of TFAS is performed by mathematically predicting the difference in the delay effects of MMAs and FMAs over the entire National Airspace System (NAS). The mathematical prediction method examines each sector within the NAS individually. Benefits are calculated by estimating the potential, NAS-wide reduction in MMAs and FMAs and the economic value of that reduction.

Greater prediction accuracy is expected to translate into reductions of the number of MMAs and FMAs. An MMA is defined as a failure to perceive that a particular sector will exceed its capacity, while an FMA is the perception that a particular sector will exceed its capacity when, in fact, no such event would occur. Occurrence of FMAs and MMAs result in inefficient traffic management decisions. In the case of FMAs, a traffic manager may decide to delay traffic unnecessarily. In the case of MMAs, the traffic manager may allow a traffic situation to develop to a point beyond the reach of cost-efficient delay measures.

This summary is primarily based upon the assessment performed by bd Systems Inc. The full citation is:

> *Preliminary Assessment of Traffic Flow Automation System Monitoring Alert Benefits*, Koushik Datta and Craig A. Barrington. Contract NAS2-98074, Task Order 4242-001, October 2001.

FUNCTIONS AND BENEFIT MECHANISMS

The FAA's Air Traffic Management System Command Center currently uses ETMS-based Monitor-Alert and Sector-Overloading tools to manage National Air Traffic Flow Control. These tools rely upon ETMS-based trajectory prediction algorithms, and are subject to inaccuracies.

TFAS is a traffic situation prediction system that uses ETMS data, but also uses NASA's Center TRACON Automation System (CTAS) technology to provide more accurate trajectory synthesis, route analysis, profile selection, performance modeling, and scheduling. TFAS thereby provides greater prediction accuracy than ETMS, and can be used as a basis for Monitor-Alert and Sector-Overloading tools, similar in function to the ETMS-based tools.

Inaccuracies of Current Approach

Tools relying on ETMS-based trajectory prediction algorithms are subject to measurable inaccuracies due to limitations of the ETMS data and trajectory modeling error. These inaccuracies occur as the result of false-negative and false-positive Monitor-Alert and Sector-Overloading alarm events. Monitor Alert and Sector-Overloading tools based upon improved trajectory models would significantly improve the effectiveness of these tools and result in reduced airborne delays.

TFAS Improvements

Each CTAS module will have built-in Monitor-Alert and Sector-Overloading tool software known as TFAS. Based on the predicted sector entry and exit times, each CTAS module will keep track of the occupancy counts of sectors within its boundaries. The TFAS software compares predicted sector occupancy (the number of aircraft traversing a sector within a 15-minute period) with the sector capacity limit. When a sector's occupancy is greater than its capacity limit, a sector Monitor-Alert condition is triggered within that CTAS module. Each module will keep track of all sector Monitor-Alert conditions that will occur inside its boundaries within a 45-minute horizon.

The predictive capability of the networked CTAS instances will improve upon current performance. TFAS will acquire flight plan, aircraft track, weather, and other information from ETMS data. TFAS will then use predictive information from the networked CTAS instances to augment or correct the ETMS Monitor-Alert predictions in real time. No new graphical user interfaces or procedures need to be developed for the current FAA tool-set.

TFAS will create the most accurate trajectories for aircraft arriving at one of the TFAS pacing airports. Although TFAS will also create trajectories for other aircraft, they will not be as accurate.

MODELING AND ANALYSIS APPROACH

Assessment of the potential benefits of TFAS was performed by mathematically predicting the difference in the delay effects of MMAs and FMAs over the entire NAS between systems operating with and without the trajectory accuracy improvement effects of TFAS. This difference was expressed in terms of U.S. dollars.

Mathematical predictions of FMAs and MMAs were accomplished by means of a Monte Carlo simulation, where the key parameters were the trajectory prediction uncertainties of the CTAS and ETMS prediction algorithms. In the Monte Carlo simulations, sector occupancy was modeled with the sector entry and exit times reflective of the trajectory uncertainties. Sector capacity and sector entry and exit data covering 852 sectors and a period of 24 hours from flight data from July 2001 were obtained for the analysis. The sector entry and exit data were analyzed to obtain a running count of aircraft within each sector. These running counts were compared to the sector capacities to estimate nominal extents of capacity, or "sector utilization." For instance, if a particular sector's capacity was 18, and there was a maximum of nine aircraft within the sector during a particular 15-minute period, then the sector utilization was 9 divided by 18, or 50 percent.

For the Monte Carlo simulations, the sector entry and exit times varied in accordance with the trajectory uncertainty. There were two types of Monte Carlo simulations conducted. First, scenarios were examined in which all prediction uncertainties were taken from a prediction error distribution derived from ETMS observations. These scenarios provided ETMS's probabilities of false and missed alerts. Additional scenarios were analyzed in which all prediction uncertainties were taken from a prediction error distribution derived from CTAS observations. These additional scenarios provided TFAS's probabilities of false and missed alerts.

The difference between alert probabilities established by the many Monte Carlo runs was used to estimate the influence of TFAS on FMAs and MMAs over the entire NAS. Any changes in projected FMA and MMA frequency were then expressed in terms of dollars by assessing the value of holding time saved.

Major Assumptions in TFAS Modeling

The major assumptions used in this analysis were the following:

- The accuracy of ETMS trajectory predictions is described by the same distribution for all aircraft subject to this accuracy.
- The accuracy of TFAS trajectory predictions is described by the same distribution for all aircraft subject to this accuracy.

- Predictions of sector occupancy are made precisely upon 15-minute intervals.
- The prediction accuracy and precision are proportional to the time from the moment that a prediction is made to the moment that the predicted event takes place.
- Sector capacities are represented by a constant integer equal to the maximum acceptable number of aircraft in a sector within any 1-minute period;
- Sector capacity data was obtained that represented Visual Flight Rules (VFR) conditions, and these were applied to the traffic data, which was generally VFR.
- The effects of ATC intervention on sector occupancy can be ignored.
- All benefits result only from fuel, oil, maintenance, and labor cost of reduced airborne delay.
- A 24-hour period of generally good weather was used to represent the average day in a year.
- The only aircraft that have enhanced prediction accuracy for sector boundary crossings are aircraft that actually arrive at a pacing airport.

Monte Carlo Simulation

For a single sector, this method produced a list of about 1,440 integers (24 hours multiplied by 60 minutes) that represented the number of aircraft in the sector for every minute over a 24-hour period. The integers were arranged into 96 groups of 15 integers, representing 15-minute periods. Each 15-minute period was examined to find the maximum occupancy, which was given the symbol “Anom”, for nominal aircraft count. The capacity of this sector was assumed to be constant over the 24-hour period, and was given the symbol “C”. The ratio of Anom to C was called the utilization ratio, or “sector utilization,” and was represented by “Unom”. The symbol “U” without a subscript was generally used to refer to sector utilization.

One more attribute of the sector quantified for this analysis was the fraction of aircraft that arrive at the sector with higher, CTAS trajectory accuracy. These are aircraft arriving at the pacing airport associated with the sector. All other aircraft arriving at the sector, including those that departed from the pacing airport that hosts the sector, were assumed to arrive at the sector with ETMS trajectory accuracy. This CTAS fraction was given the symbol “fnom” and computed for the aircraft occupying the sector during the same minute used to compute Unom. The symbol “f” without a subscript was generally used to refer to the CTAS fraction.

The output of a Monte Carlo trial contained U and f values calculated from the Monte Carlo trial sector counts. These U and f values corresponded to the Unom and fnom values previously calculated. Hence, for each Monte Carlo trial performed on a single sector, 180 double pairs of values (45 hours × 60 minutes per hour/15 minutes per period) were generated (U, f, Unom, fnom) with an associated value of τ (tau), the length of the forecasting period. After many trials were performed, the resulting output was used to create a model of the form: $U = g(\tau, Unom, fnom)$. The value of U could then be compared to the value of Unom to predict the occurrence of FMAs and MMAs.

Ten trials were performed on selected sectors to obtain sufficient data to estimate the frequency of MMAs and FMAs as a function of Unom, fnom, f, and τ. This comparison was performed for two sets of 10 trials: one set using only ETMS-based prediction error, and one set featuring enhanced, CTAS, prediction accuracy for certain aircraft (those arriving the pacing airports).

Benefits Estimation

Benefits were calculated by estimating the potential NAS-wide reduction in MMAs and FMAs and the economic value of that reduction. It was assumed that FMAs are always resolved by imposing airborne delay, and that MMAs are resolved by imposing airborne delay that could have been avoided, had the situation been correctly diagnosed. In general, a false Monitor Alert is resolved by ATC and airlines through some combination of airborne holding, ground holding (lower costs than airborne holding), and flight cancellations (a measure of last resort for the airlines). However, initial results of ETMS and TFAS predictions suggested that there would not be large differences in sector counts predicted by ETMS and TFAS. Therefore, it was assumed that the amount of flight cancellations would not be affected, and that airborne holding costs were appropriate. An additional assumption was that all FMAs result in airborne delay.

All MMAs are eventually corrected as the time of over-capacity approaches. The over-capacity situation is recognized, Monitor Alerts occur, and the situation is corrected by ATC. In this study it was assumed that the situation is corrected through the use of high-altitude airborne delay. This was estimated through a holding cost rate.

HOLDING COSTS

When aircraft are held in the air, they incur increased costs of crew labor, maintenance (for time on engines), and fuel and oil use. The dominant aircraft type in use today is classified as a two-engine, large jet. Examples are the Boeing 737 and McDonnell Douglas MD80. Block hour costs for a two-engine, large jet are shown in Table 7-1.

Table 7-1. Cost per Block Hour Flown

Aircraft type	($/hour)[a]		
	Crew	Fuel & oil	Maintenance
2-engine large jet	447	596	255

[a] Costs are given in 1997 dollars.

From the data in Table 7-1, the total cost rate is $1,298/block hour in 1997 dollars, or $21.63/block minute. Block hours flown include taxiing and airborne costs. This analysis assumed that the crew and maintenance costs are the same whether the aircraft is airborne or on the ground. This analysis also conservatively assumed that the oil and fuel costs are the same in the air as on the ground, which tended to underestimate the benefits.

To adjust the total cost rate to 2000 dollars, a 4 percent inflation rate was applied over three intervals to obtain $1,460/hour, or $24.33/minute. This quantity was symbolized by η (eta), where η = $24.33/minute.

RESULTS, FINDINGS, AND CONCLUSIONS

Single-Year Benefits Results

Output from a series of 220 Monte Carlo runs was analyzed to indicate reductions in the number of MMAs and FMAs due to TFAS. The reduction in MMAs turned out to be about zero, but potential for reduction in FMAs was evident. The number of FMA reductions ranged from 8 to 25 per day, with an average of 15.

The low results for MMAs may have been an artifact created in the original data through intervention by ATC. For instance, if ATC did not allow any sectors to become overloaded, then there would be little possibility within this methodology for MMAs (predictions that a sector will not be overloaded when, in fact, it will). This assumption may also have interfered with the assessment of FMAs, because some situations that evoked FMAs in reality would have prompted ATC to delay an aircraft. That aircraft's position would then be recorded in the data in a delayed state that would be less likely to produce a FMA in this methodology.

The potential savings is, therefore, $(\Delta NAS_FMA(\tau) + \Delta NAS_MMA(\tau)) \times \tau p/2$ (minutes) = $(15 + 0) \times 48.1/2 = 361$ minutes.

The cost of holding time was previously determined as $24.33 per minute. The daily potential was scaled to an annual economic potential by multiplying that rate by 365 days per year and the potential savings in minutes: $361 \times 365 \times 24.33$ = $3.2 million per year (2000 dollars). This savings corresponds to 2001 traffic demand.

Conclusions

The methodology used in this report represents an initial effort that could be improved. One improvement would be to construct sector occupancy “data” that are not affected by ATC intervention. This improvement should have the largest effect on allowing the estimate of potential benefits for MMAs, and a smaller effect on improving the accuracy of the estimated potential benefits of FMAs.

Another improvement would be to obtain synchronized traffic and sector capacity data for a “poor weather day.” Doing so would allow estimation of benefits on those days when the potential benefits of TFAS are expected to be the highest. Consideration of weather-constrained sector operations is expected to be a significant source of the total potential benefits of TFAS.

Chapter 8
Distributed Air/Ground Traffic Management (DAG-TM) Concept Elements 5, 6, and 11—Summary of Single-Year NAS-Wide Benefits and Life-Cycle Cost/Benefit Assessments

INTRODUCTION

NASA is conducting far-term research into a proposed concept for gate-to-gate National Airspace System (NAS) operations called Distributed Air/Ground Traffic Management (DAG-TM) in which flight deck crews, air traffic service providers (ATSPs), and aeronautical operational control facilities use distributed decision-making. NASA has defined 15 DAG-TM concept elements (CEs), 3 of which were funded for feasibility research under the Advanced Air Transportation Technologies (AATT) Project:

- *Concept Element 5:* En Route Free Maneuvering for User-preferred Separation Assurance and Local TFM Conformance. In CE-5, appropriately equipped aircraft are responsible for maintaining separation from other aircraft while exercising the authority to freely maneuver in en route airspace. Free maneuvering (autonomous) aircraft have the authority to establish new user-preferred trajectories with the restrictions that new trajectories conform to local traffic flow management (TFM) constraints and do not create traffic conflicts. The flight crew's role is to avoid conflicts with other aircraft or airborne hazards (e.g., special use airspace and weather) by maintaining separation while meeting a required time of arrival (RTA). Free maneuvering aircraft have on-board displays and decision support tools (DSTs) that enable situational awareness, allow flight crews to maintain separation from other aircraft without ATSP assistance, and provide trajectory planning capabilities.

- *Concept Element 6:* En Route Trajectory Negotiation for User-preferred Separation Assurance and Local TFM Conformance. CE-6 is a trajectory-based concept that extends today's operations in that the ATSP retains responsibility and control for separation assurance for all traffic. Through the integration of controller DST capabilities and the flight deck via data link, CE-6 enables the flight crew to exchange automated trajectory and clearance-related data and submit and/or negotiate trajectory change requests with the ATSP. The flight crew precisely follows instructions and

clearances from ATSP using an airborne flight management system (FMS).

- *Concept Element 11:* Terminal Arrival Self-Spacing for Merging and In-Trail Separation. In the CE-11 concept, equipped aircraft use flight deck DSTs in the terminal area to merge into an arrival stream and manage in-trail spacing (in units of time) with a lead aircraft, upon ATSP command. Terminal Radar Approach Control (TRACON) controllers issue clearances to equipped aircraft that designate the lead aircraft and self-spacing time interval to be achieved at the runway threshold. CE-11 is expected to enable greater runway throughput at busy terminal areas and runways.

This summary of the DAG-TM cost-benefit assessments is based on the work performed under Contract Task Order 8 (CTO-8) of the Air Traffic Management System Development and Integration (ATMSDI) contract, for which the prime contractor was Computer Sciences Corporation. CTO-8 was separated into two phases. The objective of Phase 1 was to define and quantify the potential single-year benefits that may accrue from CEs 5, 6, and 11, if implemented individually, for traffic demand in 2015 and 2030. The objective of Phase 2 was to estimate the life-cycle costs and economic benefits of CEs 5, 6, and 11, if implemented individually, to show the benefit-to-cost ratio and net present value for each.

The full citations for the CTO-8 reports are:

> *Single-Year, NAS-Wide Benefits Assessment of DAG-TM CEs 5, 6, and 11, Version 3.1,* Computer Sciences Corporation, LMI, Micro Analysis & Design, and CSSI Inc. Contract NAS2–00014, Contract Task Order 8. June 11, 2003.
>
> *Life-Cycle Cost/Benefit Assessments of DAG-TM Concept Elements 5, 6, and 11, Version 4.0,* Computer Sciences Corporation and LMI. Contract NAS2–00014, Contract Task Order 8. June 30, 2004.

FUNCTIONS, BENEFIT MECHANISMS, AND METRICS

The benefit mechanisms for each of the DAG-TM concept elements are organized into the top-level metrics categories of Predictability, Capacity, Efficiency, Flexibility, Access, Environment, and Safety. The Predictability category was expanded to add a separate category of Trajectory Predictability—the extent to which the system can know and predict flight path status and intent—since it is an important interim mechanism through which multiple benefits are derived in the other categories. In addition, Increased ATSP Productivity was identified as an important sub-category under Capacity, because there are many component controller workload benefit mechanisms for the concept elements.

CE-5 Benefit Mechanisms and Metrics

The top-level benefit mechanisms for CE-5 are the following:

- The ability of autonomous aircraft to manage their own trajectory, including managing separation and TFM constraint conformance, allows a significant reduction of the autonomous traffic contribution to ATSP workload. The reduction of dependence between ATSP workload and autonomous traffic count partially decouples the workload from the total traffic count. This enables an increase in en route capacity and provides greater scalability.

- Broadcast of aircraft state/intent improves trajectory prediction, situational awareness, and safety.

- Autonomous aircraft have more route and altitude options to select from, thereby increasing the likelihood of matching user-preferences, conforming to required times of arrival, and reducing excessive ATSP deviations.

- Flexibility in flight paths and departure times allows efficiency gains by reducing delays and fuel consumption.

Table 8-1 summarizes the CE-5 benefit mechanisms and metrics.

Table 8-1. CE-5 Benefit Mechanisms and Metrics

Category	Benefit mechanism	Metrics
Capacity	Flights not limited to fixed route structure	"Sector" capacity, airport throughput
	Decreased separation buffers	
	Improved flow rate conformance	
	Reduction in false/missed alerts	
	Reduction in excessive deviations	
	Increased ATSP productivity, system scalability	
Flexibility	Implementation of user preferences	Qualitative
	Increased availability of options	Δ Minimum time, Δ minimum fuel, potential cost of avoiding areas/traffic, max fuel & time that can be compensated
	User determined flight prioritization	Qualitative
	User determined departures	Departure delay

Table 8-1. CE-5 Benefit Mechanisms and Metrics (Continued)

Category	Benefit mechanism	Metrics
Efficiency	Efficiency gains through flexibility	Δ Time (PAX and airframe), Δ fuel, Δ scheduled time, potential ops increase DOC $ Increase in GDP
	Arrival delay inefficiencies minimized	
	Decreased separation buffers	
	More efficient profiles	
	Efficiency gains through predictability	
	Efficiency gains through capacity	
	Improved conflict resolutions	
Workload	Increased ATSP productivity, system scalability	MAP value, % time performing monitoring
Access	Limited coverage areas	Area of potential increase
	Access to off-route areas	Qualitative
	Access to SUA	Average gain in % time available
	Access preserved for all classes of participants	Qualitative
	Public access increased through lower operating costs	Increase in passengers
	Increased airport access through restriction removal	Increase in non-GA flights
Environmental	Improved fuel efficiency yields reduced emissions	Reduction in NOx, CO, HC
	Reduction in noise exposure	Reduced EPNL
Safety	Redundancy provides robustness against any one system failure	Qualitative
	Increased situational awareness through increased information	Qualitative
	Decrease in turbulence related injuries	Annual # of injuries
Implementation costs	Decreased ground infrastructure requirements	$ Savings
	Reduced need for addressed data link bandwidth	
	Lower ATSP capital costs	

Note: PAX = passengers; DOC = direct operating cost; MAP = Monitor Alert Parameter; NOx = nitrogen oxides; CO = carbon monoxide; HC = hydrocarbon; EPNL = effective perceived noise level.

CE-6 Benefit Mechanisms and Metrics

The top-level benefit mechanisms for CE-6 are the following:

- Automatic data link of aircraft state and aircraft intent data from the aircraft to ground decision support tools (DST), along with atmospheric data, allows improvements to trajectory forecasts, thereby improving the benefits from ground-based and airborne DST capabilities.

- Automation-assisted uplink of the ATSP's instructions/clearances to the aircraft reduces ATSP and pilot workload and improves aircraft conformance to the uplinked instructions and clearances. Automatic updates in ground automation, in turn, improve the trajectory-prediction accuracy of the ground DSTs, therefore increasing the benefits from ground DSTs.

- The ATSP is enabled to automatically uplink ground-based DST-generated instructions and clearances to the aircraft, which are then flown accurately by the aircraft's Flight Management System (FMS). This allows controllers to issue complex "strategic" trajectory-related instructions to the aircraft, rather than multiple short/tactical instructions as is done today via voice communications. This in turn will allow the aircraft to execute these more precise instructions and clearances using the FMS and further reduce ATSP and pilot workload.

- Data link of trajectory preferences from the aircraft to the ATSP allows the ATSP to more easily receive, consider, and accommodate user preferences.

- Provision of situational data and TFM constraints to the flight deck allows the user to formulate requests with high likelihood of acceptability to the ATSP, improves situational awareness, and improves conformance.

Table 8-2 summarizes the CE-6 benefit mechanisms and metrics.

Table 8-2. CE-6 Benefit Mechanisms and Metrics

Category	Benefit Mechanism	Metrics
Capacity	Decreased separation buffers	"Sector" capacity, airport throughput
	Reduction in false alert rates	
	Reduction in excessive deviations	
	Improved schedule and sequence plans	
	Improved flow rate conformance	
	Increased ATSP productivity	

Table 8-2. CE-6 Benefit Mechanisms and Metrics (Cointinued)

Category	Benefit Mechanism	Metrics
Flexibility	Accommodation of user preferences	Δ Minimum time, Δ minimum fuel, potential cost of avoiding areas/traffic, max fuel/time that can be compensated
	User-determined flight prioritization	Qualitative
	ATSP airspace use flexibility	Qualitative
	Increased surface operations flexibility	Qualitative
Efficiency	Arrival delay inefficiencies minimized	Δ Time (PAX & airframe), Δ fuel, Δ schedule time, potential ops increase, DOC, $ increase in GDP
	Improved conflict resolutions	
	Decreased separation buffers	
	Efficiency gains through flexibility	
	Increased acceptable trajectory changes	
	Efficiency gains through predictability	
	More efficient profiles	
	Efficiency gains through capacity	
Workload	Increased ATSP productivity	MAP value, % of time performing monitoring task
Access	Improved access to non-scheduled users	Fraction that can be accommodated
	Access to restricted airspace	Average gain in % time available
	Airspace access via dynamic restrictions	Number of flights affected
	Increased public access	Increase in passengers
	Airspace access through buffer reduction	Number of airports w/increase in non-GA flights
Environmental	Reduction in emissions via fuel efficiency	Reduction in NOx, CO, HC
	Decrease in noise exposure	Decrease in EPNL
Safety	Reduction in missed alerts	Number of MAs
	Enhanced situational awareness	Qualitative
	Improved advisory performance	Qualitative
	Reduction of human error	Number of errors
Miscellaneous	Increased voice channel availability	Channel availability
	Accurate, consistent information display	Qualitative

CE-11 Benefit Mechanisms and Metrics

The top-level benefit mechanisms for CE-11 are the following:

- ATSP issuance of a strategic clearance for maintaining spacing to the flight crew of suitably equipped aircraft under all conditions allows a trailing flight to achieve a specified time-based spacing at the runway threshold behind an ATSP-designated lead aircraft. Through this delegation, the aircraft exercises tighter control over the spacing interval, thereby allowing a more precise crossing interval at the threshold. By decreasing the variance of the threshold-crossing interval, buffers used to decrease missed approach frequencies can be decreased. This increases the runway throughput.

- Merging operations can be delegated to the flight crew of suitably equipped aircraft. The designated flight must merge behind an ATSP-specified lead aircraft that may be in a different arrival stream but will subsequently be in the same arrival stream. By providing this instruction before the merge, the aircraft has more time available to obtain and maintain the required spacing. This also reduces the variance in spacing between aircraft, thereby increasing throughput as in the prior mechanism.

- Aircraft are allowed to maneuver within ATSP-specified maneuver corridors. This added degree of freedom enables the flight crew to meet the spacing requirements under a wide set of operational disturbances, including some adverse weather scenarios. By providing aircraft with a lateral degree of freedom, including the potential for corners to be cut, previously unattainable spacing is now achievable. This allows spacing gaps to be reduced, decreases the spacing over the threshold, and thus increases runway throughput.

- Broadcast of aircraft state/intent improves trajectory prediction, situational awareness, and safety.

Table 8-3 summarizes the CE-11 benefit mechanisms and metrics.

Table 8-3. CE-11 Benefit Mechanisms and Metrics

Category	Benefit mechanism	Metric
Capacity	Reduced in-trail spacing	Airport capacity IFR/VFR
	Precise merging operations	
	Metering areas	
	Customized spacing requirements	
	Increased throughput via flexible corridors	
	Flexible maneuvering routes under adverse weather	Frequency of occurrence, flights affected, throughput, delays
	Currently underutilized airports	# Airports & capacity
Flexibility	User-preferences through flexible routes	Range of time/fuel to meet spacing & merging constraints
	Increased availability of options in adverse weather	Fraction of incidents
	User-preferences through self-spacing and separation	Range of fuel to meet objectives
	More options for ground operations	Qualitative
	Flexibility increased en route	Qualitative
Efficiency	Increased arrival time predictability	Δ Time (PAX & airframe), Δ fuel Δ scheduled time potential ops increase, DOC, $ increase in GDP
	More optimal routing	
	Reduction in average delay via reduced buffers	
	Reduction in average delay via increased predictability	
	More efficient merging and spacing	
Workload	Reduced buffers for managed aircraft	Average buffer size
	Increased staffing flexibility	Workload predictions
Access	Underutilized airports	# Airports
	Flexible routes = improved access to airspace	Qualitative
	Access to airports increased in adverse weather	# Ops possible
	Mixed equipage preserves access	Qualitative
	Decreases in costs increase access	# Passengers
Environment	Environmental benefits through efficiency	CO, NOx, HC
	Environmental benefits through reduction in airborne delays	
	Environmental benefits through accommodation of noise procedures	EPNL contours

Table 8-3. CE-11 Benefit Mechanisms and Metrics

Category	Benefit mechanism	Metric
Safety	Increased situational awareness	Qualitative
	Flexibility to avoid inclement weather	
	Redundancy provides failure robustness	
Implementation costs	Reduced ground infrastructure costs	$ Savings
	Lower demand for voice frequencies	
	Necessity for new ground-based infrastructure obviated	

MODELING AND ANALYSIS APPROACH

Individual cost-benefit assessments were performed for the three DAG-TM concept elements as potential solutions to the problem of insufficient capacity, under nominal conditions, of the NAS to accommodate forecasted demand. If the NAS capacity is not expanded sufficiently, there will be an economic loss to the nation as a portion of future demanded flights will not be scheduled and flown, and those flights that remain will suffer increased delays. Although DAG-TM is anticipated to also deliver significant off-nominal benefits (for example, mitigating throughput loss to severe weather-impacted operations), the off-nominal benefits were not estimated.

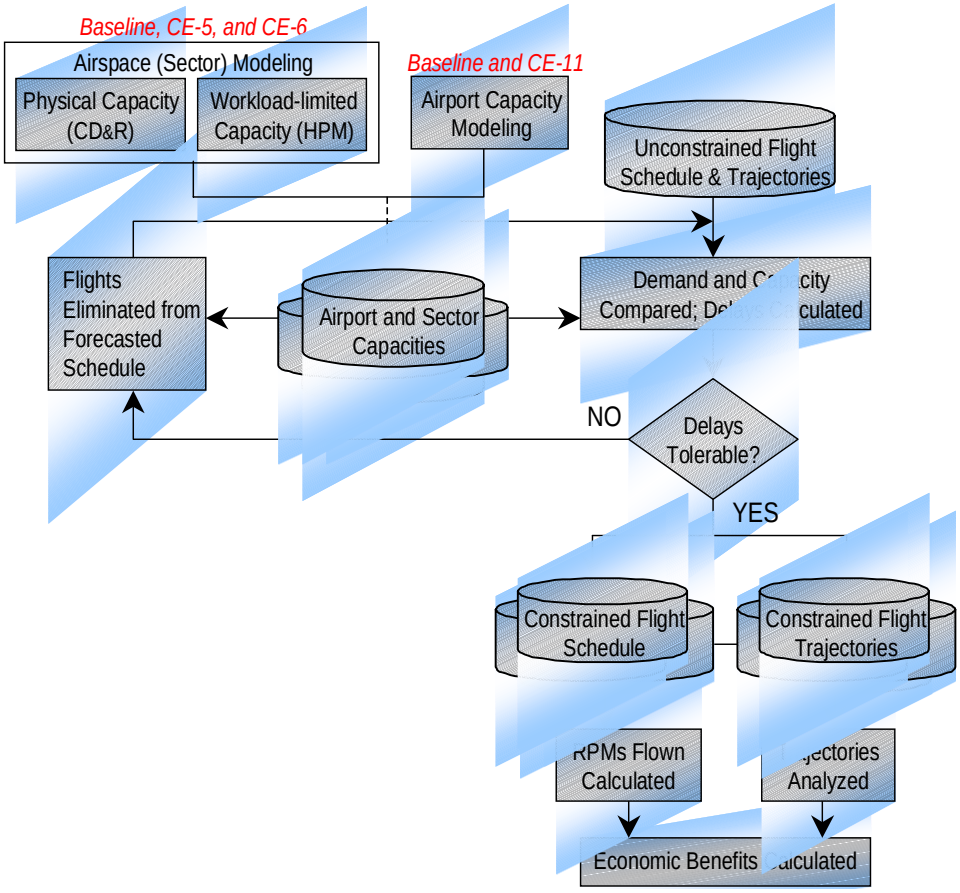
The study used as a baseline a postulated state of the NAS in 2015 (called the "pre-DAG baseline") that reflected a best-case scenario of the future NAS in which the Federal Aviation Administration's Operational Evolution Plan (OEP) is implemented perfectly, additional technologies currently being developed are also deployed successfully across the entire NAS, and all possible benefits of the various technology, procedural changes, and infrastructure improvements are indeed realized.

The benefits of the DAG-TM concept elements were estimated as those that could be realized beyond those attributable to this pre-DAG baseline which could, particularly in the en route domain, already accommodate a large portion of the future forecasted demand. This approach ensured that the estimated benefits for DAG-TM were inherently conservative. This also means that DAG-TM did not get charged with the costs of implementing the pre-DAG baseline modernization initiatives.

Benefits Assessment

The cornerstone of the benefits assessment involved comparing forecasted demand for air travel, in the target years of 2015 and 2030, with a more realistic forecast of feasible air travel service that explicitly accounts for the impact of airport and airspace capacity constraints on flight schedule planning. Figure 8-1 illustrates the overall process.

Figure 8-1. Benefits Assessment Methodology Overview[1]



The methodology begins by forecasting a future unconstrained flight schedule, for nominal day-to-day operations, and a trajectory for each flight. The term "unconstrained" means that the schedule embodies the expected demand at airports while the associated trajectories embody the demand on the airspace, without consideration of capacity limitations.

The process continues by comparing the demand to baseline capacities of the airports and airspace. The airport capacities are calculated based on the number of runways, the configuration being used, and the meteorological conditions. For the

[1] CD&R = conflict detection and resolution; HPM = human performance modeling; RPM = revenue passenger mile (one revenue passenger transported by one statute mile).

airspace, the sector capacities are calculated in two ways: by an analysis of the physical capacity constraints, including the conflict detection and resolution maneuvers required based on the computed trajectories; and by the controller workload limit that is reached as the number of aircraft is increased. The capacities of airports and airspace are modeled to reflect the pre-DAG baseline described above. The predicted capacity/demand imbalance would result in unacceptable levels of chronic congestion and delays. Flights are eliminated until delays do not exceed tolerable limits, to produce a tenable flight schedule in which some demand remains unsatisfied due to the capacity constraints and the remaining flights fly with increased delays.

Thus, a constrained schedule and its corresponding trajectories are created which together serve as the baseline traffic demand scenario. The DAG-TM concept elements scenarios are constructed by modeling the direct effects on the airspace (CE-5 and CE-6) and airport (CE-11) capacities, with the hypothesized benefit being that more flights can be scheduled and flown—i.e., the new "with DAG-TM" constrained flight schedules will be closer to the unconstrained flight schedule. The magnitude of how much closer determines the economic benefits resulting from capacity increases, which are expressed using the concept of consumer surplus.

CE-5 and CE-6 also enable more efficient and user-preferred trajectories; this is a secondary benefit of much smaller magnitude relative to the capacity benefit of allowing more flights to be accommodated without unacceptably high levels of delay. For CE-11, the primary benefit is the achievement of airport capacities appropriate for visual flight rules under conditions that would ordinarily require instrument flight rules. The increased airport capacity allows greater overall throughput with reduced delays, which is translated to decreased variable operating costs.

Even allowing for the additional capacity afforded by the pre-DAG baseline, the study showed that demand still outstrips nominal capacity. The study quantified how much of the remaining nominal capacity shortfall is recovered by the three DAG-TM concept elements. The single-year benefits assessments culminated in estimates of benefits by concept element, by equipage level, for two particular years, 2015 and 2030. Note that the reported benefits of CE-5 and CE-6 are only those that were estimated for nominal operations, excluding benefits that may be accrued during off-nominal conditions such as adverse weather, which were not modeled.

This benefits assessment may have significantly underestimated the potential benefits for the following reasons:

- The assessment did not include off-nominal (adverse weather) benefits of the en route concept elements (CE-5 and CE-6), which are expected to be significant.

- The benefits assessments were measured relative to a very capable NAS baseline. The pre-DAG baseline itself accounted for a 68 percent improvement in nominal en route sector capacity compared to current operations, primarily from Controller-Pilot Data Link Communications.

- The assessment of CE-11 benefits only considered improvements to in-trail spacing; the aspects of CE-11 which improve merging and maneuvering were not modeled.

Costs Assessment

The methodology for estimating the costs associated with the DAG-TM concept elements started by defining the elements of the pre-DAG baseline, and then identifying and estimating the additional costs to implement DAG-TM from the perspectives of both the ATSP/government and aircraft owner/operator.

Costs were calculated for each concept element separately. Costs of implementing the three concept elements were calculated in annual terms from the present through 2034 and through 2044, corresponding to 20- and 30-year life cycles. They are presented in terms of constant 2004 dollars and net present value.

ATSP/Government Costs

The OEP served as the primary basis for identifying the programs and technologies expected to be fielded prior to DAG-TM implementation. Beyond the systems included in the pre-DAG baseline (whose costs will not be borne by DAG-TM), additional costs must be borne by the ATSP (primarily ground equipment costs) and federal government research and development agencies. These costs comprise a minority of the total cost of implementing DAG-TM. Table 8-4 shows the ATSP and government costs required for each concept element:

Table 8-4. ATSP/Government Costs of Concept Elements

Concept element	Cost
CE-5	• En route Automatic Dependent Surveillance Broadcast (ADS-B) and Traffic Information Service Broadcast (TIS-B) • Upgrades to en route automation • Procedure development and controller training • Continued government research and development
CE-6	• Data link message addition • FAA air traffic control message costs • Upgrades to en route automation • Procedure development and controller training • Continued government research and development

Table 8-4. ATSP/Government Costs of Concept Elements (Continued)

Concept element	Cost
CE-11	• Terminal ADS-B and TIS-B • Upgrades to terminal area automation • Procedure development and controller training • Continued government research and development

AIRCRAFT OWNER/OPERATOR COSTS

For the airborne pre-DAG baseline, aircraft will be equipped with some combination of avionic equipment as a result of pre-DAG programs as of January 1, 2015. Flight Management Computers (FMCs), Flight Management Systems (FMSs), transponders, digital radios, global positioning system receivers, and other flight deck equipment is needed for the concept elements, and many aircraft will have some or all of this equipment prior to DAG-TM. To determine the airborne pre-DAG baseline, the study forecasted the legacy fleet and its associated avionics, and then forecasted the new airplanes that will enter the fleet in 2015 and their associated avionics. The year-end 2014 level of equipage was forecasted by starting with the current equipage, aging the fleet, removing aircraft that reach their respective end of service lives, and forecasting avionics equipage based on the incentives provided by the pre-DAG baseline programs.

Each of the concept elements has particular avionics requirements that will result in costs ultimately borne by aircraft owners and operators. When that avionics equipment is not available in the pre-DAG baseline aircraft, the concept element must absorb the costs to equip to accrue the benefits of the concept element. Table 8-5 identifies the avionics costs that must be borne by each concept element:

Table 8-5. Avionics Costs of Concept Elements

Concept Element	Cost
CE-5	• ADS-B and TIS-B transceiver • An autoflight system from which to derive limited intent, such as FMS/FMC/Mode Control Panel, or flight-planning GPS. • Autonomous Operations Planner capability • Cockpit Display of Traffic Information (CDTI) • Aircraft simulator modifications and pilot training
CE-6	• FMS • Autoload capability from digital communications to FMS • En Route Data Exchange (EDX) • Aircraft simulator modifications and pilot training

Table 8-5. Avionics Costs of Concept Elements (Continued)

Concept Element	Cost
CE-11	• CDTI • ADS-B and TIS-B transceiver • On-board spacing tool, such as Advanced Terminal Area Approach Spacing (ATAAS) prototype • Aircraft simulator modifications and pilot training

Note: FMC = Flight Management Computer.

Life-Cycle Cost/Benefit Assessment

To compare benefits and costs, the study employed an analytical solution that interpolates between known benefit points. Two schedules were modeled: one a straight-line avionics equipage schedule, for new and old aircraft, as often assumed in cost benefit analyses; the other a slower schedule that assumes only new aircraft will be equipped with compliant avionics. The latter is called a "forward fit" equipage schedule, and the per-aircraft costs of including compliant avionics are lower, since it is assumed that installation is easier and that concept element avionics certification is subsumed under whole aircraft certification, making the certification cost charged to the concept element effectively zero.

Under forward fit, aircraft owners and operators are assumed to begin to acquire compliant avionics in all new aircraft in 2010. Under both equipage schedules, 15 percent of all fleet aircraft must have the requisite avionics, and all government ATSP ground systems supporting DAG-TM technologies must be fully in place, by 2015. Thus, avionics costs accrue under forward fit starting in 2010, but benefits are not measured until 2015. These analytical equipage curves were used to interpolate benefit points between the single-year benefit estimates. Increasing demand was accounted for, as well as for increasing equipage.

RESULTS, FINDINGS, AND CONCLUSIONS

Technical Performance Metrics

CE-5 AND CE-6

Workload-Based Airspace Capacity Results

The product of this modeling was an estimate of the sector capacity increase due to CE-5 and CE-6, as compared to the pre-DAG baseline. The study found that the pre-DAG baseline itself showed a 68 percent increase in sector capacity compared to current operations. The CE-5 and CE-6 results are shown in Table 8-6.

Table 8-6. CE-5 and CE-6 Sector Capacity Results

	Aircraft equipage level			
	15%	50%	85%	100%
CE-5 sector capacity increase from pre-DAG baseline	17%	73%	330%	(no workload-based sector capacity limit)
CE-6 sector capacity increase from pre-DAG baseline	7%	8%	10%	11%

For CE-6, the results show a natural trend as equipage level is increased, but the overall sector capacity increase is small, due to the fact that CE-6 is an evolutionary concept that leverages data link (which is included in the pre-DAG baseline) and does not change the basic ATSP control paradigm. The CE-5 sector capacity increase is quite dramatic as more and more aircraft are equipped. Based on the assumptions regarding the modeling of CE-5 benefits, at 100 percent equipage there is no controller utilization limit, regardless of the sector loading. Sector capacity would only be limited by physical airspace capacity and the ability of the aircraft conflict resolution DSTs to find acceptable solutions.

The CE-5 sector capacity increase results illustrate that a key benefit, scalability, is realized. By allowing properly equipped aircraft to fly autonomously, CE-5 strives to decrease the number of aircraft for which ground controllers have responsibility over separation and TFM constraints. The reduction of dependence between controller workload and autonomous traffic count partially decouples the workload from the total traffic count (which includes both the equipped autonomous aircraft and unequipped “managed” aircraft. This enables an increase in overall en route capacity and allows the autonomous aircraft population to grow, possibly to the limits of physical airspace capacity (or threshold of unacceptable delay).

Increased Throughput Results

The sector capacity increases were used to generate constrained traffic schedules associated with each scenario. This indicated how many flights would have to be eliminated in the face of capacity constraints in the pre-DAG baseline case, and how many additional flights (increased throughput) were enabled in each concept element scenario relative to the pre-DAG baseline, in order to keep delays at a tolerable level. The percentages of revenue passenger miles (RPMs) recovered are shown in Table 8-7 for year 2015 and in Table 8-8 for year 2030.

Table 8-7. CE-5 and CE-6 RPM Recovery, 2015

	Percentage of aircraft equipped			
	15%	50%	85%	100%
CE-5 RPM recovery from pre-DAG baseline (%)	8.54	9.05	9.05	9.05
CE-6 RPM recovery from pre-DAG baseline (%)	6.64	6.74	7.22	7.54

Table 8-8. CE-5 and CE-6 RPM Recovery, 2030

	Percentage of aircraft equipped			
	15%	50%	85%	100%
CE-5 RPM recovery from pre-DAG baseline (%)	4.73	7.16	7.16	7.16
CE-6 RPM recovery from pre-DAG baseline (%)	2.08	2.37	2.72	2.84

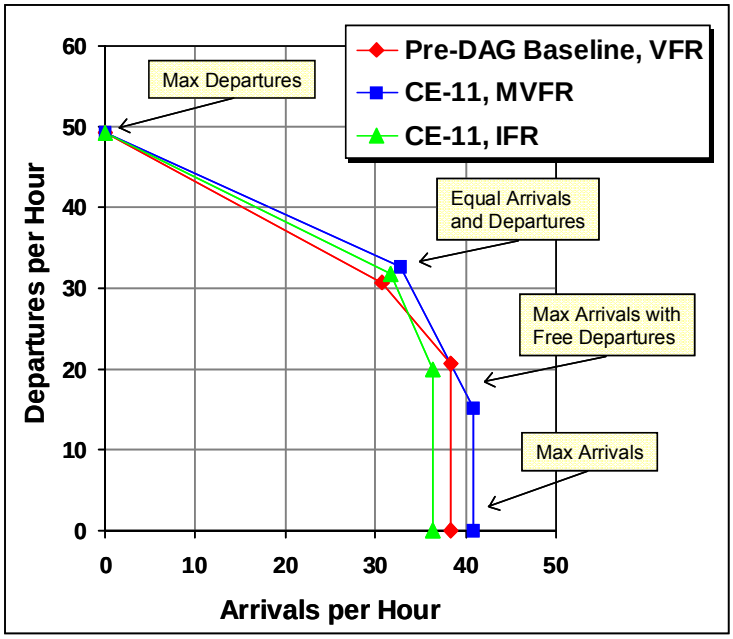
CE-11

Airport Capacity Analysis Results

The first step in the CE-11 analysis was to validate, through fast-time modeling, the stated objective that CE-11 will allow Visual Flight Rules (VFR) airport capacities in Marginal Visual Flight Rules (MVFR) and Instrument Flight Rules (IFR) conditions. In CE-11 the controller gives a strategic clearance allowing the flight crew to do precision flying utilizing real-time Automatic Dependent Surveillance–Broadcast and global positioning system data. The flight crew can maneuver for gross adjustments and make speed changes for fine adjustments, thus achieving the desired spacing during the final landing approach pattern.

In the modeling, these benefits translated to a reduction in the speed and position uncertainties of the arriving aircraft. Figure 8-2 shows the results of the modeling for a single example runway using model parameters set to estimate the effects of the pre-DAG baseline (including terminal area decision support tools which improve flight scheduling and sequencing) and CE-11 technology.

Figure 8-2. Pre-DAG Baseline VFR, CE-11 MVFR, and CE-11 IFR Capacities



The study found that CE-11 capacity in MVFR slightly exceeded the pre-DAG baseline VFR capacity, while the CE-11 IFR capacity was slightly lower. Based on this finding, the study assumed that the use of pre-DAG baseline capacity for CE-11 MVFR and IFR was an acceptable approximation.

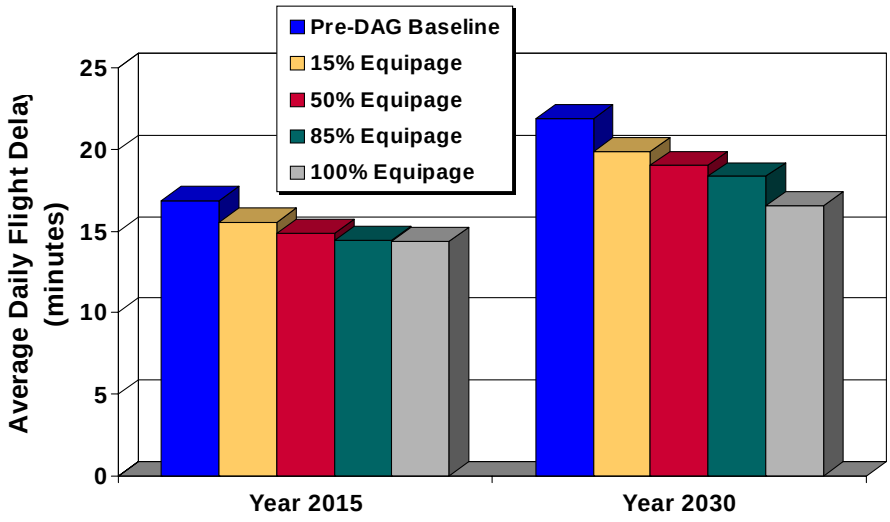
CE-11 Benefits Considering Various Weather Conditions

Having verified that it was reasonable to use VFR capacities to model CE-11 MVFR and IFR capacities, the study assessed the benefit of CE-11 for three types of weather days from 1996. (Using days from 1996 was of no consequence to the analysis; it was simply used as available and representative weather data.) The demand used was from the study target years of 2015 and 2030. The 3 days used were April 8 and November 29, each of which experienced bad weather in different parts of the country, and June 12, which was a good weather day. The weather data were used to determine whether each of the 102 modeled airports was running at VFR, MVFR, or IFR conditions during each 15-minute interval for the 24 hours of each of the 3 weather days.

A year's worth of weather was synthesized from a composite of the 3 selected weather days. It is generally accepted that good weather days occur approximately 80 percent of the time. Thus the good weather conditions on June 12 were used as a representative of 80 percent of the weather days. The degraded weather conditions on April 8 were used as a representative of 10 percent of the weather days, and the degraded conditions of November 29 were used as representative of the remaining 10 percent.

The flight schedules were generated using 2015 and 2030 demand and with the pre-DAG baseline airport capacities. Since these are constrained schedules, some of the demanded flights were eliminated to achieve tolerable delay levels. However, no additional flights were eliminated due to large flight delays caused by the bad weather effects we modeled. Since flight schedules are created assuming good weather capacity and CE-11 does not enable an appreciable increase in good weather capacity, the benefits are measured only by the reduction in average delays. Accordingly, the study calculated the average delay per flight for 2015 and 2030, as shown in Figure 8-3.

Figure 8-3. Average Delay Per Flight With CE-11 Equipage Effects



It is important to emphasize that these delay results are shown as an average of all flights, not just those that had operations at airports with reduced conditions. Those IFR and MVFR flights would have received a larger delay reduction benefit than the average flight, since flights operating entirely under VFR conditions would receive no direct delay benefit over the pre-DAG baseline.

In every case, CE-11 reduced the amount of delay significantly. A rather dramatic result can be seen when comparing the 2030 CE-11 delays to the 2015 pre-DAG baseline delays: Even with the 2030 level of demand, the average delay is approximately the same as the 2015 baseline delay. In other words, the use of CE-11, with 100 percent equipage, would preserve delay levels from 2015 until 2030.

Single-Year NAS-Wide Benefits

CE-5 AND CE-6

As described above, the study calculated how many flights would have to be eliminated in the face of capacity constraints in the pre-DAG baseline case and how many additional flights (increased throughput) were enabled in each concept

element scenario relative to the pre-DAG baseline, in order to keep delays at a tolerable level.

The additional flights were converted into additional RPMs, which were then valued in terms of economic consumer surplus. The definition of consumer surplus[2] is "the maximum sum of money a consumer would be willing to pay to consume a given amount of a good, less the amount actually paid." In the context of this benefits assessment, consumer surplus represents the total value of the additional demanded RPMs that can be delivered because of CE-5 and CE-6, coupled with the resultant lower price of travel to the flying public (the fares paid for both the baseline and additional demanded RPMs).

CE-5 and CE-6 also enable more fuel- and time-efficient trajectories. When assessing the trajectory benefits, the study considered reduced fuel consumption due to improved flight trajectories and reduced fuel consumption due to more efficient conflict avoidance.

Table 8-9 shows the economic benefits in constant 2002 dollars.

Table 8-9. Total Modeled CE-5 and CE-6 Economic Benefits (100% Equipage, Constant 2002 Dollars)

	CE-5		CE-6	
	2015	2030	2015	2030
Increased throughput	$577 M	$1,382 M	$477 M	$529 M
Trajectory efficiency	$222 M	$260 M	$177 M	$241 M
Total modeled economic benefits	$799 M	$1,640 M	$654 M	$771 M

CE-11

The benefits from the reduction in delays are significant on an annual basis. The FAA specifies a value of $2,601 per hour for variable operating costs of aircraft in scheduled commercial service. Annualizing the delay by multiplying by 365 days results in a large increase in the CE-11 benefits among the scenario years, as the increase in demand increased not only the delay reduction, but also the number of flights affected. The results are shown in Table 8-10 in constant 2002 dollars.

[2] Consumer surplus is the economic measure recommended by the Office of Management and Budget for use in benefit-cost analyses of federal programs.

Table 8-10. Total Modeled CE-11 Economic Benefits (Constant 2002 Dollars)

Year	CE-11 aircraft fleet equipage ($M 2002)			
	15%	50%	85%	100%
2015	$741	$1,130	$1,380	$1,430
2030	$1,210	$1,710	$2,320	$3,610

These benefits are only measured at the 102 airports included in the study. Though these airports do not represent all the flights in the NAS, they do represent almost all of the flight delays encountered due to airport congestion. Therefore, the delay reductions that will result from the CE-11 benefits will likely occur almost exclusively at the 102 airports that are included in this study.

Life-Cycle Cost-Benefit Results

A top-level summary of the life-cycle benefits and costs for each concept element is presented in Table 8-11, where the decision support tools' service life is assumed to be 20 years. Note that the benefits of CE-5 and CE-6 are only those that were estimated for nominal operations, excluding benefits that may be accrued during off-nominal conditions such as adverse weather, which were not modeled.

Table 8-11. Life Cycle Benefits and Costs Results, Year 2004 Present Value

	CE-5		CE-6		CE-11	
	Base case	Forward fit scenario	Base case	Forward fit scenario	Base case	Forward fit scenario
Life cycle benefits ($M, present value)	5,912	5,817	3,217	3,079	7,380	6,668
Life cycle costs ($M, present value)	2,463	1,508	944	502	1,194	752
Breakeven year	2016	2016	2015	2016	2015	2015
Net present value ($M)	3,448	4,309	2,273	2,577	6,186	5,916
Benefit-to-cost ratio (present value)	2.4	3.9	3.4	6.1	6.2	8.9

For CE-5, it is hypothesized that there may be significant benefits if CE-5 free-maneuvering aircraft can navigate around en route weather obstacles without contributing to the ATSP workload/congestion that often limits en route throughput during convective events. CE-6 lends itself to the rapid distribution of complex weather-induced route changes to active flights, thus allowing the ATSP and airspace users to quickly adapt to weather impacts with less workload.

Each concept element has a benefit-to-cost ratio significantly greater than 1. The forward fit scenario indicates a notable result, in that benefits are only slightly reduced while costs are reduced dramatically due to the large reduction in avionics costs. This results in a much higher benefit-to-cost ratio for the forward fit equipage scenario, for each concept element.

While a straight-line equipage schedule is typically assumed for cost-benefit assessments, from the results seen here, it is clear that for DAG-TM the forward fit equipage schedule is more appropriate and would be more likely to be adopted when DAG-TM is implemented. This is because such a large proportion of the costs associated with the concept elements is incurred by the aircraft owners/operators, and thus it would be financially prudent to only acquire the required avionics as part of normal fleet renewal aircraft purchases, instead of retrofitting their existing aircraft.

SUMMARY OF CE-5 AND CE-6 CONCLUSIONS

To summarize the benefits of the en route DAG-TM concept elements, the analysis shows that CE-5 and CE-6 enable increased airspace (en route sectors) capacity and more efficient, user-preferred flight trajectories. The capacity increase leads to higher NAS throughput, meaning that more of the future demanded flights can be accommodated and flown without incurring intolerable levels of delay. This is valued in terms of economic consumer surplus and is the largest portion of the benefits assessed.

The flight trajectory efficiency benefits are significantly smaller than the capacity/throughput benefits, particularly for higher levels of aircraft equipage; they are quantified in terms of reduced fuel consumption. The capacity/throughput benefits and the efficiency benefits are additive—CE-5 and CE-6 allow more flights to be flown, and those flights are able to fly more efficiently.

The benefits assessment shows significant benefits and makes evident the value of CE-5 and CE-6. To provide some context to the results, note that NAS constraints exist in the en route airspace but are even more restrictive in the terminal areas. NASA's overall DAG-TM operational concept addresses both domains. Since CE-5 and CE-6 focus specifically on en route capacity, their benefits must be considered from two perspectives: how well they solve the part of the problem they are designed for, and how well they solve the overall problem.

This assessment leads to the conclusion that they are extremely effective under the former viewpoint but only moderately under the latter. CE-5 in particular showed tremendous benefits, including the potential for a great degree of system scalability: if properly equipped to be autonomous, enough aircraft can be accommodated in the en route airspace to easily meet the projected demand out to 2030 (and likely beyond that). This is due to the increased sector capacity enabled by shifting workload from ground controllers to the flight crews of autonomous aircraft. The benefits relative to the overall NAS are capped, however, by terminal

area constraints in the future—a problem, of course, that CE-5 is not intended to address.

An aspect of the benefits assessment that affects the interpretation of the results is that modeling estimated only the benefits as they affect nominal condition operations of the NAS. CE-5 and CE-6 are also expected to provide significant benefits during off-nominal conditions, such as adverse weather en route. In particular, there may be substantial benefits if CE-5 autonomous aircraft are able to navigate around en route weather obstacles without contributing to the ATSP workload/congestion that often limits en route throughput during convective weather events. Therefore, the study comprises only a portion of the overall CE-5 and CE-6 benefits. The results reported here are a conservative subset of the entire potential benefits.

The robustness of the defined pre-DAG baseline also complicates the interpretation of the results. The results showed a 68 percent sector capacity increase from current operations to the pre-DAG baseline (mainly due to data link). This in turn meant that there was considerably less of an en route problem left for CE-5 and CE-6 to solve. This again means that the results are conservative, because it is quite possible that the state of the NAS prior to DAG-TM implementation will not be as advanced and capable as the pre-DAG baseline implies.

Despite the use of all the conservative assumptions, the life-cycle cost/benefit assessment resulted in benefit-to-cost ratios of 2.4 and 3.4 for CE-5 and CE-6, respectively (for the base case). Thus it is evident that these DAG-TM concept elements provide a viable solution for the en route congestion problem anticipated in the future.

SUMMARY OF CE-11 CONCLUSIONS

The analysis shows that Concept Element 11 enables significant reductions in average delay by allowing terminal area reductions of in-trail spacing, which we modeled as reduced speed and position uncertainties. This translates into an increase in airport capacity and throughput. The analysis found little or uncertain capacity benefit for CE-11 when visual landing approaches are allowed (typically during good weather), but found a large benefit when flights are required to use instrument approaches (typically during bad weather). In fact, for those airports whose runway configuration does not change between visual conditions and instrument conditions, the study found that CE-11 allows the airport to maintain the same capacity; currently airports typically suffer a dramatic decrease in capacity when operating under degraded weather conditions.

Although the NAS is characterized roughly 80 percent of the time by good weather conditions in which visual landing approaches are allowed, the remaining 20 percent is when the most delays are observed. Therefore, when estimating annual benefits, CE-11 proved to be very effective in reducing average delay. The corresponding economic benefit of reduced variable operating costs is likewise

impressive. CE-11 also includes merging and maneuvering before the final approach. The analysis did not model scenarios in which maneuvering and merging play a significant role in achieving the threshold crossing interval target (for example, multiple arrival streams feeding single runways, which would require merging, or runway load balancing, which would require both merging and maneuvering). Thus, the study comprises a conservative subset of the entire CE-11 potential benefits.

The benefits of reducing in-trail spacing, especially when instrument landing approaches are required, could possibly be achieved by other methods or technologies. But given that the life-cycle cost/benefit assessment resulted in a benefit-to-cost ratio of 6.2 (for the base case), CE-11 certainly is a very strong contender as a solution.

Chapter 9
Expedite Departure Path (EDP)—Summary of Single-Year NAS-Wide Benefits and Life-Cycle Cost/Benefit Assessments

INTRODUCTION

The overall goal of Expedite Departure Path (EDP) is to help controllers efficiently direct traffic into en route streams. EDP is one of the DSTs that is slated to provide Terminal Radar Approach Control (TRACON) Traffic Management Coordinators (TMCs) with appropriate departure traffic demand and scheduling information, as well as provide departure controllers with advisories for tactical control of TRACON departure traffic. The ultimate function of EDP advisories is the ability to assist TRACON departure controllers in efficiently sequencing, spacing, and merging departure aircraft into en route traffic streams.

This summary of EDP is primarily based upon the assessment by bd Systems Inc. The full citation is:

> *Life-Cycle Cost/Benefit Assessment of Expedite Departure Path (EDP),* Jianzhong Jay Wang, Paul Chang, and Koushik Datta. Contract NAS2-98074, Task Order 24242-001, August 29, 2003.

The primary objective of this benefit study is to provide a refined life-cycle cost/benefit assessment (LCCBA) for EDP. The assessment is stand-alone, as it does not take into account the successful deployment of the many other DSTs developed under the AATT Project. The sole exception to this is the inclusion of the Surface Management System (SMS). This integration assumption was necessary in order to accurately assess some benefits of EDP, specifically benefits due to reduction of departure queue delay/taxi delay.

FUNCTIONS, BENEFIT MECHANISMS, AND METRICS

Benefit mechanisms and potential benefits for EDP were identified based on discussions with the NASA researchers developing the tool. The quantifiable potential benefits of EDP include:

- Reduced flight time
- Reduced departure queue delay/taxi delay

- Reduced fuel burn (associated with reduced departure queue delay/taxi delay, listed above)
- Reduced arrival delay (for dual-use runways)

Other benefits identified include:

- Precision spacing
- Improved departure sequencing
- Expedited climb profiles

The identified benefits were categorized according to EDP functionality and the presence or lack of SMS. These categories are:

- Climb without SMS
- Climb with SMS
- Merge with SMS
- Climb and Merge with SMS

Five EDP functions are identified, described here along with the benefit mechanisms and associated metrics.

- *Climb Advisories:* Through climb advisories, EDP is able to accurately predict future aircraft position, providing controllers with suggested opportunities to safely advise expedited climbs.
- *Merging Advisories:* EDP merging advisories are designed to reduce inefficiencies in sequencing and create precision spacing by achieving a reduction in the variance of capacity constrained departure spacing, and reducing the number of clearances required to achieve desired spacing or sequencing.
- *Tactical Advisories:* Through tactical speed and heading advisories, EDP facilitates precision tracking of prescribed trajectories that are conflict-free and meet objectives for schedules, fuel efficiency, and/or noise mitigation. Also, these advisories enable EDP to meet merging constraints. EDP can proactively minimize community noise impact and reduce the cost of environmental impact studies.
- *Accurate Time-to-Fly Estimates:* EDP's accurate departure time-to-fly estimates can be used in forming departure sequences that will optimize the airport throughput.

- *Direct Route Advisories:* An anticipated future EDP capability is direct en route transition, which will increase the potential value of wind-optimal routes to the airspace user by eliminating routing restrictions with EDP's direct route advisories.

These functions and their associated benefit mechanisms and metrics are summarized in Table 9-1.

Table 9-1. EDP Benefit Mechanisms and Metrics

EDP function	Benefit mechanism	Metrics
Climb advisories	Expedition of climb	◆ Flight time ◆ Fuel burn ◆ Departure queue delay/taxi delay ◆ Arrival delay (for dual-use runways) ◆ Emissions ◆ Noise impact
Merging advisories	Precision spacing	◆ Flight time ◆ Fuel burn ◆ Departure queue delay/taxi delay ◆ Arrival delay (for dual-use runways) ◆ Emissions
Tactical advisories	Precision trajectory tracking	◆ Emissions ◆ Noise impact
Accurate time-to-fly estimates	Improved departure sequencing	◆ Departure queue delay/taxi delay (resulting in reduced Fuel burn) ◆ Arrival delay (for dual-use runways) ◆ Emissions
Direct route advisories	Eliminating routing restrictions	◆ Flight time ◆ Fuel burn ◆ Departure queue delay/taxi delay ◆ Arrival delay (for dual-use runways) ◆ Emissions ◆ Noise impact

MODELING AND ANALYSIS APPROACH

The LCCBA methodology included deployment site selection analysis, deployment schedule development, benefit and cost assessment methods, and a life-cycle cost/benefit assessment method.

Deployment Site Selection

NASA's EDP developers identified 14 TRACONS as potential future EDP deployment sites. These were sorted into three groups based on a Relative Potential Benefit (RPB) calculation derived from an analysis of complexity and volume of operations. The results, shown in Table 9-2, were normalized to a value of 1.00 for the Potomac TRACON.

Table 9-2. Potential EDP Deployment Sites and Calculated RPB

Site ID	Location	RPB
N90	New York	1.29
SCT	Southern California	1.22
PCT	Potomac	1.00
NCT	Northern California	.66
I90	Houston	.30
C90	Chicago	.29
A80	Atlanta	.15
D10	Dallas Ft. Worth	.14
MIA	Miami	.13
D01	Denver	.09
D21	Detroit	.09
M98	Minneapolis	.09
A90	Boston	.08
PIT	Pittsburgh	.07

As a result of the site selection process, the authors decided to study two scenarios: a partial deployment scenario, including the first of two EDP deployment banks of nine sites; and all three of the EDP deployment banks, with a total of 14 sites.

Site Deployment Schedule

The site deployment scheduling methodology from a previous EDP study was used, and the deployment schedule was based on patterns observed from Free Flight Phase 1 and 2 (FFP1 and FFP2) deployment of Traffic Management Advisor (TMA). Included in the report are specific assumptions regarding the site deployment schedule, as measured in half-year units. The authors note that EDP is expected to reach Technology Readiness Level (TRL) 4 completion by September 2003, and that the typical time interval between TRL 4 completion and TRL 6 completion is 3-1/2 years. Table 9-3 lists the schedule assumptions used in this assessment.

Table 9-3. Site Deployment Schedule Assumptions

Time between TRL 6 completion to IDU at the 1st site	0.5 years
Time between IDU and PCA at a site	0.5 years
Time between installation and IDU at a site	1.0 years
Time between installation of the 1st site and 2nd site	1.5 years
Time between installations of the rest of sites	0.5 years
Time between installation at last site of a group and first site of next group	1.0 years

Benefits Assessment

The authors chose to adopt a fast-time air traffic simulation approach for the benefit assessment of EDP. This decision was made because in previous studies there was a lack of detail, and the authors note that fast-time air traffic simulation is a valid approach in air traffic control studies.

TAAM

Total Airspace and Airport Modeller (TAAM) was chosen for this study, because it allows users to simulate air traffic within various traffic management situations, and provides analysis and visualization tools that can be used to verify simulation results. One TAAM feature that posed a potential problem for the study team is the lack of an adequate conflict resolution feature. However, it was determined that without this feature enforced, the authors were able to ensure that a certain level of safety is maintained throughout the simulations.

Simulation Modeling Site Selection

The study team selected the Potomac (PCT) TRACON as the site for the simulation modeling portion of this assessment. PCT was chosen because the Washington DC area has one of the most complicated air traffic flows in the United States. It includes many prohibited and restricted areas, and most departures and arrivals must still be handed off to controllers in adjacent TRACON sectors until they can be transferred to the center controllers. The PCT TRACON is composed of four formerly separate TRACONs (ADW, BWI, DCA, and IAD).

The potential benefits at PCT were used as the basis for benefits extrapolation to other years and other sites.

Simulation Scenarios

The following scenarios were developed to model the performance of EDP:

- Baseline
- Simulation of expedite climb profiles

- Simulation of precision spacing
- Simulation of all EDP benefit mechanisms.

A separate simulation for improved departure sequencing was not required, as the benefits from EDP's ability to improve departure sequencing is achieved through the other two EDP simulations. The results from the above simulations were compared to the baseline results, and the differences in total airborne time and taxi time of the flight to and from the studied airports were converted to dollar amounts using the FAA's economic values for evaluation of investment and regulatory programs. The economic benefits of the EDP benefits simulation methodology include savings for crew time, fuel, maintenance, and taxi time.

Cost Assessment

The EDP annual costs and benefits were assessed based on the schedule of deployment at the various sites.

The life-cycle cost (LCC) estimation methodology from the *Initial Life-Cycle Cost/Benefit Assessment of Multi-Center Traffic Management Advisor* (August 2002) was used for this assessment. That study's methodology addresses key characteristics, including:

- Consideration of all cost types (coverage)
- Quantification of these costs (estimation)
- Establishment of temporal schedules to incur these costs (LCC phase).

The cost assessment model took into account a combination of parametric, analogy, and expert opinion techniques, and was updated and calibrated to reflect actual FAA DST deployment costs. The calibrated cost assessment model, with EDP-appropriate input parameters, was used to assess the life cycle costs of EDP.

Life-Cycle Cost/Benefit Assessment

For all cases studied, the following LCCBA results are provided:

- Annual costs and benefits
- Net present value (NPV)
- Benefit to cost ratio (B/C ratio)
- Breakeven point (BEP)

The authors note that it is important to determine the base year of analysis, the economic service life (ESL) of the system, and the discount rate for NPV calcula-

tions. The assessment performed was of potential costs and benefits, and the likelihood that the DST will be able to achieve the potential costs and benefits was not analyzed.

All costs and benefits were expressed in year 2000 dollars. Also, costs to date (year 2003) were considered sunk costs; the discount rate used was 7 percent; and the deflation/inflation rate was assumed to be the same as the Consumer Price Index. EDP was assumed to have an ESL of 20 years.

RESULTS, FINDINGS, AND CONCLUSIONS

Technical Performance Metrics

With respect to the EDP expedited climb profiles simulation, there was less airborne time and ground departure time used, with savings of 9.7 and 1.1 hours. On average, there is a reduction in time to reach cruise altitude of 1.2 minutes (about 6.7 nautical miles) per departure. In addition, a side effect was that departure queue delays/taxi delays were also reduced in this case. Arrival flights were essentially not affected in this simulation.

With respect to the EDP Precision Spacing simulation, the anticipated savings in the form of reduced airborne times of the Washington departure flights are not evident. The effect of a reduction of departure queue delay/taxi delay results in a reduction of over 11 hours for the Washington departure flights, or more than 19 seconds per flight. The increased total arrival of airborne time is insignificant. When dual-use runways are involved—the case for most of the runways at PCT—analysis becomes more complicated. When only jet aircraft are considered, there is a savings of 28 airport minutes, but this is potentially at the expense of additional airborne delay for slower turboprop and piston aircraft.

With respect to the Combined EDP Simulation Results, the results were roughly additive. The airborne time savings is a little over 10 hours, the departure delay/taxi delay savings is 11.4 hours, and the departure flight time savings are 17 seconds per departure in the air and 20 seconds on the ground. When comparing the in-trail separation distance results to those of the baseline and precision spacing simulations, it can be seen that the change in the distribution of in-trail separation distance is rather uniform, and the overall number of aircraft pairs requiring lateral separation decreased, suggesting better use of vertical separation.

With respect to conflicts counted during simulations, the number of conflicts decreased during the EDP-Climb simulation and increased during the EDP-Merge and EDP-Both simulations. The study team expected this result. In the EDP-Merge simulation, 80 percent of the conflicts were concentrated in just a few sectors, and out of these conflicts, 86 percent of them were between the arrival-arrival pairs of aircraft on final approach. The authors note that the EDP simulations are reasonable when investigated from the standpoint of realistic air traffic.

Single-Year Benefits

The study team categorized the assessed potential EDP benefits into two groups: Without SMS, and With SMS. Table 9-4 shows the results for the Potomac TRACON.

Table 9-4. Potential EDP Benefits at PCT Calculated From Simulation Results (Year 2000 $)

		2005 daily	2005 annual
EDP-Climb	Without SMS	$18,000	$6.6 M
	With SMS	$25,600	$9.3 M
EDP-Merge	With SMS	$27,700	$10.3 M
EDP-Both	With SMS	$52,900	$19.3 M

By using the benefit extrapolation methodology described in the study report, the authors computed the benefits at other airports. Detailed results are provided in the study report Appendix. Table 9-5 shows the estimated potential EDP benefits in 2005 at the proposed 14 sites for the example scenario.

Table 9-5. Estimated EDP Potential Benefits for the Year 2005 (Year 2000 $M)

Site ID	Location	Climb without SMS	Climb with SMS	Merge with SMS	Both with SMS
N90	New York	$9.3	$13.2	$14.3	$27.2
SCT	Southern California	$8.6	$12.2	$13.2	$25.3
PCT	Potomac	$6.6	$9.3	$10.1	$19.3
NCT	Northern California	$4.1	$5.8	$6.3	$12.0
C90	Chicago	$2.3	$3.3	$3.6	$6.8
A80	Atlanta	$2.4	$3.4	$3.7	$7.0

Table 9-5. Estimated EDP Potential Benefits for the Year 2005 (Year 2000 $M) (Continued)

Site ID	Location	Climb without SMS	Climb with SMS	Merge with SMS	Both with SMS
D10	Dallas Ft. Worth	$1.2	$1.6	$1.5	$3.4
D01	Denver	$1.0	$1.5	$1.6	$3.0
I90	Houston	$0.9	$1.3	$1.4	$2.7
A90	Boston	$0.7	$1.1	$1.1	$2.2
D21	Detroit	$0.7	$0.9	$1.0	$1.9
MIA	Miami	$0.7	$1.0	$1.0	$2.0
M98	Minneapolis	$0.5	$0.7	$0.8	$1.5

Site ID	Location	Climb without SMS	Climb with SMS	Merge with SMS	Both with SMS
PIT	Pittsburgh	$0.5	$0.7	$0.7	$1.4
Total		$39.4	$55.9	$60.5	$115.4

Life-Cycle Cost-Benefit Results

Two scenarios, a 14-site case and a 9-site case, were studied for EDP LCCBA, and they were each evaluated over a 20-year ESL.

EDP LIFE-CYCLE COST

The life-cycle costs for both cases are shown in Table 9-6.

Table 9-6. EDP Life-Cycle Cost Results (Year 2000 $M)

Scenario	Life-cycle cost (before discounting	Life-cycle present value (after discounting)
14-site	$417.3	$151.7
9-site	$349.2	$135.6

Figures 9-1 and 9-2 show the annual and cumulative costs for both scenarios, before discounting. The leveling-off of the annual costs starts from 2016 for the 14-site scenario, and from 2013 for the 9-site scenario, and is when the project enters the sustainment phase.

Figure 9-1. EDP Annual and Cumulative Costs at 14 Sites (Before Discounting)

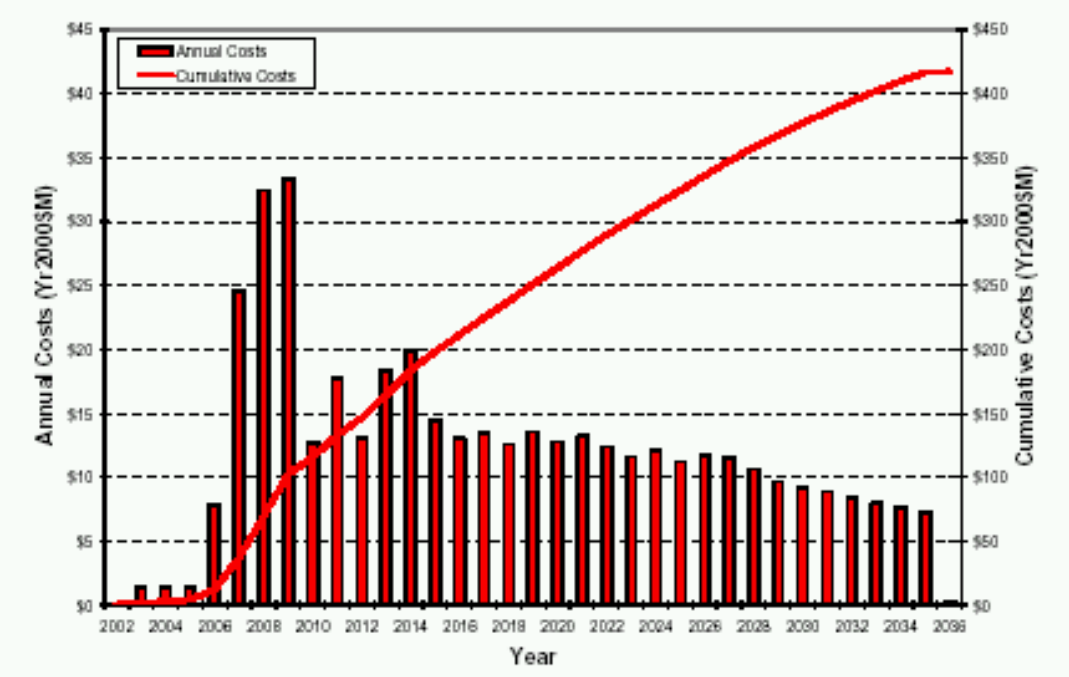
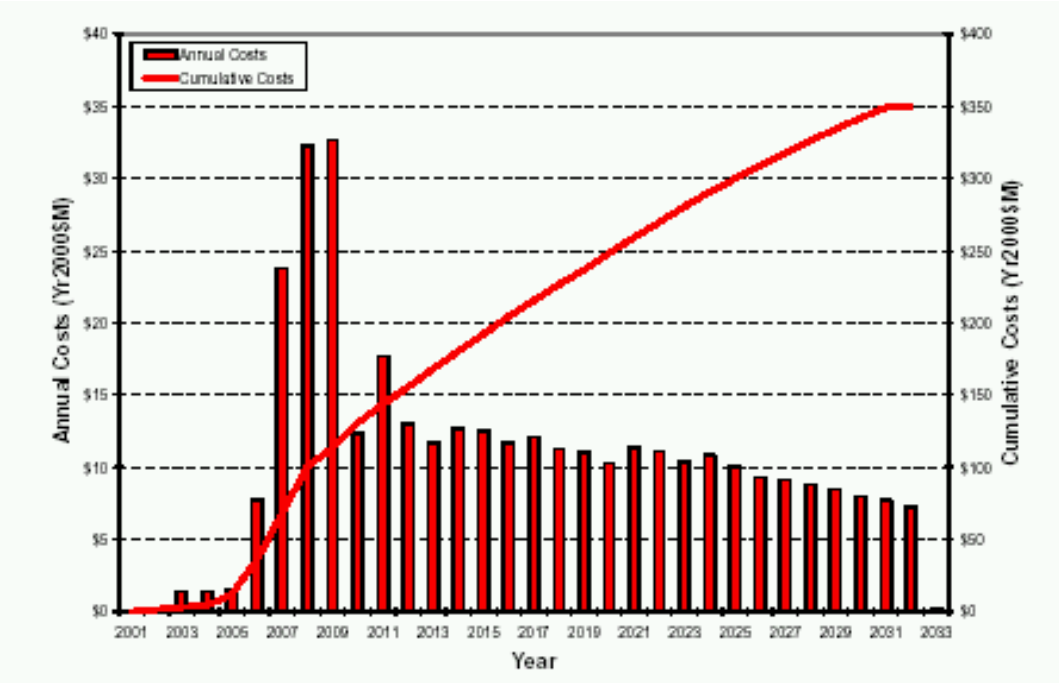


Figure 9-2. EDP Annual Cumulative Costs at 9 Sites (Before Discounting)



EDP LIFE-CYCLE BENEFIT

The life-cycle benefits for both cases are shown in Table 9-7.

Table 9-7. EDP Life-Cycle Benefit Results (Year 2000 $M)

Scenario		Life-cycle benefit (before discounting)	Life-cycle benefit present value (after discounting)
14-site	EDP-climb without SMS	$1,078.5	$296.6
	EDP-climb with SMS	$1,530.6	$420.9
	EDP-merge with SMS	$1,654.8	$455.1
	EDP-both with SMS	$3,158.4	$868.6
9-site	EDP-climb without SMS	$985.6	$277.6
	EDP-climb with SMS	$1,398.8	$394.1
	EDP-merge with SMS	$1,512.3	$426.0
	EDP-both with SMS	$2,886.4	$813.1

Figures 9-3 and 9-4 show the annual and cumulative benefits for both scenarios, before discounting. Several possible potential EDP benefits are not included in this assessment, and therefore the authors note that this assessment could be conservative.

Figure 9-3. EDP-Climb Without SMS Annual and Cumulative Benefits (14 Sites, Before Discounting)

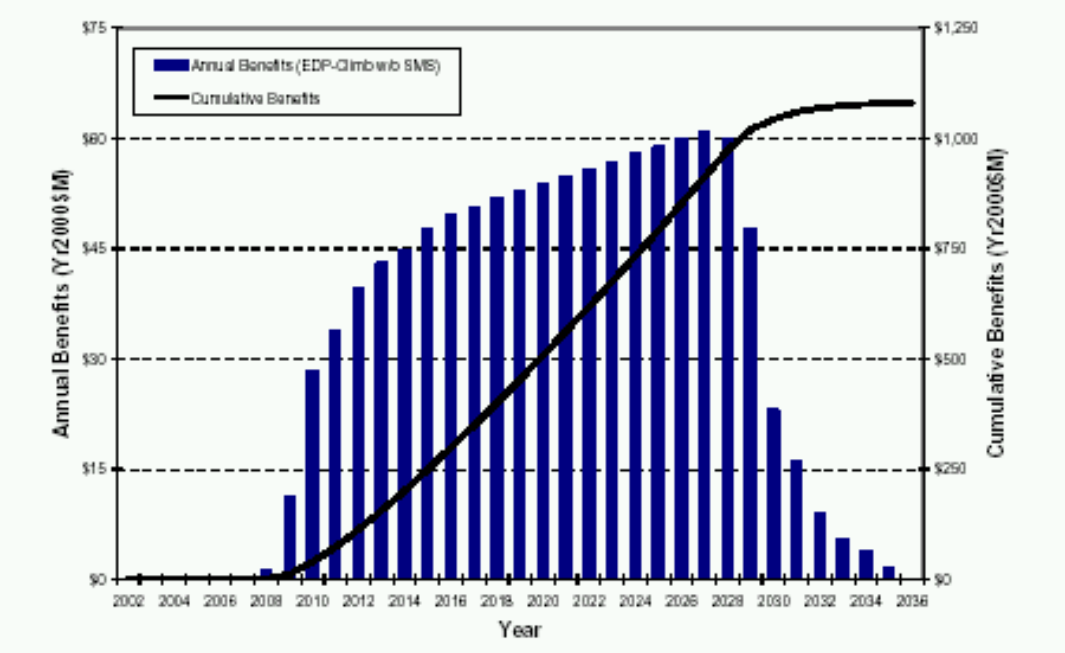
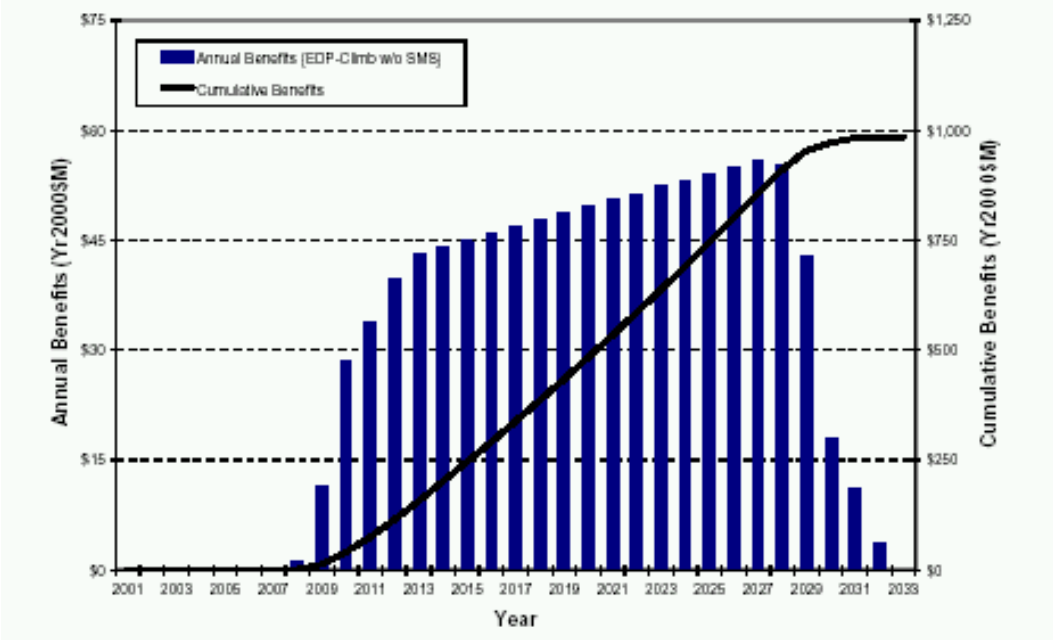


Figure 9-4. EDP-Climb Without SMS Annual and Cumulative Benefits (9 Sites, Before Discounting)



LIFE-CYCLE COST/BENEFIT ASSESSMENT

Only one LCC case each for the 14-site and 9-site scenarios was assessed in the study report, because the authors did not estimate EDP's integration cost with SMS. Table 9-8 shows the EDP life-cycle cost/benefit assessment results.

Table 9-8. EDP Life-Cycle Cost/Benefit Assessment Results

		Discounted benefits (Year 2000 $M)	Discounted costs (Year 2000 $M)	B/C ratio	NPV (Year 2000 $M)	BEP
14-site	EDP-climb without SMS	$296.6	$151.7	1.96	$144.9	2015
	EDP-climb with SMS	$420.9		2.77	$269.2	2013
	EDP-merge with SMS	$455.1		3.00	$303.4	2012
	EDP-both with SMS	$868.6		5.73	$716.9	2011
9-site	EDP-climb without SMS	$277.6	$135.6	2.05	$142.1	2015
	EDP-climb with SMS	$394.1		2.91	$258.5	2013
	EDP-merge with SMS	$426.0		3.14	$290.5	2012
	EDP-both with SMS	$813.1		6.00	$677.6	2011

Figures 9-5 and 9-6 show the discounted life-cycle costs and benefits for the 14-site and 9-site scenarios.

Figure 9-5. EDP Cumulative Discounted Life-Cycle Costs and Benefits (14-site Scenario)

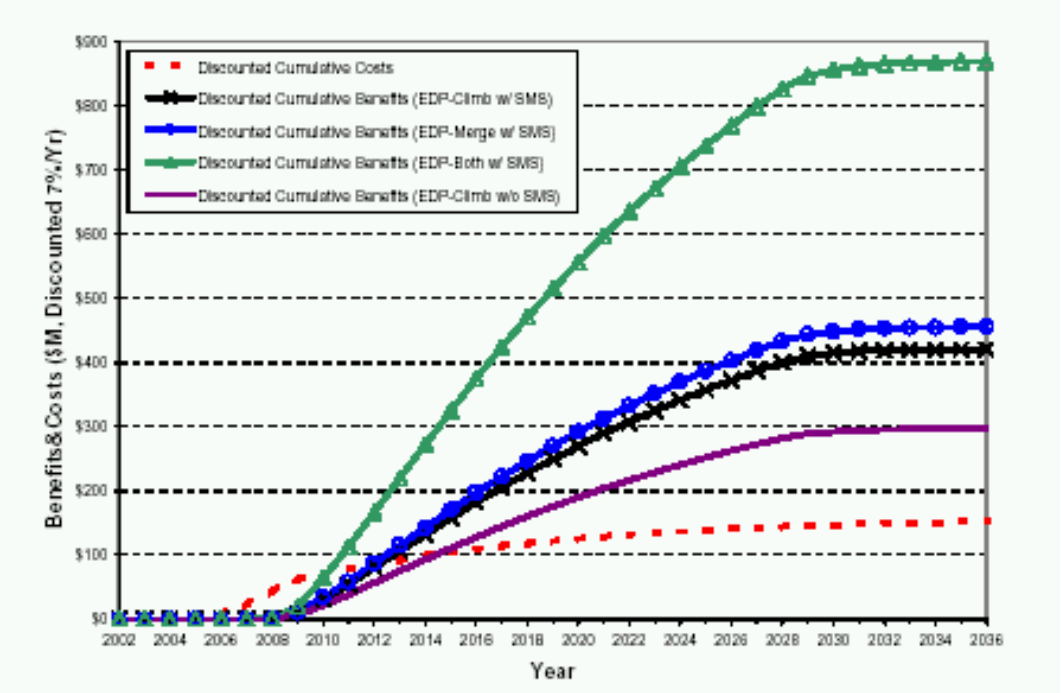
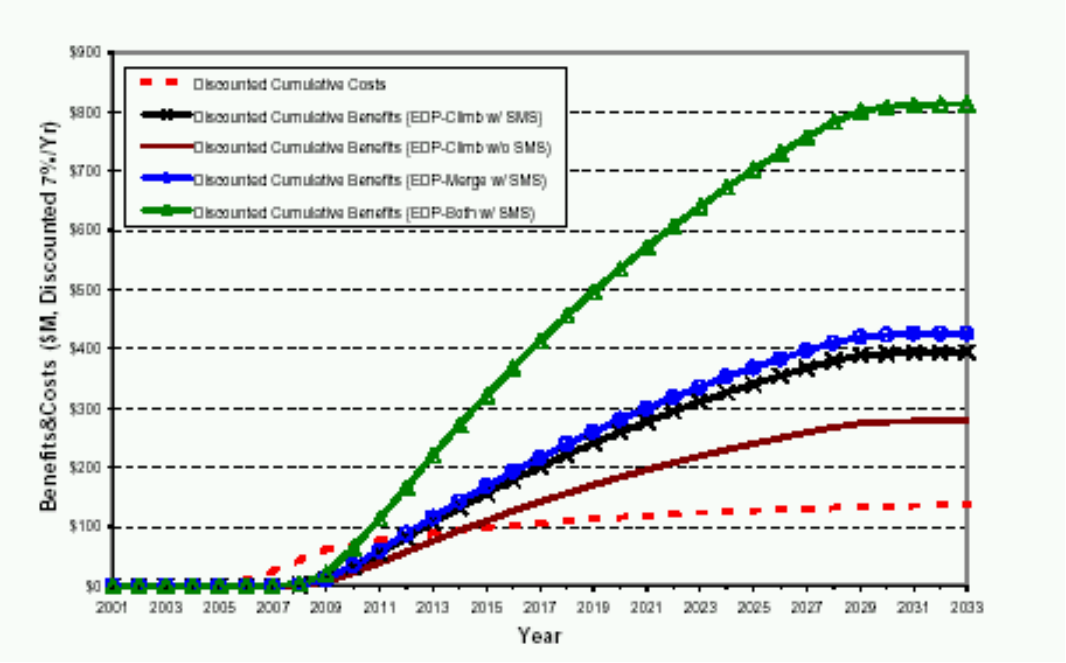


Figure 9-6. EDP Cumulative Discounted Life-Cycle Costs and Benefits (9-Site Scenario)



Conclusions

The total EDP life-cycle costs for the 9-site and 14-site scenarios are estimated at $135.6 million and $151.7 million, respectively. The results show that potential benefits from implementing EDP for both scenarios studied would exceed potential costs for every site. For the 14-site scenario, the cost-benefit translates to a NPV of $144.9 million, a B/C ratio of 1.96, and a breakeven point in the year 2015. Indirect benefits from cooperation of a surface DST, like SMS, increases the NPV to $269.2 million, improves the B/C ratio to 2.77, and moves the breakeven point 2 years earlier. The NPV and B/C ratio for the 9-site scenario surpasses the 14-site scenario with the same breakeven point.

Chapter 10
En Route Descent Advisor (EDA)—Summary of Benefits Assessment Compilation

INTRODUCTION

The En Route/Descent Advisor (EDA) tool is part of a suite of software Decision Support tools (DSTs) under the Center-TRACON Automation System (CTAS) project. EDA is designed to aid the FAA En Route ATC by providing more efficient management of air traffic within and between Air Route Traffic Control Centers (ARTCCs). EDA serves aircraft at all phases of en route flight, including climb, cruise, and descent.

The overall goal of the EDA tool is to reduce deviations from the airspace users' preferred trajectory due to separation assurance and conformance with metering flow restrictions.

This summary of EDA is based upon the assessment by Seagull Technology Inc. under subcontract to Systems Research Corporation (SRC) for NASA's Advanced Air Transportation Technologies (AATT) program. It represents the compilation and update of several EDA benefit studies performed by Seagull Technology Inc. dating back to 1996. The full citation for the assessment is:

> *Benefits Assessment Compilation for the En Route Descent Advisor (EDA) AATT Decision Support Tool*, Tara J. Weidner. NASA Prime Contract NAS2-98005, SRC Subcontract 99-0249, December 2000.

The primary objective of the benefit study was to compile and refine previous EDA benefits efforts, as well as present cross-comparable annual National Airspace System (NAS)-wide quantitative benefits estimates using common baselines and assumptions. These new estimates were based upon improved models and recent field tests of en route trajectory prediction.

The report identified several potential EDA benefits from previous and ongoing research. These benefits resulted primarily from EDA-calculated maneuver advisories based on improved arrival trajectory prediction and integration of metering conformance flight changes with conflict probe tools. Below are the five major benefit mechanisms evaluated in the report:

- *Increased Airport Throughput:* More accurate metering fix schedule adherence leads to reduced runway gaps and increased throughput of the runway system.

- *Improved Center/TRACON Delay Distribution:* Ability to absorb delay more efficiently in center airspace while still maintaining a given TRACON entry rate.

- *Improved Metering Conformance Efficiency:* By assisting controllers in formulating and executing a traffic delay strategy to meet arrival metering fix crossing schedule, EDA allows controllers to more effectively use fuel-efficient delay strategies, such as speed control.

- *Improved Separation Assurance Interruptions:* With more accurate EDA arrival intent, ATM would less frequently perceive aircraft to be incorrectly or out of conflict (missed and false alerts), resulting in fewer ATM flight interventions and associated resolution fuel penalties.

- *Arrival Trajectory Optimization:* Optimization of existing metering fix restrictions and the relaxation of metering fix restrictions allows controllers to delay arrival merging as long as safely possible and shorten flight paths, resulting in more fuel-efficient arrivals.

In addition, the study described several benefits that were not quantified in any of the studies but were deemed critical benefits of the EDA tool. Qualitative benefits cited most often were the impact on workload and safety. By assisting controllers in the formulation of problem-resolution strategies to meet the dual objectives of separation assurance and compliance with flow-rate restrictions, EDA reduces controller workload and the need for additional corrective interruptions. Early EDA testing found that over two-thirds of EDA clearances provided to controllers required no modification. The EDA tool also improves workload distribution among sectors via path-independent routes.

FUNCTIONS, BENEFITS MECHANISMS, AND METRICS

In the EDA future system, FAA Free Flight Phase 1 (FFP1) operations are enhanced with the integrated capabilities of the CTAS En Route/Descent Advisor (EDA) tools. EDA enhances the FFP1 baseline in three ways:

1. It improves the efficiency with which controllers direct traffic to conform to flow-rate restrictions, including time-based arrival metering and en route miles-in-trail (MIT) spacing.

2. It integrates flow-rate conformance capabilities with conflict detection and resolution (CD&R) tools, which reduces the rate of conflict probe false alarms and missed alerts.

3. It attempts to enable a shift toward a trajectory orientation with user flexibility, by enabling efficient controller actions that work cooperatively across sectors.

As in the baseline case, EDA system functionality includes TMA metered arrival scheduling and delay feedback, and Passive Final Approach Spacing Tool (pFAST) TRACON sequencing and scheduling assistance.

The following are additional functions of the EDA system:

- Ability of the controller to plan and execute a traffic delay strategy to conform to the TMA schedule by quickly and accurately assessing the impact of various delay methods and generating EDA maneuver advisories
- Built-in conflict prediction/resolution capability that results in maneuver advisories with conflict-free trajectories; this capability also assists controllers in accommodating user-requested arrival preferences.

In the case of EDA with data exchange, the following data is exchanged:

- Wind/temperature measurements
- Aircraft weight and thrust/drag coefficients (critical to DST modeling of climb/descent profiles)
- Arrival/departure speed intent
- Next two waypoints.

MODELING AND ANALYSIS APPROACH

Study Cases

All of the benefit assessments in this summary computed EDA benefits by comparing air traffic management (ATM) operations using EDA for ATM operations in a baseline system. The benefits summary also includes a case where the EDA system is augmented with user-ATM data-exchange.

The baseline case reflects en route operations aided by FFP1 arrival metering and conflict probe tools. This program uses a set of first-generation advanced ATM DSTs, including Traffic Management Advisor (TMA), User Request Evaluation Tool—Core Capability Limited Deployment (URET CCLD), and pFAST. In this FFP1 suite of tools, the metering conformance (TMA) and conflict probe (URET CCLD) functions are not integrated, and the conflict probe's ability to determine potential conflicts suffers by being unaware of the controller metering conformance flight changes.

Benefit Analysis Process

The author used a benefit analysis process that quantified how improved DST calculations and ATM advisories led to changes in ATM operations and modeled

these changes over a typical day at one or more airports. These data were then used as a basis for annual and NAS-wide benefit estimation. The four primary analysis steps used were:

1. *Technology Definitions:* Statistical values for various parameters used to define the accuracy of an aircraft trajectory were used to estimate the accuracy of DST trajectory predictions relative to the nominal trajectory followed in each case.

2. *Trajectory Prediction Accuracy Model:* The statistical parametric values were used to calculate DST expected timing and position errors. These errors were used to predict excess spacing buffers that would be imposed by controllers to protect against separation minima violations.

3. *Air Traffic Operations Simulation:* The scenarios, parameters, and spacings defined for baseline and EDA cases were combined with a traffic scenario and ATM operating procedures to compute measures of the DST improvements to scheduling/airport capacity, conflict probe flight interruptions, and overall flight fuel-efficiency.

4. *Economic Models:* The simulated ATM performance improvements were converted into operating cost savings (time and fuel), which were then extrapolated to annual and NAS-wide levels (37 airports were chosen to represent high-demand NAS airports) using 1996 FAA traffic data.

RESULTS, FINDINGS, AND CONCLUSIONS

Table 10-1 is a summary of the benefits calculated for each major benefit mechanism. In sum, the studies revealed $290 million in NAS-wide annual EDA benefits. Trajectory optimization clearly realized the greatest cost savings; both under existing metering fix restrictions and a future where restrictions are lifted. The second and third largest EDA benefit estimates resulted from the related mechanisms of Center/TRACON delay distribution and airport throughput, with savings of over $40 million per year. Improved separation assurance interruptions were estimated to save only $2 million annually.

Despite the significant reductions in false and missed alert rates from this mechanism, the low average cost for these interruptions led to low cost benefits. However, the qualitative benefits of this mechanism in terms of reduced workload are likely to be significant.

Table 10-1. NAS-Wide Annual EDA Benefits

Benefit mechanism	EDA time/fuel savings	Annual NAS cost savings ($M 1998)
Airport throughput	1-2 seconds of delay, $2.35 per operation	$42.93
Center/TRACON delay distribution	114 lbs. of fuel, $11.42 per rush arrival	$47.73
Metering conformance efficiency	59 lbs. of fuel, $6.80 per arrival metering conformance interruption	$25.09
Separation assurance	5% reduction in separation assurance interruptions	$2.80
Trajectory optimization: near-term optimization of existing metering fix restrictions	202 lbs. of fuel, $20.26 per operation	$84.73
Trajectory optimization: far-term anchor point concept	111 lbs. of fuel, $11.12 per operation	$88.34

Note: Extrapolated cost savings are based on 1996 FAA traffic data and represent 1996 estimated annual cost savings, in 1998 dollars.

Airport Throughput Benefits

Air traffic controllers often impose a spacing buffer in addition to the minimum spacing required between adjacent aircraft in order to insure that these minima are not violated because of trajectory uncertainties. EDA functionality leads to less variance in arrival trajectory prediction accuracy. This further allows for less excess spacing at the runway threshold without compromising safety. This reduction in spacing gaps between aircraft on final approach increases the throughput of the runway system.

In this study, parameter accuracy distributions (for turn variation, deceleration, and threshold speed) were used as inputs to model trajectory prediction accuracy at various stages of flight in terms of arrival metering fix uncertainty and the resulting excess spacing buffer contribution. These contributions were then combined to calculate runway spacing buffers for each study case. Using a computer simulation model, the study used these buffer estimates and minimum separation requirements to evaluate airport throughput and traffic delay.

Twenty-nine airports were individually modeled using a typical daily traffic schedule. These models resulted in four categories of delays:

- Instrument Flight Rules (IFR) Arrival Delay
- Visual Flight Rules (VFR) Arrival Delay

- IFR Departure Delay
- VFR Departure Delay.

At each airport, delays declined with a reduction in the runway threshold spacing buffer. Traffic delay savings per operation were extrapolated to annual cost savings by airport, using a unique delay cost rate for each airport. Delay savings from the eight NAS airports not simulated were estimated using information from the closest simulated airport. EDA saved an average of 1–2 seconds of delay, or $2.35 per operation (time and fuel) for a total NAS-wide savings of 445 hours and $42.93 million annually.

Figure 10-1 clearly indicates that large, capacity-constrained airports (LGA, LAX, and ORD) accrued the most significant benefits from EDA.

Center/TRACON Delay Distribution Benefits

Improved arrival metering fix timing accuracy provided by EDA also allows ATM to improve how delays are absorbed and distributed. During busy traffic periods, controllers tend to allocate more delay to TRACON airspace in order to ensure aircraft are available to use the runway system. As trajectory prediction improves and variance in arrival metering fix delivery accuracy is reduced, less delay is needed in TRACON airspace to maintain high runway system throughput. The increase in the proportion of total delay taken in center airspace provides cost savings due to the ability of center airspace to absorb delay more efficiently.

In this study, estimated fuel savings from this reallocation of delay using EDA were calculated at three airports (LAX, ATL, and DFW) and extrapolated to annual and NAS-wide levels. As in the first study, baseline and EDA-defined data parameter accuracies were used to calculate the expected meter fix timing error. These timing errors were used to identify optimum levels of TRACON delay.

The maximum delay that could be absorbed in each TRACON route category was identified based on ATM facility-provided data as well as discussions with each facility. The study also evaluated a typical day’s operations at each of the facilities to identify and characterize arrival rushes. The optimal TRACON delay settings were then compared to the maximum settings. Fuel savings per arrival and per rush using EDA were then calculated for each airport. Daily savings were also calculated, as shown in Table 10-2.

Figure 10-1. NAS Annual EDA Cost Benefits Resulting From Reduced Delays

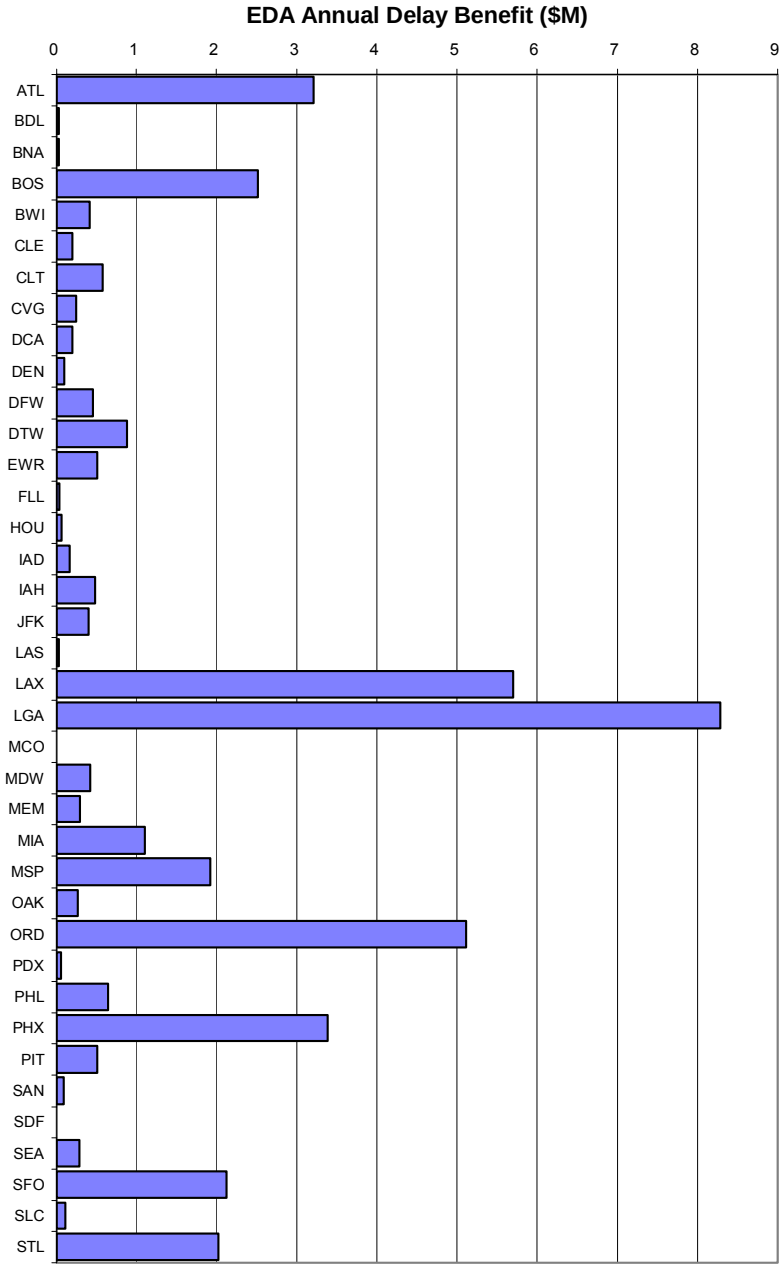
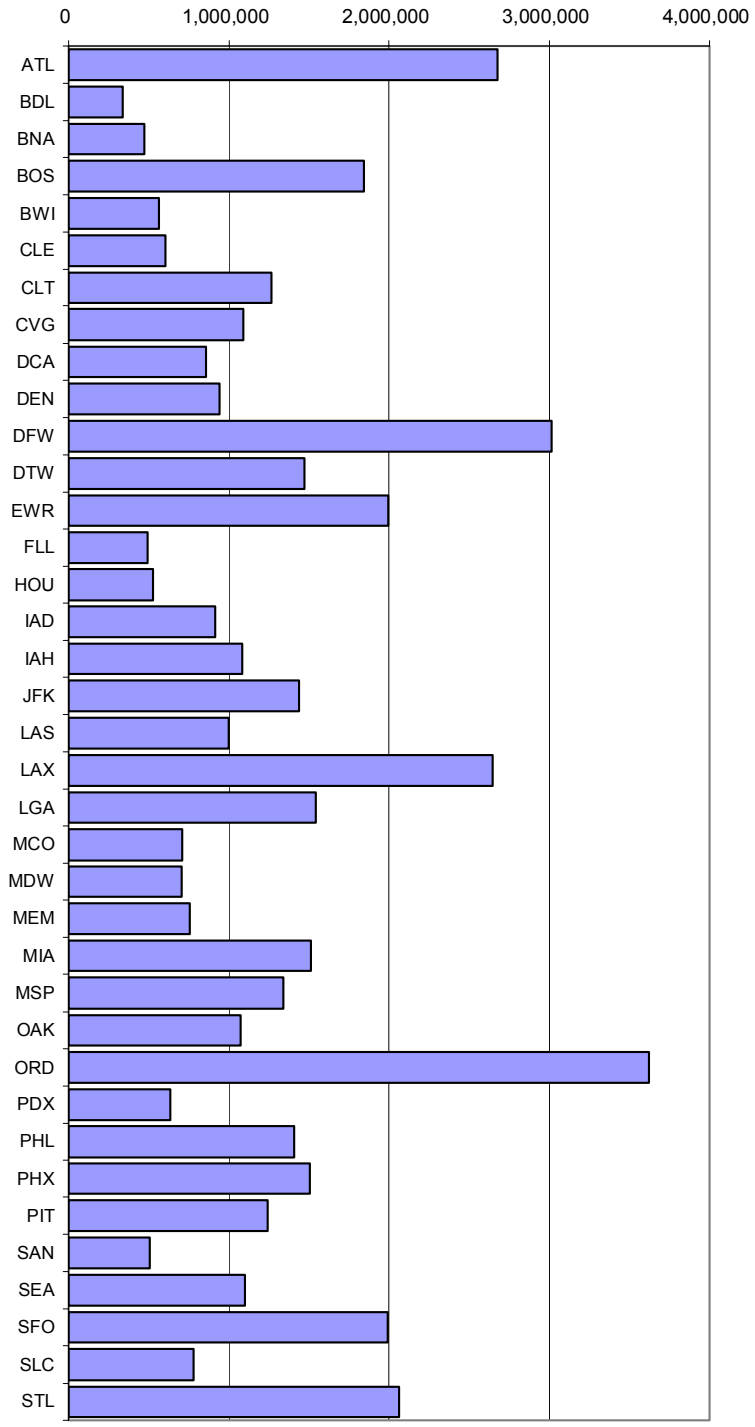


Table 10-2. EDA Center/TRACON Delay Distribution Fuel Savings Summary

	EDA daily center/TRACON delay distribution benefits			
	ATL	DFW	LAX	Airport average
Rush operations rate (per 100 airport ops)	35.7	27.0	27.0	30.4
ARTCC delay shift (sec)	137 sec	128 sec	150 sec	138 sec
Average fuel savings ($)	$12.40/op $977/rush $8,794/day	$9.82/op $577/rush $5,772/day	$11.86/op $1,262/rush $6,311/day	$11.42/op $939/rush $6,959/day

LAX and ATL show greater benefits because of the larger number of aircraft per rush at these airports. The daily DFW savings were extrapolated to an annual level and to 34 other high-demand NAS airports using 1996 operation totals at each airport, as well as an “airport factor” to adjust for variations in congestion at each airport. Annual savings for each airport are charted in Figure 10-2.

Figure 10-2. EDA Center/TRACON Delay Distribution Cost-Savings Benefits



Again, large hub airports showed the most significant cost savings with EDA. EDA shifted an average of 138 seconds of rush arrival delay from TRACON to center airspace, saving $11.42 in fuel per rush arrival. Benefits at all 37 NAS airports totaled $47.73 million annually.

Arrival Metering Conformance Efficiency Benefits

A third benefit mechanism of EDA is the ability to improve how controllers plan and execute flight deviations in order to conform to flow-rate restrictions. By reducing unnecessary deviations and improving the efficiency with which necessary "interruptions" are implemented, both user costs and controller workload can be reduced. Arrival metering delay can be executed using a variety of airborne delay absorption methods, including changes in speed, cruise altitude, vectoring, and time-shift. EDA automation assists in controller strategy development by providing metering conformance maneuver advisories that allow the controller to quickly assess the impact of various methods. These advisories also provide more precise speed and vectoring recommendations that help compensate for controller cognitive limitations. Earlier execution of these strategies allows for an increased use of fuel-efficient speed control delay methods, as opposed to the more expensive vectoring methods.

In this study, the cost of ATM interruptions for metering conformance was calculated for each technology (FFP1 baseline and EDA). In order to address the impact of arrival direct routing on metering conformance, two separate EDA cases were analyzed, standard terminal arrival routes (STARs) and direct arrival routes.

Parametric effects, attributes of both the baseline and EDA metering conformance delay absorption strategies, and information from a DFW daily traffic schedule were used as input to an "ATM Interruptions Model." This model generated a set of interruption costs, based on each aircraft and the metering conformance strategy used. Fuel costs were then calculated using fuel burn rates based on speed and altitude. EDA metering conformance benefits were calculated as the difference between the total time and fuel arrival delay costs of the baseline and EDA cases.

Because there was no significant difference in metering conformance results between the EDA direct arrival routes and STARs, they were addressed jointly as EDA results. Table 10-3 displays the number of metering conformance interruptions and share of the total delay absorbed by each method.

Table 10-3. Metering Conformance Delay Methods

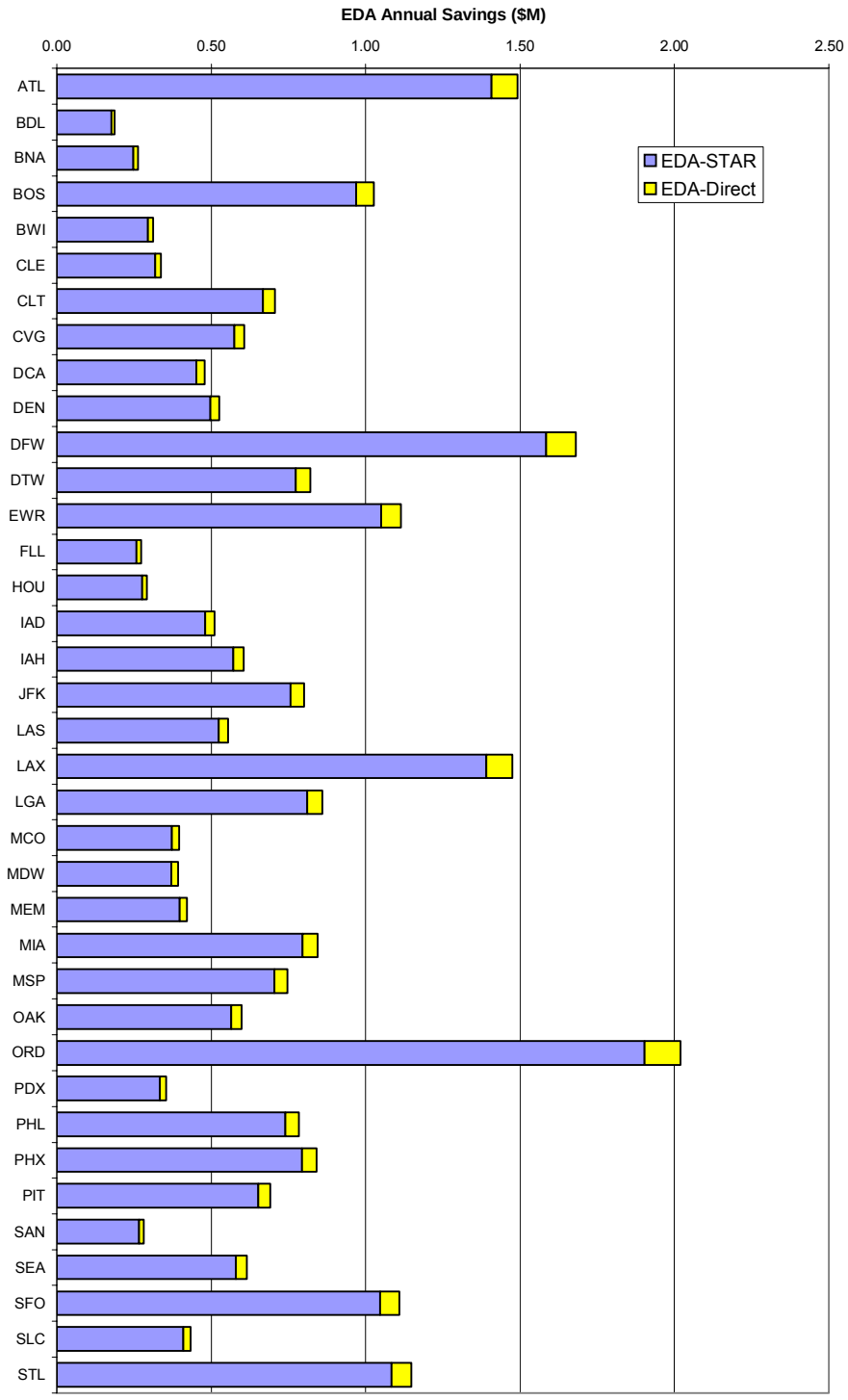
	Number	Delay (min)		Method frequency (%)*			Share of total delay (%)		
	Delayed arrivals	Ave.	Total	Altitude	Speed	Vector/ TS	Alt/Spd	Vector	Time shift
FFP1 baseline	662	4.0	2682	41.2	38.4	84.9	16.2	47.2	36.6
EDA	662	4.0	2654	47.0	74.0	65.9	31.8	34.4	33.8

As seen in Table 10-3, EDA replaces the baseline's use of vectoring and time shift with more cost-effective speed control and altitude arrival delay methods.

Overall, EDA saved about $4,000 worth of fuel in the daily simulation. While both cases reflected the same traffic scenario and flow-rate constraints, less vectoring turn back error was applied to the EDA case, based on prototype EDA observations. This did increase the baseline time by 1 percent and increased the daily EDA cost savings by $500. The similar benefits estimated for STAR and direct arrival routing implies that direct routing does not inhibit EDA metering conformance efficiency. In addition, the direct arrival route actions actually had a slight fuel advantage, but the more conservative STAR results were used in order to be consistent across benefit mechanisms.

These simulated daily interruption costs were then extrapolated to annual NAS-wide levels using the total number of 1996 operations at each facility; the results appear in Figure 10-3. Again, rush arrival rates were adjusted by an airport factor to account for variations in congestion at each facility. EDA saved an average of $6.80 per arrival metering conformance interruption, with a total annual savings of $25.09 million across all 37 NAS airports. Once again, the airports with larger operations realized the greatest savings.

Figure 10-3. EDA Metering Conformance Cost-Savings Benefits



ATM Separation Assurance Benefits

In addition to metering conformance interruptions discussed in the previous section, separation assurance flight interruptions also deviate flights from users' preferred trajectories. ATM relies on accurate predictions of future flight positions within conflict probe DSTs to accurately identify and alert controllers of pending conflicts. In the current system, deviations must be recorded as a flight path amendment in order for conflict probe DSTs to become aware of the changed aircraft intent. The future integration of conflict probe, direct routing, and metering conformance tools can significantly reduce conflict probe prediction inaccuracies. As trajectory prediction becomes more accurate using EDA, controllers will become confident in the consistency of more accurate conflict predictions, and buffers will shrink.

In order to analyze the benefits that result from more accurate conflict alerts, this study used baseline and EDA-defined data parameter accuracies in a Trajectory Prediction & Accuracy Model to calculate the expected position error in CTAS' conflict probe prediction. This timing error was then converted into spacing buffers that would be imposed by controllers to limit separation minima violations. As in the last benefit study, these spacing buffers were combined with the same DFW daily traffic schedule information identified in the earlier studies, in an ATM Interruptions Model. Given the delays that would be necessary to meet airport capacity restrictions, a conflict detection algorithm was used to identify actual and potential conflicts that would occur without ATM intervention. ATM perception of conflict was characterized by four metrics that varied between baseline and EDA cases and by phase of flight:

- Trajectory Prediction Accuracy
- Acceptable Controller Spacing (ACS)
- Perceived Miss Distance
- Probability of Perceived Conflict.

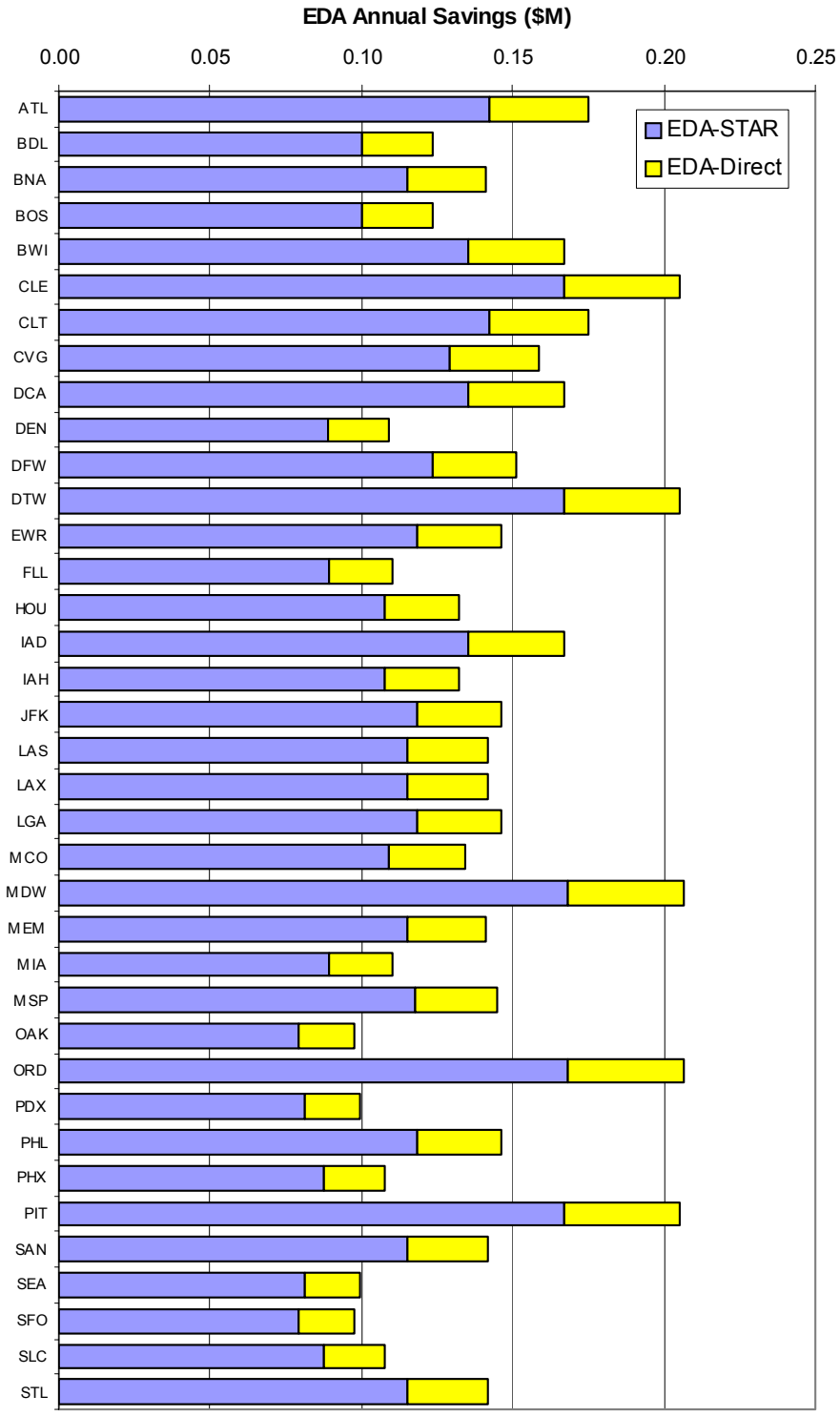
For this model, the frequency of inaccurate intent in the FFP1 baseline case was assumed to be 15 percent for all flight modes. This was based on discussions with conflict probe experts and Indianapolis Center observations that only 18 percent of all route clearances are documented. With the integration of arrival metering and conflict probe tools in the EDA case, it was assumed that arrival intent errors would be removed, while departure and overflight intent inaccuracy would remain unchanged.

The study found that EDA reduced the missed alert rate from 62 percent to 31 percent and the false alert rate from 61 percent to 37 percent. EDA reduced overall separation assurance interruptions by 5 percent. The distance of the additional flight segment required in these interruptions were used to calculate additional

fuel costs. EDA (STAR) reduced the daily cost of “interruptions” at DFW from $4,123 to $3,360.

As in the studies described earlier, the simulated daily interruption rates and resolution costs at DFW were extrapolated to annual and NAS-wide levels using 1996 operations information. Annual savings, NAS-wide, were estimated to be over $2 million. In this study, EDA with direct route arrivals saved about 23 percent more than STAR routes. Despite a slightly higher interrupt rate in the EDA-direct case, the smaller per operation resolution cost resulted in larger overall annual NAS-wide benefits. Airport-by-airport benefits are shown in Figure 10-4.

Figure 10-4. EDA Separation Assurance ATM Interruptions Cost-Savings Benefits



Arrival Trajectory Optimization Benefits

EDA enables two types of trajectory optimization benefits: optimization to existing metering fix restrictions, and the relaxation of metering fix restrictions enabled by precise metering.

This study evaluated benefits per operation for four separate benefit mechanisms for EDA arrival trajectory optimization:

- Existing Metering Fix Restrictions—Top of Descent (TOD) Optimization
- Existing Metering Fix Restrictions—Arrival Direct Routing
- Relaxed Metering Fix Restrictions—Horizontal Anchor Point
- Relaxed Metering Fix Restrictions—Vertical Anchor Point

The TOD optimization and vertical anchor point mechanisms shift the TOD location downstream and delay the start of the descent. The direct routing and horizontal anchor point mechanisms attempt to shorten aircraft flight path lengths. All of these mechanisms affect fuel consumption. Additionally, controller workload is also expected to benefit from the assistance of the EDA advisories, the enhanced situational awareness, and confidence in conflict-free clearances that meet separation requirements and flow-rate restrictions.

All of the studies conducted to evaluate these benefit mechanisms identified flight improvements by comparing baseline operations, represented by radar track data from five airports (ATL, BOS, DFW, LAS, LAX), to EDA-optimized trajectories. Distance improvement per operation was based on analysis of three hourly high-demand periods at each airport. In most cases, these EDA path distance savings were converted to fuel savings using aircraft-specific fuel burn rates from an analytical model. In the case of TOD optimization, theoretical fuel savings using a higher fidelity aircraft performance model were defined relative to an idle descent at the optimum TOD location. The resulting five-airport average EDA savings per operation were then extrapolated to annual and NAS-wide levels. Mechanisms tied to existing metering fix restrictions were assumed to apply to metered arrivals only (non-metered arrival optimization is currently practiced), while the new relaxed metering fix benefits were applicable to all arrival operations.

TOD Optimization

The TOD optimization mechanism affects the vertical profile of an aircraft descent trajectory from cruise to the metering fix altitude, while maintaining current arrival metering fix restrictions. Ideally, the TOD is moved as far downstream as possible, with a steep descent profile. By facilitating optimal TOD locations, EDA provides fuel efficiency benefits for metered aircraft. Baseline TOD locations were determined using radar track data, and each observed descent trajectory was

characterized with a constant flight path angle, based on TOD and bottom-of-descent (BOD) flight range and altitudes. The study compared the fuel burn of flights under baseline and the latest point where an aircraft can begin an idle descent and still satisfy existing arrival metering fix restrictions (assumed EDA-enabled TOD location). The idle-thrust descent fuel burn for EDA was derived from simulations of a single B727 aircraft, extrapolated fleet-wide.

Under EDA TOD optimization, aircraft would be able to travel an additional 20–40 nautical miles (nm) in cruise before beginning their descent, saving an average of 182 lbs. of fuel, or $18.16 per operation.

Arrival Direct Routing

The EDA arrival direct routing mechanism aims to improve flight efficiency by enabling user-preferred routing to the arrival metering fix, while adhering to metering fix restrictions. This direct routing shortens the flight path by flying directly to the metering fix.

Again, radar track data at five airports were examined to determine baseline aircraft paths. These paths were characterized with respect to their directness to the TRACON. Direct routing benefits were based on the path length savings between baseline and the most direct path to the arrival metering fix. Fuel savings were then calculated by assuming the shorter path distance represented a fuel burn rate at a typical cruise altitude, weighted by airport fleet-mix during the hours studied.

On average, EDA direct route optimization saved arrival aircraft 1–3 nm and 21 lbs. of fuel, or $2 per arrival operation.

Vertical Anchor Point Concept

Like TOD optimization, the EDA vertical anchor point (VAP) concept attempts to maximize aircraft flight time at cruise altitude. EDA maneuver advisories allow the controller to direct an aircraft to a new BOD, or VAP, that is downstream of the current metering fix.

As in the previous studies, radar track data were used to determine baseline anchor point locations, and these was compared to various locations downstream from the metering fix location (assuming EDA-enabled VAPs). The potential for benefits was largely tied to the airport’s existing ability to match the aircraft BOD with the existing metering fix location.

On average, EDA VAP optimization saved 8.94 nm, 74.96 lbs. of fuel, and $7.50 per operation.

Horizontal Anchor Point Concept

Like arrival direct routing, the EDA horizontal anchor point (HAP) concept aims to improve the efficiency of aircraft trajectory by shortening path length. This is

done by lifting the restriction of a single metering fix and allowing arrivals to enter the TRACON at a location along a straight-line path to the runway. Once again, radar tracking data were used to characterize the horizontal path of aircraft entering the TRACON. EDA-enabled trajectories using HAPs were determined by assuming that aircraft could fly directly to a point 15 nm downstream of the metering fix, without passing through the metering fix. The difference in path length and resulting fuel savings were then calculated. Only aircraft that clearly diverted from a direct path to fly through the metering fix were assumed to benefit from this mechanism.

On average, EDA HAP optimization saved 3.05 nm, 36.20 lbs. of fuel, and $3.62 per operation.

Overall Benefits

Table 10-4 shows the five-airport average savings per operation for each of the four benefit mechanisms.

Table 10-4. Average Savings for Benefit Mechanisms

Parameter	TOD optimization	Arrival direct routing	Vertical[a] anchor point	Horizontal anchor point
ATL–Atlanta Hartsfield International Airport	$10.72	$1.05	$17.83	$3.26
DFW–Dallas Ft. Worth International Airport	$14.24	$2.31	$5.33	$4.59
LAS–Las Vegas McCarren International Airport	$18.88	$2.29	$5.25	$4.44
LAX–Los Angeles International Airport	$27.00	$3.67	$4.67	$5.20
ORD–Chicago O'Hare International Airport	$19.98	$1.18	$8.84	$0.61
Average Savings Per Applicable Operation	$18.16	$2.10	$7.50	$3.62
Applicable Operations Rate (per 100 Airport ops)	30.4[b]	30.4[b]	50.0	50.0

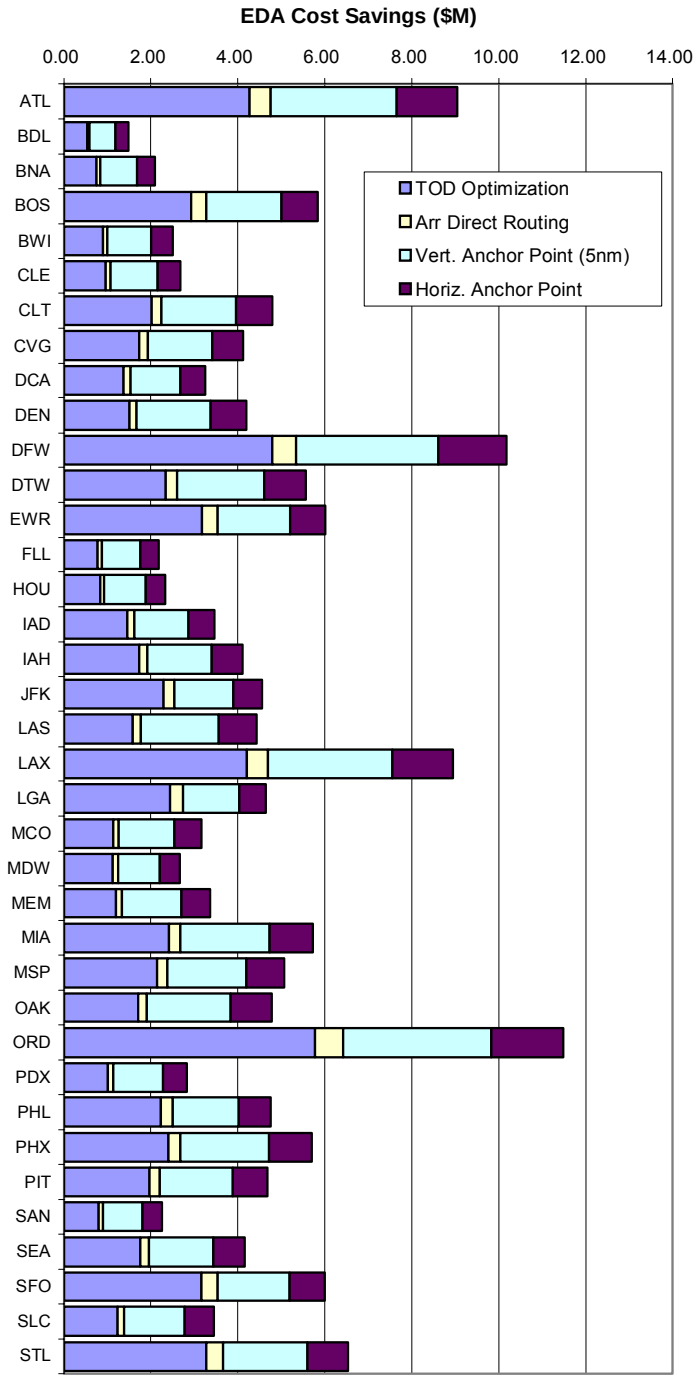
[a] Assumes VAP 5 nm downstream from existing anchor point location, and no benefit in peak hour at DFW and ORD due to delays.

[b] DFW rush arrival rate, airport factor (based on FAA delay data) applied to extrapolate to other airports.

The cost savings from all four benefit mechanisms were extrapolated to annual/NAS-wide levels, taking into account the total number of operations at each facility and the frequency of operations expected to benefit from each mechanism.

Figure 10-5 shows the resulting savings for all 37 NAS airports, which range from $1.5 million to $11.5 million per year. The total annual benefit was almost $173 million.

Figure 10-5. EDA Trajectory Optimization Cost-Savings Benefits



As in most of the other studies, large hub airports reaped the most benefit from the EDA benefit mechanisms. The greatest benefit came from EDA TOD optimization under existing metering fix restrictions ($76 million, or 44 percent of savings), followed by the EDA vertical anchor point mechanism under relaxed metering fix restrictions.

Chapter 11
En Route Data Exchange (EDX)—Summary of Benefits Assessment Compilation

INTRODUCTION

NASA is currently developing decision support tools (DSTs) to enhance the capacity, efficiency, and flexibility of the National Airspace System (NAS). The goal of these tools is to reduce deviations from the airspace user's preferred trajectory.

Accurate prediction of future aircraft trajectories is essential for en route DSTs to provide reliable conflict predictions and efficient schedules. The exchange of calibration, intent, user preference, and air traffic management (ATM) system state data between DSTs and airspace users has the potential to greatly enhance the trajectory prediction accuracy of DSTs. Indeed, the En Route Data Exchange (EDX) project, part of NASA AATT, is tasked with investigating the operational benefit and feasibility of user-Center/TRACON Automation System (CTAS) data exchange. The overall goal of initial EDX phases is to improve CTAS performance and accommodation of user preferences through near-term data exchange of airspace user information.

The integration provided by these data exchanges will improve the accuracy of the en route decision support tools and Flight Management System (FMS) models for trajectory prediction, allow ATM to receive and accommodate user preferences, and allow more informed collaborative decision-making among the airspace users and ATM.

This summary of EDX benefits is based upon the assessment prepared by Seagull Technology Inc. under subcontract to Systems Research Corporation (SRC) for NASA's Advanced Air Transportation Technologies (AATT) program. The full citation is:

> *Benefits Assessment Compilation for En Route Data Exchange (EDX),* Tara J. Weidner and Tysen Mueller. NASA Prime Contract NAS2-98005, SRC Subcontract 99-0249, December 2000.

The primary objective of this benefit study was to compile and refine previously examined benefit mechanisms expected from EDX, as well as present cross-comparable annual NAS-wide quantitative benefits estimates using common baselines and assumptions. Older studies dating back to 1995 were combined with

new results based upon improved models and recent field tests of en route trajectory prediction and ATM interaction.

FUNCTIONS AND BENEFIT MECHANISMS

Economic EDX benefits result primarily from the improved trajectory prediction accuracy afforded by more reliable estimates of aircraft state and intent. The following are five major benefit mechanisms evaluated:

- *Increased Airport Throughput:* En route user-ATM data exchange that leads to better trajectory prediction is expected to reduce runway threshold separations, which further leads to increased airport throughput and reduced aircraft delay.

- *Improved Center/TRACON Delay Distribution:* User-ATM DST data exchange is expected to reduce variability in arrival metering fix crossing time, which allows delays to be absorbed more efficiently in center airspace.

- *More Fuel-Efficient Climbs/Descents:* FMS downlink of its preferred altitude-speed profile to meet crossing times would allow for more fuel-efficient climbs/descents.

- *Improved Separation Assurance Interruptions:* Increased accuracy in DST predicted trajectories due to user-ATM data exchange is expected to lead to reduced controller interventions to meter aircraft and resolve separation conflicts.

- *Increased Direct Routing:* Increased accuracy in DST predicted trajectories due to user-ATM data exchange is expected to reduce the buffers that controllers will use and the likelihood that more direct routes will be employed.

MODELING AND ANALYSIS APPROACH

Study Cases

Six evolutionary EDX scenarios were evaluated relative to two baseline systems:

- *Passive Baseline:* This case utilizes Free Flight Phase 1 (FFP1) ATM decision support tools, including CTAS Traffic Management Advisor (TMA) to schedule and meter arrival flights, Passive Final Approach Spacing Tool (pFAST) to provide runway assignments, and the User Request Evaluation Tool/Core Capability Limited Deployment (URET CCLD) conflict probe and trial planning tool. Because the metering conformance and conflict probe functions are not integrated in FFP1

operations, the conflict probe's performance suffers by being unaware of the controller metering conformance flight changes.

- *Active Baseline:* In addition to the tools available in the passive baseline system, this system includes an integrated En Route/Descent Advisor (EDA) with a built-in conflict prediction/resolution capability. The integration of metering conformance, flight changes, and conflict resolution improves performance and reduces false and missed alert rates.

Each of the following six evolutionary EDX scenarios provides improved perception by supplementing the baseline DST trajectory prediction with aircraft-specific flight information:

- EDX1: Weather (wind/temperature)
- EDX2: Weather, Aircraft Weight, Thrust/Drag Coefficients
- EDX3: Weather, Aircraft Weight, and En Route Speed Intent
- EDX4: Weather, Aircraft Weight, Speed Intent, and Threshold Crossing Speed Intent
- EDX5: Weather, Aircraft Weight, Speed Intent, Next Two Waypoints
- EDX6: Weather, Aircraft Weight, RTA/Speed Intent

Benefit Analysis Process

The authors used a benefit analysis process that quantified how improved DST calculations and ATM advisories led to changes in ATM operations and modeled these changes over a typical day at one or more airports. These data were then used as a basis for annual and NAS-wide benefit estimation. The four primary analysis steps used were:

1. *Technology Definitions:* Statistical values for various parameters used to define the accuracy of an aircraft trajectory were used to estimate the accuracy of DST trajectory predictions relative to the nominal trajectory followed in each case.

2. *Trajectory Prediction Accuracy Model:* Statistical parametric values were used to calculate DST expected timing and position errors. These errors were used to predict excess spacing buffers that would be imposed by controllers to protect against separation minima violations.

3. *Air Traffic Operations Simulation:* Scenarios, parameters, and spacings defined for baseline and EDX cases were combined with a traffic scenario and ATM operating procedures to compute measures of the DST

improvements to scheduling/airport capacity, conflict probe flight interruptions, and overall flight fuel-efficiency.

4. *Economic Models:* The simulated ATM performance improvements were converted into operating cost savings (time and fuel), which were then extrapolated to annual and NAS-wide levels (37 airports were chosen to represent high-demand NAS airports) using 1996 FAA traffic data.

RESULTS, FINDINGS, AND CONCLUSIONS

Annual NAS-wide benefits are presented in Table 11-1. The table identifies the incremental benefits of each successive data exchange case beginning with EDX1 compared to the active and passive baselines.

Of the over $20 million annual NAS-wide benefits (when comparing against either baseline), the largest savings came from enabling direct routing, which saved over $12 million in time and fuel. The related mechanisms of airport throughput and Center/TRACON delay distribution resulted in $7 million and $10 million in savings (under passive and active baselines). In addition, significant controller and pilot workload benefits expected from EDX have not been quantified, including overall safety enhancement with improved EDX surveillance and a reduction in the need for corrective interruptions.

Although these benefits may appear small relative to those expected for a new ATM DST, the study's authors remind us that implementation of EDX concepts requires only minor changes to existing or planned data link, ATM DST, and aircraft FMS technologies.

Table 11-1. NAS-Wide Annual EDX Benefits

37-Airport annual benefits ($000, 1998) benefit mechanism	Baseline	EDX 1 wind, temp	EDX 2 +Wt, thrust/drag	EDX 3 + Arr/dep spd intent	EDX 4 +TH Xing speed	EDX 5 +next 2 waypoints	EDX 6 +RTA/Spd Intent
Airport throughput	Passive	0 hrs $0	16.7 hrs $1,614	32.8 hrs $3,167	NA	NA	Future
	Active	6.6 hrs $637	6.8 hrs $659	0 hrs $0	NA	NA	Future
Center/TRACON delay distribution	Passive	2.2 M lbs $215	1.6 M lbs $159	21.2 M lbs $2,119	24.2 M lbs $2.424	NA	Future
	Active	16.2 M lbs $1,617	19.8 M lbs $1,981	0 lbs $0	24.3 M lbs $2,425	NA	Future
FMS descent speed profile	Passive	NA	NA	NA	NA	NA	NA
	Active	Future (1)	Future (1)	Future (1)	NA	NA	11.3 M lbs $1,129 (1)
Separation assurance interruptions	Passive	NA	NA	NA	NA	NA	NA
	Active	3.5 M lbs $351	6.1 M lbs $605	23.3 M lbs $2,328	NA	3.9 M lbs $298	Future
Enabled departure direct routing	Passive	148 hrs 40.4 M lbs $12,482 (3) (4)			NA	Future	NA
	Active	142 hrs 44.6 M lbs $13,423 (3) (4)			NA	Future	NA

(1) EDX6 benefit assumes EDX1, EDX2, EDX3 data exchange in the baseline although these benefits are not quantified.

(2) EDX1-EDX5 reduced the number of missed alerts (MAs) by 25 percent, false alerts (FAs) by 7 percent, and overall conflict alerts by 10 percent.

(3) Includes EDX1, EDX2, and EDX3 data exchange benefits. Using Separation Assurance Interruptions Benefit ratios, 11 percent, 18 percent, and 71 percent, would be attributable to EDX1, EDX2 and EDX3, respectively.

(4) EDX benefits could be extended to enable arrival direct routes, with EDA picking up metered arrival direct routes in the Active Baseline.

Note: Extrapolated cost savings are based on 1996 FAA traffic data and represent 1996 estimated annual cost savings, in 1998 dollars.

Airport Throughput Benefits

A key benefit of improved trajectory prediction is the ability to increase airport throughput, as improved trajectory prediction allows controllers to tighten in-trail spacing at the same level of safety. The reduction in trajectory uncertainty due to data exchange would result in a reduction in the size of excess spacing buffers needed to compensate for trajectory variances.

The EDX cases evaluated in this study included EDX1 through EDX3 relative to both a passive and an active baseline. Baseline and EDX-defined data parameter accuracies were used as inputs to model trajectory prediction accuracy. Timing

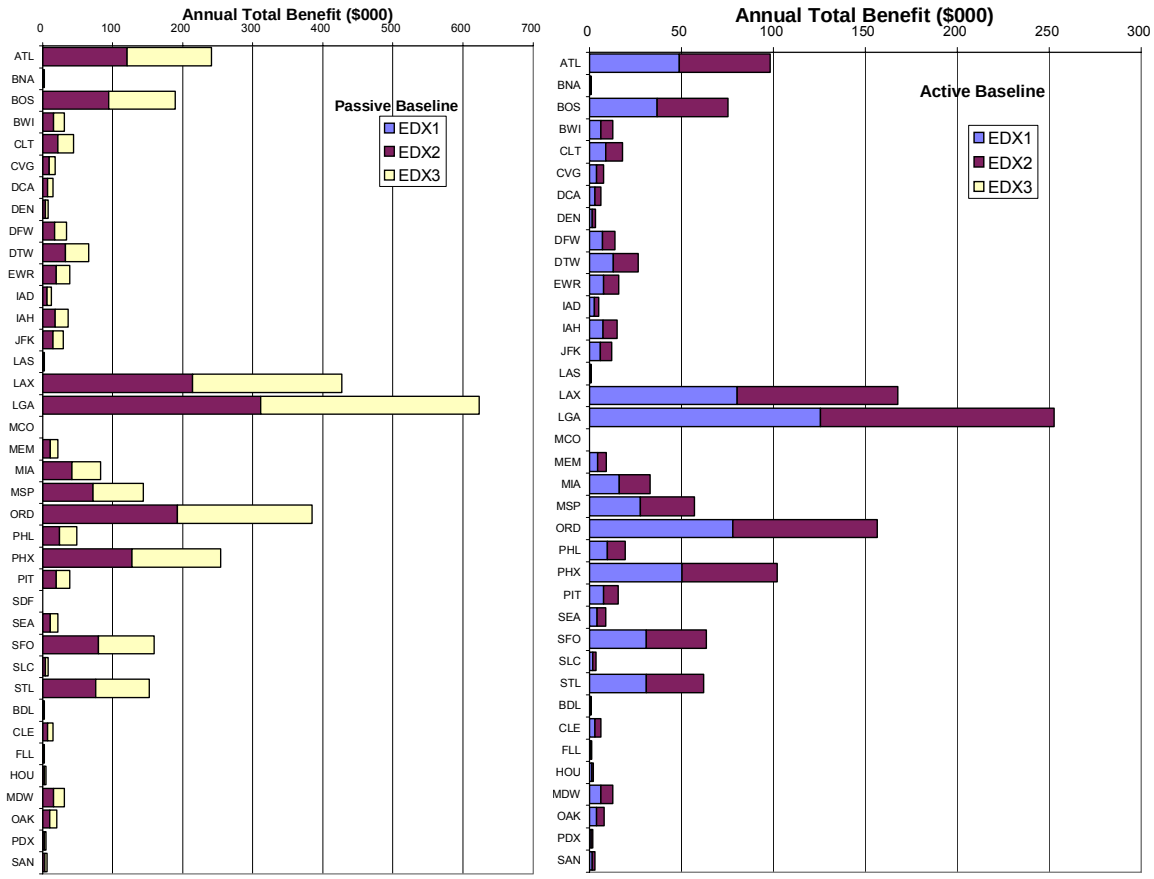
errors were then converted into excess spacing buffers that would be imposed by air traffic controllers to limit minima violations. Using a computer simulation model, the study used the buffer estimates for baseline and EDX cases to evaluate airport throughput and traffic delay at 29 airports using a typical daily traffic schedule.

Daily traffic delay savings were then extrapolated to annual cost savings for each airport using detailed aircraft operating costs and airport traffic information. Per operation delay savings for the eight NAS airports not simulated were assumed equivalent to the closest simulated airport based on FAA 1996 delay data.

EDX enhancements to the passive baseline realized the most savings. EDX2 and EDX3 enhancements to passive baseline operations saved an average of 70 seconds of delay, or $0.26 per operation (time and fuel costs). EDX1 and EDX2 enhancements to the active baseline operations saved 19 seconds of delay, or $0.07 per operation. Total NAS-wide, annual savings totaled $1.3 million.

Figure 11-1 clearly depicts that large, capacity-constrained airports (LGA, LAX, ATL, PHX, and ORD) accrued the most significant benefits from EDX. Two EDX cases showed no benefit. EDX1 showed no improvement over the passive baseline, because the wind/temperature information had a negligible impact on metering fix delivery accuracy. Also, EDX3 (speed intent downlink) showed no improvement compared to the active baseline, since EDA already makes this improvement for arrivals.

Figure 11-1. NAS Annual EDX Airport Throughput Benefits



Center/TRACON Delay Distribution Benefits

Improved arrival metering fix timing accuracy provided by EDX also allows ATM to improve how delays are absorbed and distributed. During busy traffic periods, controllers tend to allocate more delay to TRACON airspace in order to ensure aircraft are available to use the runway system. As trajectory prediction improves and variance in arrival metering fix delivery accuracy is reduced, less delay is needed in TRACON airspace to maintain high runway system throughput. The increase in the proportion of total delay taken in center airspace provides cost savings due to the ability of center airspace to absorb delay more efficiently.

The EDX cases evaluated in this study included EDX1 through EDX4 relative to the passive and active baselines. Estimated fuel savings for each of the EDX cases were calculated at three airports (LAX, ATL, and DFW) and then extrapolated to annual and NAS-wide levels. As in the first study, baseline and EDX-defined data parameter accuracies were used to calculate the expected meter fix timing error. These timing errors were used to identify optimum levels of TRACON delay. EDX delay settings were then compared to baseline cases, and the resulting fuel burn savings were calculated.

The delay shift for each case and associated daily savings for each airport are summarized in Table 11-2.

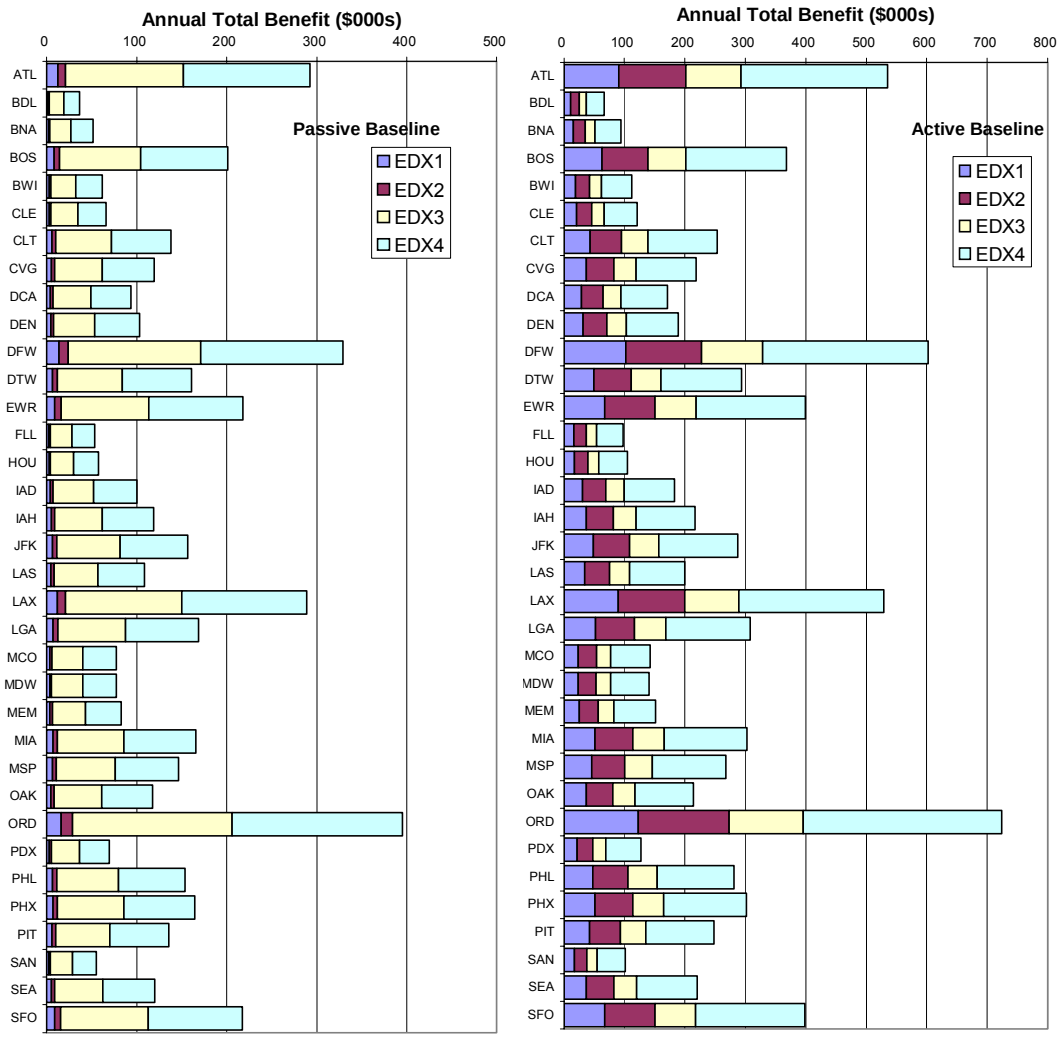
Table 11-2. EDX Center/TRACON Delay Distribution Daily Fuel Savings Summary

	Passive baseline				Active baseline		
	EDX1	EDX2	EDX3	EDX4	EDX1	EDX2/3	EDX4
ATL							
ARTCC delay shift (sec)	0–1	0–2	6–8	13–15	4–5	8–11	15–18
Fuel savings							
($/op)	0–0.09	0–0.18	0.54–0.73	1.18–1.36	0.36–0.45	0.73–1.00	1.36–1.63
($/rush)	2–5	2–10	22–79	47–148	15–53	29–116	54–190
($/day)	$33	$56	$204	$910	$290	$661	$1112
DFW							
ARTCC delay shift (sec)	0–1	0–2	3–8	10–15	2–5	4–11	11–18
Fuel savings							
($/op)	0–0.08	0–0.15	0.23–0.61	0.77–1.15	0.15–0.38	0.31–0.84	0.84–1.38
($/rush)	0–7	1–11	4–66	13–123	3–41	5–90	14–147
($/day)	$31	$58	$296	$611	$192	$435	$750
LAX							
ARTCC delay shift (sec)	0–2	0–3	5–9	12–16	4–6	8–13	15–20
Fuel savings							
($/op)	0–0.16	0–0.24	0.40–0.71	0.95–1.27	0.32–.048	0.63–1.03	1.19–1.59
($/rush)	0–18	2–27	12–154	29–274	10–103	20–223	37–342
($/day)	$30	$50	$334	$629	$225	$478	$773

As Table 11-2 shows, EDX4 resulted in the greatest savings compared to both the passive and active baselines. Although the EDX4 case (in which threshold crossing speed information is exchanged) does not affect the metering fix delivery accuracy, it improves the accuracy in predicting the TRACON time-to-fly, and thus has the same impact of requiring less TRACON front-loading to account for flight variability.

These daily savings were extrapolated to annual, NAS-wide levels by using 1996 operation totals at each airport, as well as an “airport factor” to adjust for variations in congestion at each airport. Annual savings for each airport are charted in Figure 11-2.

Figure 11-2. EDX Center/TRACON Delay Distribution Cost-Savings Benefits



Again, large hub airports (ORD, DFW, ATL, LAX) showed the most significant cost savings with EDX, saving over $270,000 per year relative to the passive baseline and $330,000 per year relative to the active baseline. The passive baseline savings were lower because many cases were restricted by the maximum TRACON delay that could be absorbed.

Benefits at all 37 NAS airports totaled $4.9 million relative to the passive baseline and $6.0 million relative to the active baseline. Relative to the passive baseline, EDX shifted 11–20 seconds of rush arrival delay from TRACON to center airspace. This saved an average of 12 lbs. of fuel, or $1.18 per rush arrival. Relative to an active baseline, EDX shifted 11–20 seconds of rush arrival delay from TRACON to center airspace. This saved 14 lbs. of fuel, or $1.44 per rush arrival.

FMS Descent Speed Profile Benefits

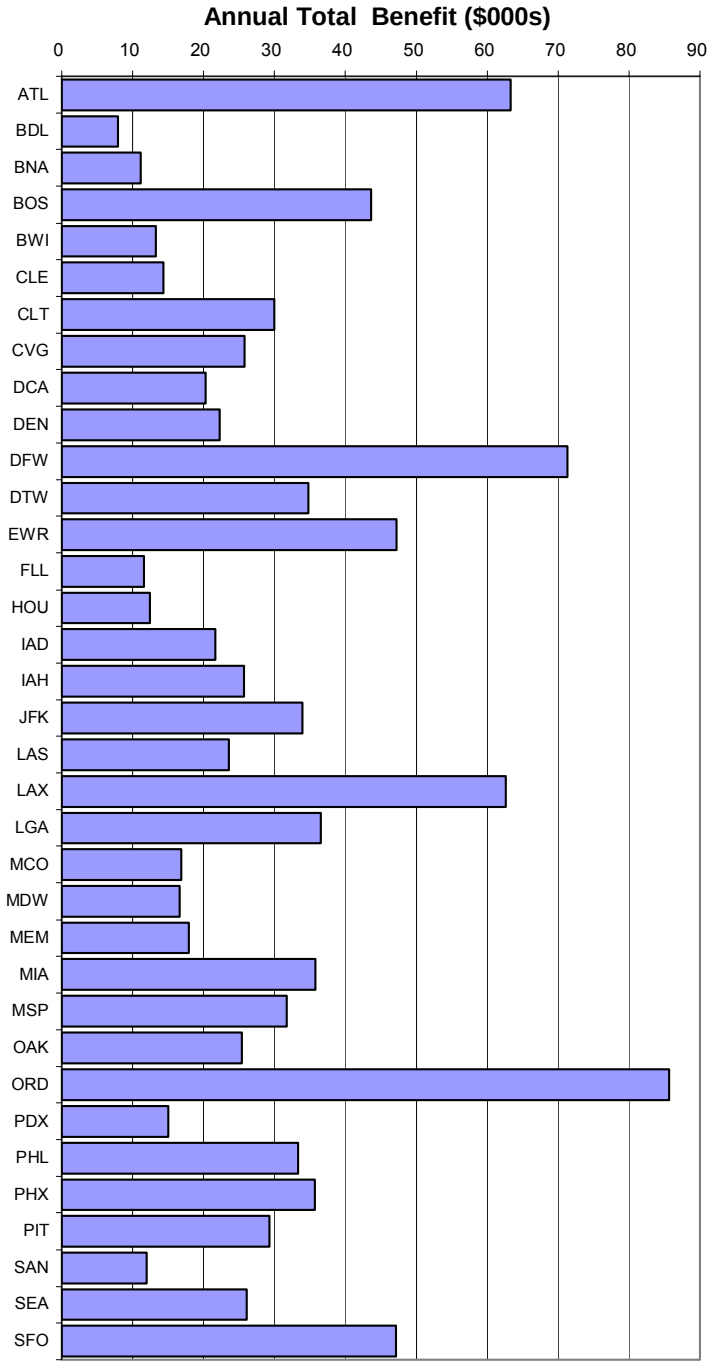
Data exchange can also augment a static DST database with specific speed profiles by airline and/or aircraft tail number. Additionally, since conditions at the time of descent are frequently quite different from those anticipated during preflight planning, real-time downlink of FMS descent speed preferences could be beneficial. If a particular aircraft is not delayed due to airport capacity restrictions, the preference can be accommodated directly, improving user flexibility and ATM trajectory prediction accuracy. During delayed operations, DSTs can uplink an arrival fix required time of arrival (RTA), which the FMS can use to calculate optimal top-of-descent (TOD) and descent speed profile and downlink for use in ATM DSTs. This FMS computed speed profile is based on proprietary performance data and policy for a specific aircraft type, and is assumed to be more fuel-efficient than DST calculations alone.

The EDX cases evaluated in this study included EDX6 relative to the active baseline with the EDX1 and EDX2 capabilities to exchange weather and aircraft weight data. Under EDX6, the EDA speed advisory is assumed to be replaced with the FMS user-preferred speed profile and a simple real-time “negotiation” that takes place between CTAS and the aircraft FMS.

In this study, traffic operations for Fort Worth Air Route Traffic Control Center (ZFW) airspace around DFW were analyzed. Flight trajectories for a typical day were used to generate “undelayed” trajectories, trajectories representing what each flight would do if left alone to fly the user’s preferred trajectory. Because speed control can only absorb 1–2 minutes of delay, only those arrival delays of 2 minutes or less were examined for this benefit mechanism.

Aerodynamic and propulsion performance models were used in this study to simulate aircraft trajectories and fuel burn estimates for two aircraft types under both CTAS and FMS speed control strategies. The simulation results were extrapolated fleet-wide with scaling factors based on Eurocontrol Base of Aircraft Data (BADA) aircraft performance characteristics. The DFW daily savings using FMS speed control were then further extrapolated to annual NAS-wide levels by accounting for the total number of 1996 operations at each facility and adjusting DFW rush arrival rates to account for variations in congestion at each facility. Annual savings for the 37 NAS airports are charted in Figure 11-3.

Figure 11-3. EDX FMS Speed Profile Cost-Savings Benefits



Relative to the active baseline, EDX saved 3 lbs. of fuel, or $0.27 per rush arrival, with a total annual savings of $1.1 million. This does not include the benefits of EDX1 and EDX2, assumed to be part of the baseline. Once again, hub airports realized some of the most significant benefits using this mechanism.

Separation Assurance Benefits

ATM relies on accurate predictions of future flight positions within conflict probe DSTs to accurately identify and alert controllers of pending conflicts. DSTs enhanced with data exchange have the potential to reduce unnecessary deviations and improve the efficiency with which necessary deviations are implemented, by more accurately predicting flight trajectories and supporting useful clearance decisions.

In particular, the downlink of aircraft/FMS horizontal route intent data could significantly reduce conflict probe prediction inaccuracies. Incorrect knowledge of route intent because a flight plan amendment has not been filed can lead to incorrect or inaccurate DST conflict predictions and increased false and missed alert rates.

The EDX cases evaluated under this benefit mechanism include EDX1, EDX2, EDX3, and EDX5 relative to the active baseline. Each case improved on the trajectory prediction accuracy of various flight modes (climb, cruise, descent). The study used baseline and EDX-defined data parameter accuracies in a Trajectory Prediction & Accuracy Model to calculate the expected position error in CTAS' conflict probe prediction. This timing error was then converted into spacing buffers that would be imposed by controllers to limit separation minima violations. These modeled controller spacing buffers were then combined with a DFW daily traffic schedule in an ATM Interruptions model to identify the conflicts or near-conflicts that ATM would recognize as conflicts requiring resolution.

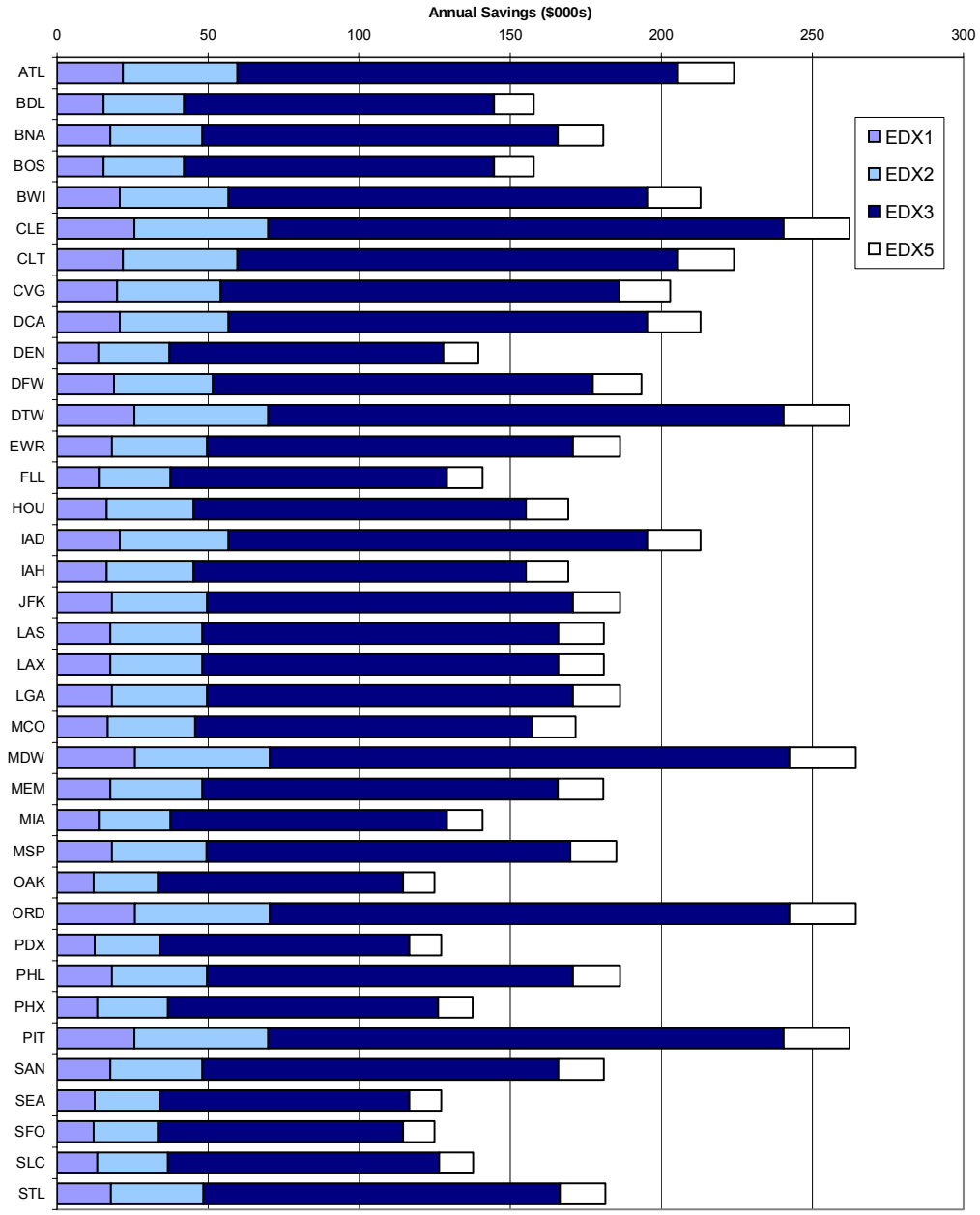
ATM perception of conflict is characterized by four metrics that varied with each data exchange scenario and phase of flight:

- Trajectory prediction accuracy
- Acceptable controller spacing
- Perceived miss distance
- Probability of perceived conflict.

In this study, the frequency of inaccurate intent during departure and overflight for the active baseline case and EDX1, EDX2 and EDX3 was assumed to be 15 percent. This was based on discussions with conflict probe experts and Indianapolis Center observations that only 18 percent of all route clearances are documented. With the integration of arrival metering and conflict probe tools in the EDA case, it was assumed that arrival intent errors would be removed, while departure and overflight intent inaccuracy would remain unchanged. Under EDX5, the aircraft was assumed to automatically downlink the next two waypoints, improving intent for all flights and removing aircraft intent errors on all flight modes.

Fuel costs for resolving all ATM perceived conflicts identified in the simulation were calculated. Daily DFW savings under each of the EDX cases were extrapolated to an annual NAS-wide level by accounting for the total number of 1996 operations at each facility. Annual savings at each airport are illustrated in Figure 11-4.

Figure 11-4. EDX Separation Assurance Cost-Savings Benefits



The primary benefit resulted from the EDX5 waypoint intent (44 percent) and EDX3 speed intent (40 percent), which affected all flight modes. EDX2 aircraft weight (12 percent) and EDX1 weather (4 percent) resulted in smaller shares of

the overall savings. These results were highly sensitive to the order in which these incremental improvements were made.

Relative to the active baseline, EDX reduced separation assurance interruptions by 10 percent, with each interruption saving an average of 2 lbs. or $0.21, for a total savings of $3.6 million annually, assuming NAS-wide deployment at 37 airports. EDX also reduced the number of missed alerts by 25 percent, and the number of false alerts by 7 percent.

Departure Direct Routing Benefits

Controllers will often employ direct routes if doing so will resolve conflicts and not create any new conflict. The identification of new conflicts depends upon ATM perception of separation and the buffers placed on the aircraft. As discussed in the last section, increased trajectory prediction accuracy with data exchange is expected to reduce these buffers, leading to fewer perceived conflicts. As a result, more Direct-To advisories may be employed, saving both aircraft time and fuel.

The EDX cases evaluated under this benefit mechanism included EDX3 relative to the passive baseline and two versions of the active baseline. Both the Standard Terminal Arrival Route (STAR) and direct route arrival versions of the active baseline were included to better understand the variability in the results.

An en route set of air-traffic “demand” trajectories for a typical day in the Fort Worth Air Route Traffic Control Center (ZFW) airspace were simulated. The only modifications to the user’s preferred trajectory were flight maneuvers necessary to delay the DFW arrival and departure aircraft, in order to meet metering fix flow-rate restrictions. The frequency of enabling direct route departures with EDX and the associated fuel and time cost savings per operation were then estimated.

An estimate of the daily savings at DFW is summarized in Table 11-3.

Table 11-3. DFW EDX Direct Departure Savings

	Passive baseline (STAR arrivals)	Active baseline (STAR arrivals)	Active baseline (direct arrivals)
Number of impacted departure operations	71	146	68
Enabled rate (per 100 airport operations)	32.55	66.94	31.18
Average savings per operation	1.03 min/op 78 lbs/op $24.12/op	1.20 min/op 81 lbs/op $25.74/op	1.03 min/op 90 lbs/op $27.09/op
Daily fuel savings	$1,713	$3,758	$1,842

On average, time savings were 1.12 minutes costing $17.67, with fuel savings of 82 lbs. costing $8.17. Time savings comprised approximately two-thirds of the total savings.

These daily DFW savings were extrapolated to an annual NAS-wide estimate by accounting for the total number of 1996 operations at each facility and adjusting airport rush arrival rates by an airport factor to account for variations in congestion at each facility.

The EDX enabled departure direct route cost savings benefits are shown in Table 11-4.

Table 11-4. EDX Enabled Departure Direct Route Cost Savings Benefits

Airport	EDX1-EDX3 annual cost savings ($000s, 1998)		
	Passive baseline (STAR arrivals)	Active baseline (STAR arrivals)	Active baseline (direct arrivals)
Atlanta (ATL)	606.7	1,331.2	652.5
Nashville (BNA)	126.2	277.0	135.8
Boston (BOS)	177.7	389.9	191.1
Bradley (BDL)	363.2	796.9	390.6
Baltimore (BWI)	212.1	465.5	228.2
Cleveland (CLE)	228.5	501.5	245.8
Charlotte (CLT)	358.9	787.5	386.0
Cincinnati (CVG)	309.0	678.1	332.3
Washington National (DCA)	243.2	533.7	261.6
Denver (DEN)	356.7	782.7	383.6
Dallas–Ft. Worth (DFW)	683.1	1,498.8	734.6
Detroit (DTW)	417.1	915.1	448.5
Newark (EWR)	348.2	764.0	374.5
Ft. Lauderdale (FLL)	185.6	407.2	199.6
Houston Hobby (HOU)	198.1	434.6	213.0
Washington Dulles (IAD)	259.5	569.4	279.1
Houston–Intercontinental (IAH)	307.8	675.3	331.0
N.Y. Kennedy (JFK)	283.1	621.2	304.5
Las Vegas (LAS)	376.6	826.4	405.1
Los Angeles (LAX)	600.0	1,316.4	645.2
N.Y. LaGuardia (LGA)	269.1	590.3	289.3
Orlando (MCO)	268.5	589.2	288.8
Chicago Midway (MDW)	199.7	438.3	214.8
Memphis (MEM)	285.8	627.1	307.4

Table 11-4. EDX Enabled Departure Direct Route Cost Savings Benefits (Continued)

Airport	EDX1-EDX3 annual cost savings ($000s, 1998)		
	Passive baseline (STAR arrivals)	Active baseline (STAR arrivals)	Active baseline (direct arrivals)
Miami (MIA)	429.1	941.6	461.5
Minneapolis (MSP)	379.7	833.2	408.4
Oakland (OAK)	405.6	889.9	436.2
Chicago O'Hare (ORD)	714.0	1,566.6	767.8
Portland (PDX)	240.3	527.2	258.4
Philadelphia (PHL)	318.9	699.8	343.0
Phoenix (PHX)	427.5	938.0	459.7
Pittsburgh (PIT)	351.4	771.0	377.9
San Diego (SAN)	191.3	419.7	205.7
Seattle (SEA)	312.2	685.1	335.8
San Francisco (SFO)	347.3	762.1	373.5
Salt Lake City (SLC)	293.6	644.1	315.7
St. Louis (STL)	406.3	891.4	436.9
37-Airport Total/Average	12,482	27,387	13,423

Once again, the high-volume airports gained the most benefit from EDX.

The total EDX benefit varied significantly depending upon the baseline. The active baseline benefits proved larger than passive baseline benefits, with the active baseline (STAR arrivals) having significantly higher benefits than the direct arrivals case. This is because both the passive baseline and active baseline using direct arrivals can enable 70 percent of the departure direct routes without conflict, even before EDX is used.

Chapter 12
Collaborative Arrival Planner (CAP)—Summary of Benefits Assessment

INTRODUCTION

The Collaborative Arrival Planner (CAP) is one of several decision support tools (DSTs) being developed by NASA's Advanced Air Transport Technology project. Within this program, the primary function of CAP is to enhance the collaboration between the airspace user community and the Air Traffic Service Providers (ATSPs) in order to improve the within-terminal-area scheduling of aircraft arrival.

CAP would allow for user input from airline operations centers (AOCs) concerning preferences over arrival times and delays. It would provide flexible arrival slot scheduling through slot swapping between airplanes, or with open arrival slots to produce pure delay reductions. Additionally, CAP would work with Enhanced Traffic Management System (ETMS) data to produce better estimates of arrival times. Through improved communication and data-delivery, AOCs would be able to better manage operations in order to reduce flight delays that interrupt gate management, as well as crew, equipment, and passenger connections.

The benefits assessment summarized here reviews the potential reductions in those delayed flights and, in more general and less extensive ways, monetary savings stemming from the implementation of CAP. By simulating the functions of CAP, the study details multiple areas in which the DST demonstrates improvements over current arrival scheduling methods. In several places, the study compares estimated time of arrival (ETA) predictions generated by CTAS with those currently available from ETMS.

Benefits resulting from the use of the CAP tool were derived through modeling the tools functions and quantifying the impact on several areas of flight-arrival performance.

Through the use of CAP, the study indicates the following benefits:

- Improved aircraft arrival prediction accuracy
- Improved basis for making hold/go and diversion decisions
- Airborne holding and expected clearance times

- Savings from an Inter-carrier Delay Exchange Program
- Savings from an Intra-carrier Delay Exchange Program
- Savings from arrival time adjustments toward carrier schedules
- Restoration of Ground Delay Program (GDP)-issued Controlled Times of Arrival (CTAs).

The primary findings of this benefits assessment are best-estimate potential increases in NAS-wide on-time arrivals of 152,931 flights per year by swapping among all air carriers, and 2,855 flights per year for a single carrier. Savings from reduced delays are approximately $29,914,527 per year across all carriers, and an average of $558,339 per year for each carrier. Additionally, 19.21 percent of CTAs for flights in a GDP could be restored to their original ETAs. It should be noted that these best estimates are the lower bounds for the potential results.

This summary of CAP benefits is based on the assessment authored for Metron Inc. under subcontract to SRC Inc. The full citation is:

> *Refined Benefits Assessment of the Collaborative Arrival Planner AATT Decision Support Tool.* Robert Hoffman. SRC Inc. Task Order 47, November 17, 2000.

FUNCTIONS AND BENEFIT MECHANISMS

The CAP assessment identifies several primary functions of the DST. These functions are briefly described below, including their attendant benefit mechanisms.

- *Passive transmission of CTAS data to air carriers.* By providing AOCs with real-time aircraft movement information, better planning can mitigate potential flight delays, and thus crew, equipment, and passenger delays.
- *Delay exchange programs.* This would include both inter- and intra-carrier functionality. By separating delays into discreet categories, flights can be arranged into ascending levels of priority, allowing for swapping of arrival slots based on ability to either speed up or slow down relative to other flights on approach.
- *Arrival time adjustments by air carrier preferences.* Communication facilitated by the CAP tool allows for flights to be moved from a longer-delay slot into a slot with a lower delay, or even into an on-time slot.

- *Controlled Times of Arrival (CTAs) restoration in Ground Delay Programs (GDPs).* Similar to the delay exchanges, this function allows for plans to be moved into slots that reduce delays; this capability is independent from other flights, however. A single flight's CTA could be restored, reducing delays for not only the individual flight, but subsequent flights as well.

The functions and associated benefits of CAP are presented in the assessment, and are presented again here for quick reference (Table 12-1).

Table 12-1. CAP Functions and Related Benefits

CAP function	Benefit mechanism	Metrics
Passive transmission of CTAS data to air carriers	Improved ETA accuracy provided by CTAS	◆ Weighted average of ETA errors (ETA less actual arrival time)
	Improved Hold/Go and Diversion decisions based on improved ETA accuracy	◆ Instances in which only the CTAS ETA or ETMS ETA fell within the range of arrival time
	Improved prediction of release time from a state of airborne holding	◆ Weighted average of ETA errors
Inter-carrier delay exchange program	Increased on-time arrival performance	◆ Increased on-times (absolute number and percent improvement) ◆ Delay savings
Intra-carrier delay exchange program	Increased on-time arrival performance per hubbing operation	◆ Increased on-times (absolute number and percent improvement) ◆ Delay savings
Arrival time adjustments	Mitigate effects of delays	◆ Increased on-times (absolute number and percent improvement) ◆ Delay savings
CTA restoration through CAP-FSM	Restore GDP equity	◆ Percentage of flights restored to CTA

MODELING AND ANALYSIS APPROACH

The bulk of the assessment was conducted by relying on data from specific days of traffic at two major airports for traffic simulations. CTAS-simulated and ETMS-generated ETAs were used to extrapolate the effect of using the CAP tool on traffic management.

Data Sources

Avoiding the use of proprietary data in order to make the benefits assessment available to a wider audience, the author relied exclusively on CTAS and ETMS data. CTAS data being harder to acquire, the author collected System Analysis Recording data for three separate days at three different airports, and converted them to CTAS through a version of CTAS TMA software owned by Merton. ETMS data was pulled from Delta files generated by the Flight Schedule Monitor. Through the study, several metrics provide results comparing CTAS and ETMS.

Airport Selection

The choice of airports for the assessment was primarily restricted by the data available. CTAS has only been adapted for a select number of airports. From that number, the author chose DFW, PHL, and DEN as a representative sample.

In the sections of the assessment focusing on benefits resulting from including user preferences from air carriers, ORD was also included because the modeling did not rely only upon ETMS data.

CAP Development

It should be noted that CAP was still in the conceptual stages of development when this assessment was conducted. As such, the author was required to make a number of assumptions about the specific nature of certain CAP functions. The following assumptions are indicated as the broadest, and therefore the most potentially limiting (if one or more of these are not present, numerous aspects of the study will be adversely affected):

- Passive information sharing allowing air carriers access to the same information that is displayed to Terminal Radar Approach Control (TRACON) and Air Route Traffic Control Centers (ARTCCs)
- Acceptance of air carrier preferences for arrival priorities as expressed on a flight-by-flight basis (replacing the current method of phone calls from air carriers)
- An algorithm to equitably balance preferences between multiple users. Such an algorithm was previously developed by Metron.
- Real-time access to the CTAs set during a GDP. CAP requires these in order to perform its CTA restoration function.
- Any advisories posted by TMA or CAP for arrival time adjustments will be carried out by the ATSP.

The use of these assumptions allows for the analysis to be carried forward, and each is given full justification in the study. These assumptions, and those in later parts of the study, will affect the results to some degree. Any bias in either direction (positive or negative) will be noted in line with the results.

Lack of Proprietary Information

This study differs from previous CAP studies in that it does not utilize proprietary data from air carriers. This was done in order to make the study accessible to a wider audience (other AATT contractors), rather than being restricted to those people with permission to see such material.

The IPE Metric

In determining ETA accuracy benefits from the use of CAP, the study relied on a metric for assessing the quality of predictions generated by both CTAS and ETMS. This Integrated Predictive Error (IPE) metric is an improvement in method over the previous method of using a “snapshot” approach. The IPE metric generates values for individual flights over the duration of their time within a specified range of the airport. Following this method allows the author to aggregate results over numerous flights, a capability the “snapshot” approach does not allow. The IPE can be understood as a weighted average of the absolute errors in a system’s prediction of ETA over a given period of time for a specific flight. One IPE value was generated for each flight into given airports on specific days, creating a distribution of IPE values for each day, per airport.

For ease of reading the results of the study, the units in which IPE results are presented are normalized to minute-hours. That is, a given value can be read as an average error in minutes over a single hour.

The lower the IPE value, the better the predictive capability.

Delay Exchange

While the precise functionality of CAP was uncertain at the time of the benefits assessment, the author was able to assume that the tool would provide the capability to manage trading arrival slots (slot swapping) among flights, both intra- and inter-carrier.

The assessment divides potential delays into “buckets” of time. These are ranges of 15-minute increments, each of which is tied to a milestone in decision making concerning late flights. Each successive bucket (from B1 to B7) corresponds with increasing complications due to the delay. Table 12-2 identifies the buckets and the potential complications.

Table 12-2. Delay Bucket Parameters

Delay bucket	Lower bound (min)	Upper bound (min)	Operational sensitivity issue
B1	0	14	On-time performance
B2	15	20	Baggage connection
B3	21	40	Passenger connection
B4	41	50	Crew connection/legality
B5	51	60	Equipment shortage
B6	61	90	Aircraft maintenance
B7	91	Inf	Flight cancellation

The author assumes the CAP tool has the ability to accept air carrier information about the various costs associated with the delays of each flight. The CAP tool would normalize the costs given by the users in order to prevent air carriers from entering inflated information, and then assign priority to each individual flight based on relative comparisons of delay costs.

Ultimately, arrival slots would be swapped between flights based on the individual plane's ability to speed up or slow down (with speeding up being the more likely possibility) in order to move flights into lower delay buckets. Moreover, swaps are only made if the exchange satisfies two conditions:

1. A given flight can be moved to a lower bucket, and

2. The flight giving up its previous slot remains within the same bucket.

The assessment relies on the ability for such swaps to be performed between flights of a single air carrier, as well as between flights of differing air carriers. An algorithm for maintaining equity between carriers (so that one carrier does not bear a larger portion of the swaps) was developed by Merton under contract from NASA. It was assumed that this algorithm would be in place for use by the CAP tool.

To evaluate the potential gains, ETMS data was filtered through a CTAS simulator in order to produce upper and lower bounds on the number of swaps possible, and the number of minutes saved.

RESULTS, FINDINGS, AND CONCLUSIONS

Benefits Related to ETA Accuracy

AIRCRAFT ARRIVAL PREDICTION

IPE values were generated for three of the airports under study (DEN, DFW, and PHL) on several dates. The results for comparing CTAS and standard ETMS are presented in the next three tables below (Tables 12-3 through 12-5) giving the distribution of these IPE values for mean, maximum, minimum, and standard deviations.

Table 12-3. Average IPE Values—DEN

DEN Average IPE Values, CTAS vs. ETMS														
	9/14/00		9/15/00		9/16/00		9/17/00		9/18/00		9/19/00		9/20/00	
Avg	331	371	349	384	322	387	306	389	299	396	277	367	315	351
Std Dev	134	160	132	146	136	149	159	170	149	146	152	149	204	175
Max	919	1199	1580	871	990	1185	1314	1357	922	979	1006	792	1706	1051
Min	48	33	46	52	33	100	35	70	14	53	37	33	4	5

Table 12-4. Average IPE Values—DFW

DFW Average IPE Values, CTAS vs. ETMS														
	8/20/00		8/21/00		8/22/00		8/23/00		8/24/00		8/25/00		8/26/00	
Avg	146	200	168	189	161	200	172	192	170	199	170	195	163	197
Std Dev	97	96	106	101	102	100	104	98	109	97	110	106	104	98
Max	876	560	789	615	707	604	864	653	1189	704	856	642	827	641
Min	17	13	13	6	3	21	3	3	18	19	8	9	13	10

Table 12-5. Average IPE Values—PHL

PHL Average IPE Values, CTAS vs. ETMS														
	9/5/00		9/6/00											
Avg	261	394	276	341										
Std Dev	149	174	214	168										
Max	1154	843	1039	921										
Min	54	26	44	41										

CTAS values

ETMS values

IMPROVED HOLD/GO DECISIONS AND DIVERSIONS

For decisions concerning hold/go as well as diversion issues, the author reviewed flight instances where exactly one of the two systems (CTAS or ETMS) generated an ETA within a specified range of the actual time of arrival, while the other system fell outside it.

Due to the imposed restriction on proprietary information from air carriers, and for hold/go decisions specifically the inability to know precise timing, the ability to measure the potential improvements in this area was highly limited. Because of this, the author concludes that there are too few data to establish clear results.

For full information on the computation of the metric, and the presentation of the ambiguous results, refer to the full assessment, section 4.3.

Airborne Holding and Expected Clearance Times

To evaluate improved accuracy in clearance times, the author intended to rely on the IPE metric. In this case, the assessment would review IPE statistics only for those flights subject to airborne holding. Due to the lack of holding statistics that were both reliable and overlapped with the days used for modeling, however, this portion of the analysis was abandoned.

Benefits Related to User Preferences

Delay Exchange via Slot Swapping

This function would allow for increased on-time arrivals and save money by reducing delays. Slot swapping simulations were run for ORD, DFW, and PHL for each day of the first six months of 1999.

Table 12-6 presents the results from the inter-carrier swapping simulation among all flight.

Table 12-6. Inter-Carrier Slot Swapping Daily Averages

Airport	Number of swaps	Swap length in minutes	Increased number of on-time arrivals	Increase in on-time performance (%)
Upper bounds				
ORD	125.01	3.79	57.85	5.37
PHL	64.07	4.46	29.22	5.42
DFW	127.41	4.00	39.62	6.53
Avg.	105.50	4.08	42.23	5.77
Lower bounds				
ORD	23.21	3.22	35.36	3.29
PHL	10.58	4.09	5.34	0.99
DFW	60.42	3.86	11.32	1.14
Avg.	31.40	3.72	17.34	1.81

Extrapolating the results NAS-wide using the figure of $49.90 per minute of flight time, the lower bound on money saved is $29,914,527 annually. The upper bound is $95,362,812 annually.

Since only hubbing operations would have enough flights to make intra-carrier slot swapping effective, the study uses ORD, looking at air carriers American Airlines (AAL) and United Airlines (UAL). The results for improvements in on-time performance for the two carriers are presented in Table 12-7.

Table 12-7. Increased On-Times for Single Carriers

Date	Airline	Flights	Increased number of on-times	Percentage increase in on-time performance
Upper bounds				
6/18/1999	UAL	543	23	4.24
	AAL	463	26	5.62
4/19/1999	UAL	560	30	5.36
	AAL	454	25	5.51
5/29/1999	UAL	529	25	4.73
	AAL	441	22	4.99
Avg.		498.33	25.17	5.05

ARRIVAL TIME ADJUSTMENT BY AIR CARRIER PREFERENCES FOR SCHEDULE PRESERVATION

In accepting arrival preferences from AOCs, delays can be adjusted in the same manner as a delay exchange without the presence of another flight with which to swap slots. In this case the flight would simply move to a lower delay bucket to produce a pure delay reduction.

The results presented below are the savings associated with the three test-case airports, as well as potential NAS-wide savings (extrapolated from the test-case savings). The first table (Table 12-8) highlights the average alterations in arrival times.

Table 12-8. Arrival Time Adjustment Daily Averages

Airport	Number of adjustments	Adjustments in minutes	Increased number of on-time arrivals	Increase in on-time performance (%)	Savings (at $49.90 per minute)
ORD	54.40	3.90	23.89	2.28	$10,586
PHL	27.08	4.23	10.68	2.05	$5,716
DFW	48.00	3.63	12.05	1.85	$8,695
Avg.	43.16	3.92	15.54	2.06	$8,332
NAS	390	3.92	174,054	2.06	$76,281

Table 12-9 translates the savings in time and increase in on time arrivals into monetary benefits.

Table 12-9. Arrival Time Adjustment, Savings for Year 1999

Airport	Daily Savings per non-GDP day	Non-GDP Days in 1999	Savings for 1999
ORD	$10,586	285	$3,017,010
PHL	$5,716	322	$1,840,552
DFW	$8,695	362	$3,147,590
Avg.	$8,332	323	$2,668,384
NAS	$76,281	285	$21,740,090

Additionally, these results were extrapolated for 2015, using the projected number of operations for that year (12,048,417).

In 1999 dollars, the projected savings for 2015 are $31,000,929. The increased number of on-time arrivals for the year 2015 is 248,197.

CONTROLLED TIME OF ARRIVAL (CTA) RESTORATION IN A GDP

Benefits from this function are realized through an increase in the number of flights in a GDP that can be restored to their FAA-issued time of arrival. As above, this assumes the presence of a CAP function for CTA restoration. It is possible such functionality could not be desirable, since it might involve reductions in speed for flights that are already delayed.

Table 12-10 indicates the percentages of CTAs that can be restored. “Max Adjust” refers to the number of minutes a flight can be sped up or slowed down.

Table 12-10. Percentage of Flights with Recoverable CTA—PHL

Percentage of Flights with Recoverable CTA- PHL				
Max Adjust δ	**45 min out**	**60 min out**	**90 min out**	**120 min out**
5 min	39.94	42.32	47.48	48.62
10 min	60.41	62.90	66.74	68.59
15 min	71.51	73.83	77.19	78.80
20 min	77.20	78.31	81.94	84.38

The above results are an upper bound on the potential benefits. The author attempts to address assumptions made in a previous assessment by calculating a "best estimate" based on new requirements that more accurately reflect the operating environment. The results are presented, along with the general results for the foregoing assessment, in Tables 12-11 and 12-12. The first is for the year 1999, the second for projections of the year 2015.

Table 12-11. NAS-Wide Benefits, 1999

NAS-wide Benefits (Hypothetical) for Year 1999								
	A	B	C	D	E	F	G	H
1	Report Section	CAP DST Function	Anticipated Benefit	AATT Category	Metric	Lower Bound	Upper Bound	Best Estimate
2	5.1	Passive transmission of CTAS data to the air carriers	Improved ETA Accuracy Provided by CTAS	Predict	Weighted average of ETA errors (ETA – actual arrival time)	30.28 seconds	64.00 seconds	47.76 seconds
3	5.2 5.3		Improved Hold-go and diversion decisions based on increased ETA accuracy.	Predict	Instances in which only the CTAS ETA (or ETMS ETA) fell within range of arrival time	Pending further analysis	Pending further analysis	Pending further analysis
4	5.4		Improved prediction of release time from a state of airborne holding	Predict	Same as 5.1 only restricted to flights that experienced airborne holding	Pending further analysis	Pending further analysis	Pending further analysis
5	6.3	*Inter*-carrier Delay Exchange Program conducted through CAP	Increased on-time arrival performance	Flex	Increased on-times	1.81%	5.77%	1.81%
6					Increased on-times	152,931 Flts	487,520 Flts	152,931 Flts
7					Delay savings	$29,914,527	$95,362,812	$29,914,527
8	6.4	*Intra*-carrier Delay Exchange Program conducted through CAP	Increased on-time arrival performance per hubbing operation	Flex	Increased on-times	2.01%	5.05%	2.01%
9					Increased on-times	2,855 Flts	7,172 Flts	2,855 Flts
10					Delay savings	$558,339	$1,492,991	$558,339
11	6.5	Arrival Time Adjustments	Mitigate effects of delays	Flex	Increased on-times	2.06%	2.06%	2.06%
12					Increased on-times	174,054 Flts	174,054 Flts	174,054 Flts
13					Delay Savings	$21,740,090	$21,740,090	$21,740,090
14	6.6	CTA Restoration through CAP-FSM	Restore GDP equity	Access	Percentage of flights restored to CTA	19.21%	44.73%	19.21%

Note: Dollar figures are in 1999 dollars.

Table 12-12. NAS-Wide Benefits, 2015

NAS-wide Benefits (Hypothetical) for Year 2015								
	A	B	C	D	E	F	G	H
1	**Report Section**	**CAP DST Function**	**Anticipated Benefit**	**AATT Category**	**Metric**	**Lower Bound**	**Upper Bound**	**Best Estimate**
2	5.1	Passive transmission of CTAS data to the air carriers	Improved ETA Accuracy Provided by CTAS	Predict	Weighted average of ETA errors (ETA – actual arrival time)	30.28 seconds	64.00 seconds	47.76 seconds
3	5.2 5.3		Improved Hold-go and diversion decisions based on increased ETA accuracy.	Predict	Instances in which only the CTAS ETA (or ETMS ETA) fell within range of arrival time	Pending further analysis	Pending further analysis	Pending further analysis
4	5.4		Improved prediction of release time from a state of airborne holding	Predict	Same as 5.1 only restricted to flights that experienced airborne holding	Pending further analysis	Pending further analysis	Pending further analysis
5	6.3	*Inter*-carrier Delay Exchange Program conducted through CAP	Increased on-time arrival performance	Flex	Increased on-times	1.81%	5.77%	1.81%
6					Increased on-times	218,077 Flts	695,194 Flts	218,077 Flts
7					Delay savings	$42,657,511	$135,985,443	$42,657,511
8	6.4	*Intra*-carrier Delay Exchange Program conducted through CAP	Increased on-time arrival performance per hubbing operation	Flex	Increased on-times	2.01%	5.05%	2.01%
9					Increased on-times	4,071 Flts	10,227 Flts	4,071 Flts
10					Delay savings	$796,266	$2,000,568	$796,266
11	6.5	Arrival Time Adjustments	Mitigate effects of delays	Flex	Increased on-times	2.06%	2.06%	2.06%
12					Increased on-times	248,197 Flts	248,197 Flts	248,197 Flts
13					Delay Savings	$31,000,929	$31,000,929	$31,000,929
14	6.6	CTA Restoration through CAP-FSM	Restore GDP equity	Access	Percentage of flights restored to CTA	19.21%	44.73%	19.21%

Note: Dollar figures are in 1999 dollars.

Conclusions

Use of the CAP tool would significantly improve communication between AOCs and ATSPs. With CAP, CTAS is, on average, slightly more than 1 minute more accurate in ETA predictions than ETMS. CAP functions that allow for slot-swapping between and among air carriers achieve reductions in the absolute number of delayed flights, as well as percentage increases in on-time performance of 1.81 percent between carriers, and 2.06 percent for a single carrier. The ability to realize pure delay reductions for a single flight could save $21,740,090 per year immediately, and up to $31,000,929 NAS-wide by 2015.

Chapter 13
Conflict Prediction and Trial Planning (CPTP)—Summary of Field Test Evaluation

INTRODUCTION

The Center/TRACON Automation System (CTAS) is a set of decision support tools designed to help air traffic controllers increase efficiency and capacity of arrival traffic flow near congested airports. The Conflict Prediction and Trial Planning (CPTP) tool capability is one of the CTAS tools that has extended the conflict prediction and resolution functions developed by previous tools.

This summary of CPTP is primarily based upon the field test evaluation prepared for presentation at a conference of the American Institute of Aeronautics and Astronautics (AIAA) in 1998. The full citation for the assessment is:

> "Field Test Evaluation of the CTAS Conflict Prediction and Trial Planning Capability." B. David McNally, Ralph E. Bach, and William Chan. AIAA Guidance, Navigation, and Control Conference, Boston, MA. August 10-12, 1998.

The objective of the evaluation was to field test CPTP under operational air traffic control conditions and to measure benefits of to air traffic controllers and airspace users. It was found that controllers aided by CPTP resolved many conflicts by issuing a direct-route clearance to one of the aircraft. A direct route often resolved a conflict well before it became tactical, gave the aircraft a shortcut, and required one fewer controller clearance.

TESTING THE CPTP TOOL

Field Test Approach

Test objectives were to:

- Test the CPTP capability under operational conditions with arrival, departure, and over-flight traffic
- Measure benefits of the technology for air traffic controllers and airspace users
- Determine how CPTP technology may increase user-preferred routing.

Denver Center was chosen because of previous experience with CTAS field testing, and the access to live all-track, all-flight-plan data from Denver Center's host computer. These tests were performed at the Denver Air Route Traffic Control Center in September 1997.

The field test was performed in two phases. During Phase I, the test controller worked the CPTP tool in "shadow" mode (without communication with the sector controller) in order to compare conflict prediction and resolution with and without the aid of the tool. During Phase II, each test controller sat next to the data-side controller position and used the CPTP tool to provide decision support directly to the sector controller.

Categorizing the Outcomes

All accepted trial plans were analyzed to determine type of trial plan used by the test controllers for each conflict resolution. Information recorded by the second test controller and the radar tracks were analyzed to determine the actual resolution type used by the sector controller. Resolution types are categorized as follows:

- Direct—fly direct to a future waypoint
- Vector—heading change, then direct to waypoint
- Altitude—altitude change
- Speed—speed change
- Multiple—a combination of changes, such as vector and altitude
- No resolution—no resolution by test controller
- Unknown—test or sector controller actions not clear
- No action—no clearance given by sector controller.

Phase I

During Phase I, the objective was to obtain a quantitative comparison of conflict prediction and resolution with and without the aid of the CPTP tool. A test controller used the tool to identify potential conflicts and develop trial-plan trajectories for conflict resolution. A second test controller observed and recorded actual conflict resolution clearances given by the sector controller and any procedural factors affecting the conflict scenario.

As shown in Figure 13-1, test controllers using the CPTP tool chose a direct route to a future waypoint in 45 percent of conflicts analyzed. The on-duty sector controllers used a direct route to resolve only 11 percent of conflicts (Figure 13-2).

This indicates a potential three-fold increase in direct route clearances with CPTP aiding.

Figure 13-1. Test Controller Resolutions (Phase I)

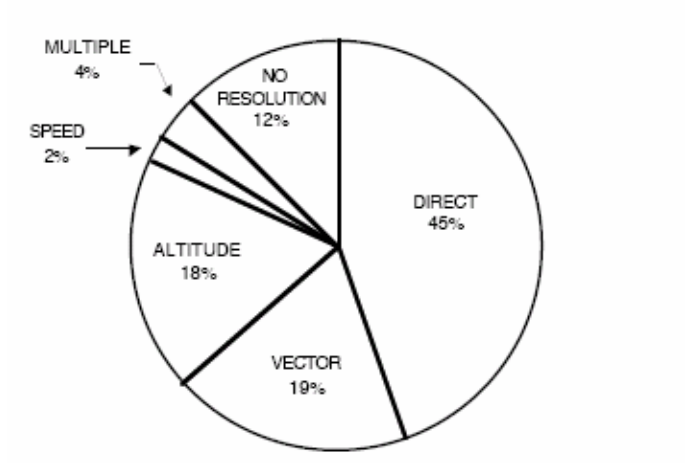
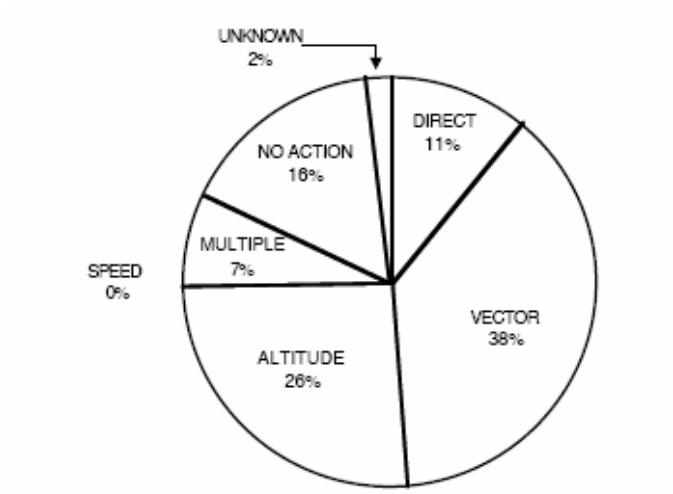


Figure 13-2. Sector Controller (Baseline) Resolutions (Phase I)



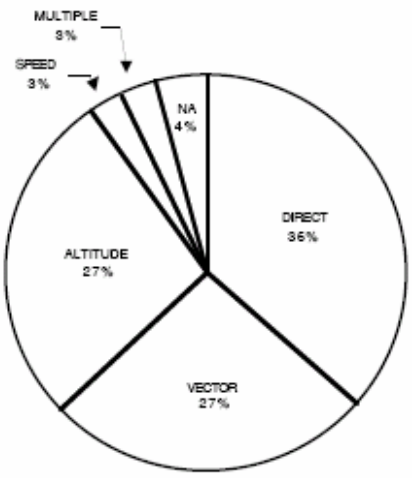
Phase II

In Phase II, each test period the sector filters on the three CPTP tools were configured to show conflicts predicted to occur inside the test sector, as well as conflicts predicted to occur outside the test sector that involved at least one aircraft currently inside the test sector. Following the initial setup, test controllers were free to adjust the sector filter as desired, and they typically adjusted their sector filters to display conflicts in multiple sectors.

The results in Figure 13-3 show more than a two-fold increase in the number of direct route clearances with the CPTP tool in use. Of the 132 CPTP-based clearances issued to aircraft, 47 (36 percent) were direct to a future waypoint,

compared to 11 percent from Phase I data (Figure 13-2) without CPTP assistance. For the Phase II data, the average time to go from current position to predicted first loss of separation at the time the trial plan resolution was accepted was 7.4 minutes; the standard deviation was 4.2 minutes. The shorter average time-to-go compared to that of Phase I (10.4 minutes) might be attributed to procedural factors for issuing clearances.

Figure 13-3. Section Controller (CPTP) Resolutions (Phase II)



CONCLUSIONS

CTAS Conflict Prediction and Trial Planning (CPTP) capability was tested for 98 sector-hours over a 13-day period in three high altitude sectors on the operational floor at Denver Center. There were 132 CPTP-aided clearances issued to aircraft during the test period. Fifteen full performance level controllers participated in the test. Many conflicts were resolved by sending one aircraft direct to a downstream fix (45 percent in Phase I and 36 percent in Phase II).

Comparison of baseline clearances with CPTP-aided clearances actually issued show more than a two-fold increase in direct route resolutions. An analysis of baseline and CPTP-aided cruise/cruise conflict resolution clearances showed an average potential savings of 12.1 nautical miles and $43 (1998 dollars) in operating cost for the aircraft given the direct route clearance. The actual savings for aircraft given CPTP-aided direct-route clearances during the test are estimated to be 3.4 nautical miles and $12 (1998 dollars) per aircraft.

Test controllers consistently identified CPTP's most powerful feature as its ability to confirm that a trial plan resolves the conflict and does not create any other conflicts. Any conflict prediction and resolution tool should allow the controller to quickly and easily check a trial plan and confirm that the trajectory is conflict-free.

Chapter 14
Traffic Management Advisor (TMA) at Fort Worth Air Route Traffic Control Center—Summary of Design and Operational Evaluation

INTRODUCTION

The primary function of the Traffic Management Advisor (TMA) is to assist traffic management coordinators (TMCs) more efficiently manage the traffic capacity of an airport experiencing high-demand periods ("rushes"). It accomplishes this through the use of functionality for time-based arrival traffic flow visualization, and runway scheduling under aircraft separation and flow rate constraints, as well as Air Route Traffic Control Center (ARTCC) controller advisories. Using these functions, the TMA is able to create minimal delay advisories that distribute the delay between center and TRACON operations.

This summary reviews the functions of the TMA and the benefits that resulted from use of the tool at the Fort Worth ARTCC. TMCs used the TMA as the primary system within a traffic management unit (TMU), relying on the preexisting Arrival Sequencing Program (ASP) as support in the event of a critical malfunction of the TMA (no such malfunction occurred during the evaluation). Installation of the TMA at Fort Worth constituted the first field test for the system.

TMA is now in operational use at eight sites in the NAS; the FAA estimates that TMA has saved users $165 million through July 2004. Analysis of the tool's full benefits in operational use is documented in the FAA Free Flight Program's metrics reports.

This summary of the TMA tool is based primarily on the initial operational evaluation published for an air traffic management R&D seminar, with additional information drawn from a report for the American Institute of Aeronautics and Astronautics (AIAA). The full citations for these documents are:

> *Design and Operational Evaluation of the Traffic Management Advisor at the Fort Worth Air Route Traffic Control Center*. Harry N. Swenson, Ty Hoag, Shawn Engelland, Danny Vincent, Tommy Sanders, Beverly Sanford, and Karen Heere. Presented at 1st USA/Europe Air Traffic Management Research & Development Seminar, Salcay, France. June 17-19, 1997.

The Challenges of Field Testing The traffic Management Advisor in an Operational Air Traffic Control Facility. Ty Hoang and Harry N. Swenson. American Institute of Aeronautics and Astronautics, NASA Ames Research Center. Moffett Field, California. 1997.

FUNCTIONS AND BENEFIT MECHANISMS

The study of the TMA tool identifies four primary functions of this DST. These functions are briefly described below, including their attendant benefit mechanisms.

1. *Time Prediction*: The algorithm for this process is the centerpiece of the TMA. The prediction functions are described as being separated into two pieces. First is the Route Analyzer (RA) that generates a two-dimensional path from an aircraft's current location to its final destination. Second is the Trajectory Synthesis (TS) mechanism. This piece takes the information from the RA and creates a four-dimensional trajectory that accounts for atmospheric conditions and the amount of fuel in the aircraft.

2. *Constraint Scheduling*: To better manage diverse operational requirements, the functional logic for scheduling uses factors associated with the separation safety requirements specified by FAA regulations. It couples a modified first-come, first-served algorithm with a Center/TRACON delay distribution function to ensure conflict-free schedules at both the meter fix and runway threshold, or the final approach fix.

3. *Flow visualization*: Interaction between the TMA and the work of the TMCs is handled by a graphical user interface (GUI) that displays time prediction, schedule, and delay information. Multiple screens give the TMCs several ways to visualize the scheduling process and to better manage flow rates.

4. *Controller Advisories*: The TMA system generates controller advisories that are then communicated to the operational air traffic control (ATC) computer. A sector controller's display will superimpose those advisories that are relevant only to the controller's specific sector. As opposed to previous systems, these advisories are presented to high-altitude controllers in a single, time-ordered list, enabling the controller to alter the arrival sequence of aircraft in response to tactical needs.

Table 14-1 summarizes these functions, their benefits, and associated metrics.

Table 14-1. TMA Functions, Benefits, and Associated Metrics

TMA function	Benefit mechanism	Metric
Trajectory prediction	Route Analyzer: more accurate estimation of path from current location to final destination. Trajectory Synthesis: more accurate estimation of path requirements resulting in better ETA estimates	Difference between ETA and actual meter-fix crossing
Constraint-based runway scheduling	Increase flow rate and efficiency	Predicted versus actual airport throughput
Traffic flow visualization	Improved management of flow	Predicted versus actual airport throughput
Time and delay advisories	Better estimates on meter fix crossing times	Predicted versus actual airport throughput Meter fix crossing time accuracy versus ASP

MODELING AND ANALYSIS APPROACH

To assess the performance of the TMA tool, the system was installed at the Dallas/Fort Worth ARTCC. During periods of high traffic, the TMA was evaluated on a number of criteria to determine the level of improvements over the prior system. In all, 39 rushes over a period of five weeks were included as the time frame across which the TMA performed.

Since the purpose of the tests was to compare the TMA with the ASP, the authors had to find “matching” rush periods. According to their desired characteristics, the authors found rushes under the ASP system that were functionally similar to those experienced under the TMA system. The collection of data is described in the report as “opportunistic” in nature. The sporadic nature of the rushes, including some that did not occur when anticipated and some that occurred when they were not anticipated, made pre-planning for specific rush periods difficult.

Test Environment Structure

The TMA was deployed in the Traffic Management Unit and the DFW arrival sectors in all areas of the Fort Worth ARTCC. Within the TMU is a group of TMCs working together to coordinate all traffic within the facility. The TMA was to be the primary tool used by the TMCs, though the ASP system was available in the case that the TMA experienced some failure (a situation that never occurred).

Data Collection

Evaluation data were collected on both the performance of the TMA itself and the opinions of the crew that was using the system. Engineering data were collected to review the technical functions of the TMA, while evaluators were on hand to administer questionnaires to collect human factor information.

“Shadow” Data

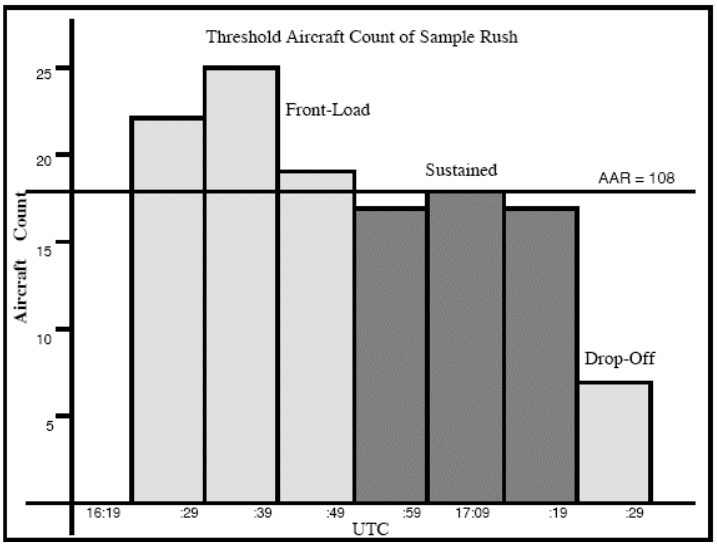
Both before and after the evaluation period of five weeks, data were recorded to establish a baseline. These data represented the functioning of the TMU while the ASP system was in operation. The period of data recording was made purposely large so as to help assure the ability to match rushes experienced under both TMA and ASP. The longer the time period recorded, and thus the more shadow data generated, the more possible it was to have similar rushes under the two tools.

Rush Periods

Technically, rush periods are those times during which an air traffic control facility experiences a demand for airspace in excess of its capacity to handle aircraft. When this occurs, flow management methods are implemented to smooth out demand and create a safe flow of traffic. The rush periods occur at generally set times of day (such as 8 a.m., 9 a.m., and 11 a.m.) and last for approximately 1 hour.

Figure 14-1 depicts the number of aircraft landing at DFW during a rush. It is important to note the process of “front loading” of aircraft in the graph. This process allows the TRACON to land aircraft in excess of the average acceptance rate (AAR) at the start of a rush, when a higher capacity is allowed.

Figure 14-1. Threshold Aircraft Count



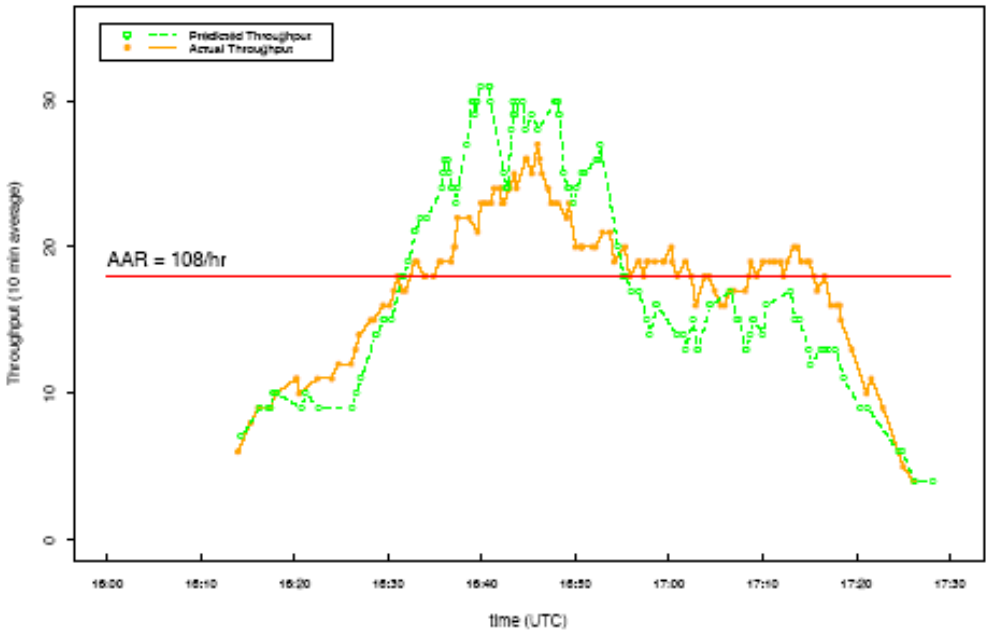
RESULTS, FINDINGS, AND CONCLUSIONS

During the entire process of evaluation, the TMA operated successfully. Backup procedures were in place but never required.

Throughput

Figure 14-2 graphs the predicted throughput of the DFW airport as well as that of the realized throughput under the TMA system. The lines depict the number of aircraft with predicted arrival times that fall within a sliding average interval of 10 minutes. The desired AAR was 108 aircraft per hour. Through front-loading, the TMA was able to operate at a rate of 132 aircraft per hour for the first 15 minutes. After the front loading period was over, the desired AAR of 108 was achieved for the next 30 minutes. This pattern follows almost precisely the one described above for front loading of planes to help smooth out demand.

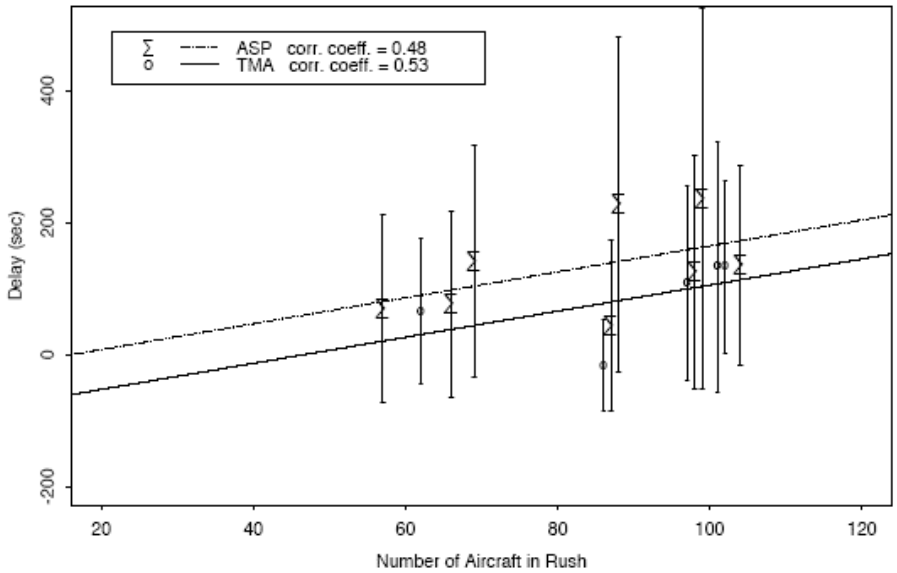
Figure 14-2. Predicted vs. Actual Throughput



Delay Times

When compared with the legacy ASP system, the TMA tool reduced delay time significantly. Figure 14-3 shows the mean delay times, given as a function of the number of aircraft in a sample rush. In this case, an 11:30 a.m. rush was used for comparison, since it is one of the most difficult to manage among the rush periods. The vertical lines represent the standard deviation (1 sigma) distributions of time delays. The reduced sizes of the distributions about the means for the TMA indicate that the delays were distributed more evenly across aircraft in the rush.

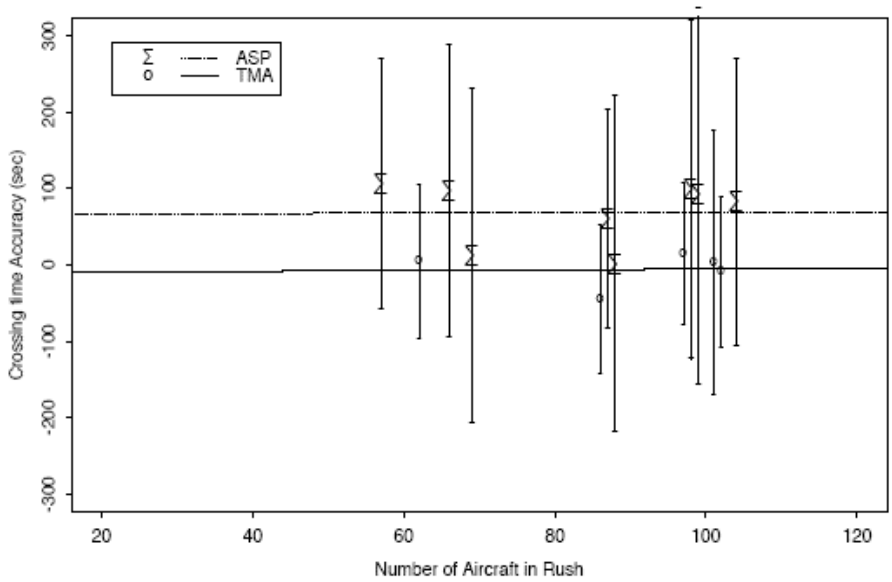
Figure 14-3. Mean Delay Times



Meter Fix Crossing Time Accuracy

By contrasting the accuracy of fix crossing times under ASP and TMA, results indicate that using the TMA resulted in much more precise crossing times. Figure 14-4 shows the mean and standard deviations for errors of crossing times as a function of the number of aircraft.

Figure 14-4. Crossing Time Accuracy



Human Factor Issues

The data here were culled from surveys, questionnaires, and interviews conducted with TMCs.

Among the primary findings was a reduction in the workload for TMCs. This was achieved though:

- development of a single metering arc reference for high-altitude jet sectors
- more representative aircraft crossing sequences
- more accurate crossing advisories
- additional crossing advisory feedback
- the ability to modify the sequence of the meter list via a controller swap function.

TRACON TMCs gave subjective reports of 2–3 minute reductions in delays, and an increase of average AAR from 102 to 108 aircraft per hour.

Additionally there were reports of smoother traffic flow into the TRACON. While the study indicates that such reports were being evaluated at the time of writing, two causes were conjectured. One, the amount of delay that the TRACON has to cope with, is user-controllable by a parameter in the scheduler function of the TMA. Two, the model used by the TMA is derived from controllers, and thus may be more representative of actual operations.

CONCLUSIONS

Along with performing without the need for backup or failure provisions, the TMA demonstrated superior performance compared with the previous system, ASP. In predicting trajectories, the TMA produced more accurate results; there were 30 percent reductions in delay distributions, indicating that more aircraft were arriving with lower delays.

In terms of flow rates, the DFW ARTCC experienced a 5 percent increase in its AAR for aircraft. With TMA's more accurate advisories, there was a 40 percent reduction in the distribution of accurate meter fix crossing times, showing a marked improvement in the ability of TMCs to meter traffic. Overall, delays were reduced an average of 70 seconds per aircraft. And lastly, better tools for visualization allowed TMCs to reduce their workload and smooth out traffic demands, while increasing the throughput of the ARTCC.

Chapter 15
Surface Movement Advisor (SMA)—Summary of Benefit Analysis

INTRODUCTION

The Surface Movement Advisor (SMA) concept was developed to help alleviate taxi delays at major airports where complex taxi patterns approach gridlock during peak traffic periods. SMA is the result of an initiative by the FAA, NASA, and MITRE Corporation's Center for Advanced Aviation System Development (CAASD).

As traffic growth puts increasing demands on the National Airspace System (NAS), a heightened emphasis is being placed on using available resources with the greatest efficiency. This efficiency becomes of particular importance at major hub airports, where delays due to traffic congestion often become the limiting factor in the performance of the entire NAS.

SMA is a tool that supports departure-balancing and data-exchange programs among the FAA, airport operators, and commercial airlines. A local area network (LAN) consisting of two dozen computer display screens is placed in various facilities, including the airlines, air traffic control tower (ATCT), ramp tower, Air Route Traffic Control Center (ARTCC), and Terminal Radar Approach Control (TRACON). By sharing situation information among airlines, airport operators, and air traffic controllers, SMA designers expect its use to reduce taxi-out delays caused by traffic congestion.

This summary of SMA is primarily based upon the analysis performed by FAA/ASD (Office of System Architecture and Investment Analysis) and MCA Research Corporation. The full citation for this assessment is:

> *Surface Movement Advisor (SMA) Benefit Analysis,* Willma Rada. FAA/ASD and MCA Research Corporation. Contract number unknown. October 14, 1997.

That report assessed the Surface Movement Advisor (SMA) prototype tested at Hartsfield Atlanta International Airport (ATL) in 1997. The objective of the analysis was to measure the value of using SMA to help manage aircraft surface movement.

Benefits were calculated based on reduced taxi-out times[1] during periods when SMA was fully operational at ATL in the ATCT, at the Delta Air Lines and city ramp towers, and in the Delta dispatch center and operations control center. These times were compared to others drawn from periods where SMA was operational in all but the ATCT locations, and finally to taxi-out times drawn from a period when SMA was completely shut down. The time savings were translated into dollar savings using standard aircraft direct operating costs and passenger value of time costs established by the FAA Office of Policy and Plans.

FUNCTIONS, BENEFIT MECHANISMS, AND METRICS

SMA touch screen displays provide quick and easy access to data. For example, ATC tower screens can display average "push-to-off" times of each aircraft and a list of aircraft currently pushing back from gates. In ramp towers, SMA lists the aircraft scheduled to depart and departure rates for various runways, helping controllers identify improved taxi plans that better balance the load across available runways. This tool gives tower supervisors the ability to balance runway queues to make for more efficient traffic flows.

In addition, SMA provides information on the impact that arriving and departing aircraft will have on ramps, gates, taxiways, and runways. By sharing tactical aircraft information among appropriate FAA, airport, and airline functional organizations, better flow plans can be developed and taxi times can be reduced.

The two primary functions of SMA and their associated benefit mechanisms and metrics are shown in Table 15-1.

Table 15-1. SMA Benefit Mechanisms and Metrics

SMA function	Benefit mechanisms	Metrics
Departure balancing	Balanced runway queues	Reduced taxi times Reduced aircraft direct operating costs Passenger time saving
Data exchange	Improved flow plans	Reduced taxi times Reduced aircraft direct operating costs Passenger time savings

The quantifiable potential benefits of SMA include:

- reduced aircraft direct operating costs
- passenger time savings.

[1] Taxi-out time is defined as the time from push back at the gate to wheels-off during take-off.

During this study, additional potential SMA benefits were identified that were not quantified. Benefits to FAA operations and personnel include the following:

- Improves queue management
- Aids tower supervisor in airfield management
- Improves productivity by reducing communication time between ATCT and ramp controllers, and between ATCT controllers and pilots
- Provides information to ground controllers that helps during times of reduced visibility.

Benefits to the airline include the following:

- Increases airline productivity (faster aircraft turnaround time, more efficient crew management, better gate utilization, and improved passenger throughput).

Benefits to the airport include the following:

- Supports “what-if” analyses for planning airfield maintenance operations
- Improves management of federal immigration and agriculture services
- Provides helpful information to ramp managers during times of reduced visibility.

MODELING AND ANALYSIS APPROACH

The benefit analysis methodology included ground rules and assumptions, alternatives assessed, data sources, estimation, and a sensitivity analysis.

Ground Rules and Assumptions

The following were ground rules and assumptions established for the analysis:

- Observations covered four to five weeks of operations for each alternative. Results were also generated for weekday versus weekend, and daytime versus nighttime traffic.
- Data used reflected the new aircraft wake turbulence categories implemented by the FAA in August 1996.
- Taxi-out times were assumed to be normally distributed.
- Benefit calculations were based on commercial aircraft departures between 5:00 a.m. and midnight. Benefits were limited to commercial

aircraft direct operating cost savings and to passenger time savings due to reductions in taxi-out times. No FAA staff reduction savings were considered.

- Terminal Area Forecast (TAF)[2] growth estimates for ATL were used to project benefits for a 10-year period of usage beginning in 1997. This growth was assumed to be unconstrained by existing runway capacity.

Alternatives Assessed

The analysis evaluated the impact of using SMA at ATL in two operating modes relative to a baseline.

- *Baseline*: Taxi-out times were computed using departure data from ATL during a period when SMA was not in use (April 20 to May 16, 1997).
- *Alternative 1:* Taxi-out times were computed using departure data from ATL when SMA was used in the ATCT, Delta Airlines and city ramp towers, and Delta dispatch center and operations control center. These data were collected during the period from February 19 to March 22, 1997.
- *Alternative 2:* Taxi-out times were computed using departure data from ATL when SMA was used in the ramp towers and Delta centers only. These data were collected during the period from March 23 to April 19, 1997.

Data Sources

Taxi-out data at ATL for the months of February, March, April, and May 1997 were collected from Airline Service Quality Performance (ASQP) data. Only operations between 5:00 a.m. and midnight were considered for the analysis. The sample includes only commercial aircraft equipped with Aircraft Communications Addressing and Reporting System (ACARS) equipment. In 1996, according to TAF data, commercial operations were 77 percent of annual aircraft operations at ATL.

The periods of analysis were chosen to allow valid comparisons across the alternatives analyzed. In order to test whether weather conditions in Atlanta were similar over the period of analysis, records of daily precipitation, mean visibility, and mean wind speed were evaluated. No significant trends or biases were apparent. If a small weather bias did exist, it would be expected to increase taxi times when SMA data was collected (February–April) over the baseline period (April–May). This would cause the results of this analysis to err in the direction of understating SMA benefits.

[2] It is not possible to determine from the report summarized which vintage of TAF was used in the analysis.

The average number of daily taxi-out operations per alternative, with their corresponding standard deviations, are as shown in Table 15-2.

Table 15-2. Daily Taxi-Out Operations at ATL

Alternative	Mean daily taxi-out operations	Standard deviation
Baseline	650.29	30.47
Alternative 1: SMA everywhere	650.75	15.97
Alternative 2: No SMA in ATCT	637.04	17.10

Estimation

The data were sorted by wheels-off time in half-hour intervals between 5:00 a.m. and midnight. Taxi-out times were evaluated to obtain averages for the previously specified periods and alternatives. Average taxi-out times with their corresponding standard deviations were calculated for each alternative and compared with the baseline scenario.

Differences in taxi time were converted to user savings using standard FAA economic values (current as of June 1997). These values equate to aircraft operating cost savings of $27.84 per minute, and passenger savings of $44.50 per minute per aircraft (using an aircraft load of 100 passengers per aircraft). Both airline and passenger savings due to reduced taxi times were computed.

A 10-year stream of benefits for the periods between 1997 and 2006 was calculated based on projected operations growth rates for ATL taken from the FAA's Terminal Area Forecast. Savings were extrapolated for the out-years, assuming a constant average taxi time savings per aircraft for each alternative. A 7 percent discount rate was used in the analysis of net present value, in accordance with OMB Circular A-94 as updated in February 1997.

Sensitivity Analysis

Expected taxi-out time savings were calculated using time segmentation of the ASQP data. The data were segmented to show the effect of SMA on weekday versus weekend traffic, and on daytime versus nighttime traffic. Weekend traffic was defined to include aircraft operations between 5:00 a.m. and midnight on Saturdays and Sundays. Daytime traffic was defined using 1997 civil twilight times for the city of Atlanta. The analysis of the segmented data included 95 percent confidence intervals for the average taxi time savings for each alternative when compared to the baseline.

The sensitivity analysis indicated that, in general, SMA brings greater benefits in the form of taxi-out savings when used during daytime and weekdays. This may reflect a correlation between traffic volume and taxi time savings; that is, SMA

may generate greater savings as traffic congestion increases. Further analysis is needed to confirm this hypothesis.

RESULTS, FINDINGS, AND CONCLUSIONS

Taxi-Out Time Savings

It was determined that a statistically significant change in taxi-out times occurred when SMA was operating. Testing the hypothesis that, on average, taxi-out times decreased when SMA was in use confirmed that hypothesis with a p-value less than 0.0001; i.e., the probability that the observed taxi times could have occurred had the hypothesis actually been false was less than one in 10,000 chances.

By comparing average taxi-out times under Alternatives 1 and 2 with the baseline, it was determined that SMA saves an average of 1.09 minutes per aircraft when used in all locations, and 1.00 minutes when used everywhere except for the ATCT. To provide a more useful estimate of taxi-out savings, a 95 percent confidence interval for the difference between the true population means (i.e., for the average taxi-out time savings per aircraft) was calculated, comparing each alternative to the baseline. Results are shown in Table 15-3.

Table 15-3. Taxi-Out Times (minutes)

Alternative	Mean taxi-out time	95% confidence interval for reduction
Baseline	17.84	N/A
Alternative 1: SMA everywhere	16.75	1.09 ± 0.16
Alternative 2: No SMA in ATCT	16.84	1.00 ± 0.15

Full-Year and 10-Year Cost Savings

Based on these results, full-year cost savings projected for the use of SMA during taxi-out operations at ATL in 1997 are as shown in Table 15-4. These cost savings include airline and passenger savings due to reduced taxi-out times.

Table 15-4. Total 1997 Taxi-Out Savings at ATL ($Millions, 1997 Dollars)

Alternative	95% confidence interval
Alternative 1: SMA everywhere	$18.5 ± 2.73
Alternative 2: No SMA in ATCT	$17.1 ± 2.56

Ten-year expected benefits for Alternative 1 are $203.4 million, and for Alternative 2 the expected benefits are $187.7 million, both measured in constant, discounted 1997 dollars.

Chapter 16
Passive Final Approach Spacing Tool (pFAST)—Summary of Operational Test Results

INTRODUCTION

The Center/TRACON Automation System (CTAS) is a set of decision support tools designed to help air traffic controllers increase efficiency and capacity of arrival traffic flow near congested airports. The Passive Final Approach Spacing Tool (pFAST), a subset of FAST functionalities, is the terminal area portion of CTAS. The main function of pFAST is to provide sequence and runway advisories to controllers in order to manage the flow of arrivals in terminal airspace. The controller may override both the relative sequence number and the runway advisory displayed by pFAST, and the system automatically adjusts to sequence number changes.

The objective of this summary is to describe the operational test results of pFAST conducted at the Dallas/Fort Worth (DFW) International Airport. The tests validated pFAST as the first-ever advisory tool for TRACON air traffic controllers to be successfully demonstrated in a live operational environment.

This summary of pFAST is primarily based upon the operational test results reported a 1997 symposium of the International Federation of Automatic Control (IFAC). The full citation for that report is:

> "Operational Test Results of the Passive Final Approach Spacing Tool." T.J. Davis, D.R. Isaacson, and J.E. Robinson III, NASA Ames Research Center; and W. den Braven, K.K. Lee, and B. Sanford, Sterling Software Inc.Presented at IFAC 8th Symposium on Transportation Systems 97, Chania, Greece. June 1997.

In addition, the T.J. Davis paper "The Final Approach Spacing Tool" and the June 2000 and June 2001 issues of the FAA's *Free Flight Metrics* reports were used to provide some information in this summary of the pFAST technology.

TEST APPROACH AND TOOL FUNCTIONS

After many years of development and hours of simulations of the pFAST tool at NASA Ames Research Center, it was determined that an operational test of the system was necessary to validate its potential savings. The FAA felt that if the pFAST tool could achieve controller acceptance while demonstrating the benefits

of the tool at DFW, then the risk of deployment to other sites would be substantially mitigated.

The controllers from DFW were involved in the definition and development of the entire FAST concept. Because of the high workload at DFW, the control of the arrival traffic is split up into as many as five sectors. Controllers working in any of these sectors make tactical decisions that add to their overall workload and also decrease the efficiency of the operation. This is because it is difficult for a controller to know the traffic load or available landing slots in any sector not adjacent to their own.

pFAST runway advisories provide the data necessary to balance the runways and the workload between controllers at the entry point into the TRACON arrival process. pFAST sequence advisories provide the information on how to efficiently merge separate traffic streams and where to build arrival slots for aircraft not yet seen. Both advisories are non-binding and continuously adjust to the actual traffic flow. pFAST ultimately enables controllers to gain situational awareness of the entire traffic flow and a strategy for efficiently controlling it.

Objectives of the Test

Objectives of the operational test were the following:

- Validate the capacity and throughput benefits of the pFAST system in a live traffic environment
- Confirm the controller acceptance observed in real-time simulations of the system
- Complete the definition of the functionality of pFAST for the national operational system.

The DFW facility provided a test team that operated the relevant traffic management, supervisory, and controller positions for the majority of the operational test. The tests were performed for periods of three days during the mid-week and were conducted for two weeks per month, all between January and July 1996. The tests included operations during both Instrument Flight Rules (IFR) and Visual Flight Rules (VFR), and spanned all major arrival rush periods at DFW. The tests also included North and South Flow runway configurations, operations with two and three arrival runways, and a variety of inclement weather conditions.

PERFORMANCE METRICS AND RESULTS

Performance Metrics

There are several overall performance characteristics (benefit mechanisms), their associated metrics, and two engineering metrics for pFAST, as show in Table 16-1.

Table 16-1. pFAST Benefit Mechanisms and Metrics

Benefit mechanism	Metrics
Throughput	1 Airport throughput 2 Excess in-trail separation on final approach
Safety	3 In-trail separation on final approach
Control performance	4 Workload 5 Controller acceptance
Sequence advisory adherence (engineering metric)	
Runway advisory adherence (engineering metric)	

The authors noted that it is important to look at the overall system performance, so as to ensure that benefits in one area do not degrade another area of performance. The test analyses for airport throughput, excess in-trail separation, and safety are based on the 11:15 a.m. “noon balloon” rush at DFW, which is characterized by high arrival rates and increased controller workload. The authors note that the results appear to be indicative of the trends seen in the other rush periods at DFW.

AIRPORT THROUGHPUT

Airport throughput is the most relevant measurement for the pFAST tests, since the advisories were intended to improve the arrival traffic flow.

Figure 16-1 shows mean throughput for arrival aircraft at DFW during the peak portion of the rush.

Figure 16-1. Comparison of Mean Airport Throughput

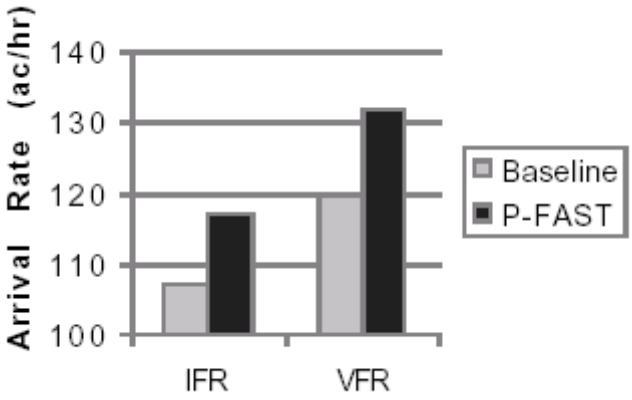


Figure 16-1 indicates that the average peak arrival rate rose 10 aircraft/hour from the baseline during IFR operations with pFAST, and 12 aircraft/hour during VFR operations with pFAST. During VFR rushes, all baselines included inboard runway landings of three to five aircraft/hour. No inboard landings of aircraft were required during any of the pFAST advised rushes. The average peak arrival throughput increased by 16 aircraft/hour when inboard landings were removed from the baseline throughput data.

During these tests, observers were placed in the DFW tower to collect additional data. These observations indicated that when pFAST was employed there was:

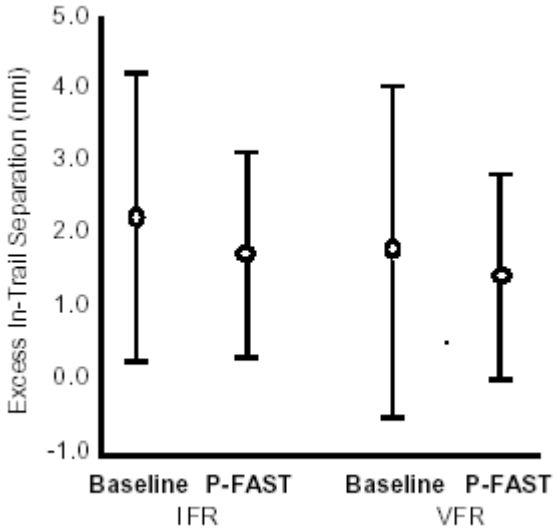
- an observed average increased landing rate of 15 aircraft/hour
- an observed average increased departure rate of 13 aircraft/hour
- an average departure queue backlog reduction of 9 percent.

Lastly, despite the increase of arrival and departure rates, the data indicated no increase in taxi-in or taxi-out times, suggesting that concern over increased surface and departure congestion was negated.

EXCESS IN-TRAIL SEPARATION

Excess in-trail separation is a measure of the efficiency of runway utilization. Figure 16-2 shows the mean and standard deviation for both IFR and VFR rushes.

Figure 16-2. Excess In-Trail Separation for IFR and VFR Rushes

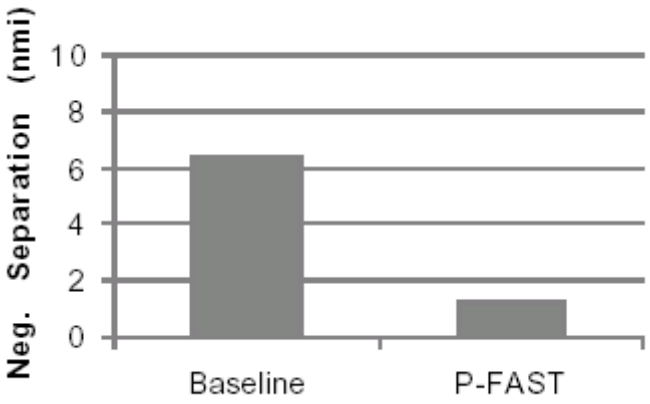


There is a decrease of 0.48 nautical miles (nm) shown in the mean, and a decrease of 0.60 nm shown in the standard deviation, of excess in-trail separation for IFR during use of the pFAST system. During VFR operations with pFAST, there is a decrease in mean excess in-trail separation of 0.33 nm, and the standard deviation is decreased by 0.96 nm. There is an overall increase in airport throughput during pFAST operations, and controllers indicated that when pFAST is employed that less time is spent on runway sequencing and decisions, and more time on separating aircraft.

SAFETY

With respect to safety considerations when pFAST is in use, the results are encouraging. As shown in Figure 16-3, in-trail separations falling below IFR standards decreased by a factor of more than five.

Figure 16-3. Mean Negative In-Trail Separation per Rush Sample at Outer Marker During VFR Operations



The controllers commented that the increased organization in the traffic flow more evenly balanced the arrival runways, which resulted in more landings without using inboard runways, all without increased workload and with more time spent separating aircraft.

ADVISORY ADHERENCE

Advisory adherence is a key metric for assessing how well the pFAST system is working, since it helps to confirm that the controllers use the advisories pFAST suggests and that the system is adapting correctly to the controllers actions.

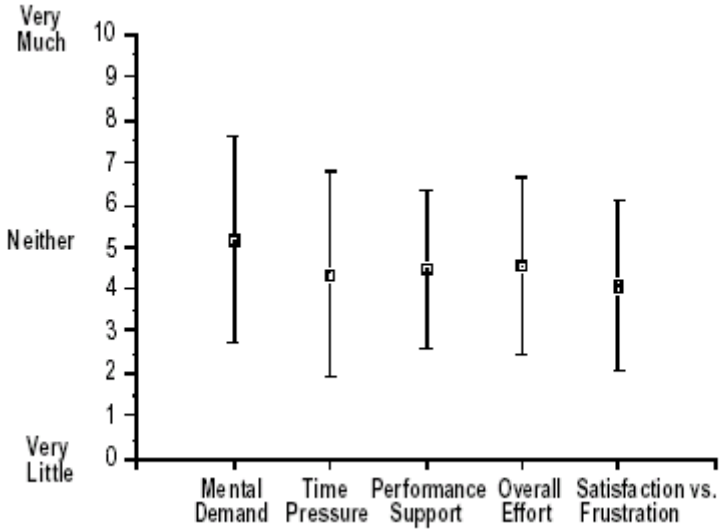
In all but one case examined, the adherence to the sequence advisories was between 83–93 percent. This result seems initially very good; however, after consulting with controllers, it was decided that the sequence advisories should be improved to always be above 90 percent before permanently installing the pFAST system. This result led to the refinement of the sequencing algorithm in order to more accurately reflect the controllers' use of altitude and speed differences. The modifications ultimately made to the algorithm show a new acceptable sequence adherence of over 95 percent, based on simulations and shadow observations.

WORKLOAD AND CONTROLLER ACCEPTANCE

In order to provide a qualitative measure of controller workload, human factors data were collected. Each controller rated workload using a modified NASA Task Load Index (TLX) and acceptance using the Controller Acceptance Rating Scale.

Figure 16-4 shows the mean workload ratings, with zero representing the most favorable rating and 10 representing the least favorable rating.

Figure 16-4. Mean Workload Ratings



The ratings are clustered around the middle of the scale and show that the controllers did not experience any significant increase in mental demand, time pressure, or overall effort. Also, pFAST was not rated as increasing their workload or reducing their job satisfaction.

Controllers provided Controller Acceptance Rating Scale (CARS) ratings to indicate acceptance after each test rush. The scale uses a 1 to reflect the most undesirable rating and a 10 to reflect the most favorable rating. The mean CARS rating across the field test was 7.82, with a standard deviation of 1.10. This rating is associated with a numerical rating of 8, and the following description: “System is acceptable and minimal compensation is needed to meet desired performance.” The controllers said that the system was acceptable as fielded for the tests, with the exception of the sequence advisory adherence. The workload ratings indicate neither an increase or decrease on workload and this is considered a positive result.

FINDINGS AND CONCLUSIONS

pFAST ultimately enables controllers to gain situational awareness of the entire traffic flow and a strategy for efficiently controlling it. The tests at DFW demonstrated airport throughput increases of more than 13 percent with no negative impact on the controller workload or safety. There appeared to be no increase of controller workload during pFAST operations. Also, the data suggested that the concern over increased surface and departure congestion was unsupported.

The operational tests of pFAST represented the first successful demonstrations of an advisory tool for TRACON controllers. Controllers accepted and utilized more than 83 percent of the sequence advisories and more than 96 percent of the run-

way advisories, showing that the pFAST system performed well. pFAST supported the controllers in increasing the airport throughput and decreasing the in-trail separation between aircraft on final approach. Also, pFAST appears to have provided a safety benefit by decreasing the number of in-trail separations below IFR standards that occurred during VFR operations. A secondary benefit was that the departure rates at DFW airport also increased during pFAST operations.

At the writing of the operational test paper, pFAST was being re-adapted for the DFW airspace to accommodate a new runway, which was added in 1996. The FAA was planning to reinstall the system at DFW on a permanent basis in mid-1997. Since then, in July 1999, American Airlines effectively added two additional aircraft being scheduled in peak arrival periods. Analyses performed support the belief that pFAST contributed to the servicing of this additional demand.

The June 2000 Free Flight Phase 1 (FFP1) report notes that pFAST became operational at DFW TRACON in 1999 and was used by a limited number of controllers. By the spring of 2000, DFW was using pFAST 100 percent of the time the airport was on a south flow, and also during north flow operations. By this time, all staff were using the pFAST system.

Due to DFW management initiatives, the combined changes in the mean related to pFAST and the post June management initiative variable, under visual approaches, is 7.5 operations. The combined changes in the mean related to pFAST and the post June management initiative variable, under instrument approaches, is 8 operations.

The June 2001 FFP1 report stated that there was an increase in arrival capacity at Los Angeles International Airport (LAX) of between 1.5 and 3.5 percent attributable to the use of pFAST.

Chapter 17
Active Final Approach Spacing Tool (aFAST)—Summary of Single-Year NAS-Wide Benefits Assessment

INTRODUCTION

NASA has been developing CTAS, an integrated set of decision support tools (DSTs), for several years under the Center TRACON[1] Automation System (CTAS) program. The Final Approach Spacing Tool (FAST) was originally included in the suite of CTAS tools, and for several reasons was subdivided into passive FAST (pFAST) and active FAST (aFAST).

aFAST is designed to deal with the complexities of inter-arrival spacing within the TRACON, particularly on the final approach path. aFAST generates "control instruction"-level advisories for controllers, so that they may issue specific speed and heading instructions based upon these advisories. Dedicated aFAST displays are provided for traffic management coordinators (TMCs) in the air route traffic control center (ARTCC) and TRACON, and are used for strategic planning. Displays are also available for air traffic control specialists in the tower, where they provide enhanced situational awareness.

This summary is based on the 2003 assessment report prepared for the AATT project at NASA Ames Research Center. The full citation for this report is:

> *Refined Single-Year Benefits Assessment of aFAST*. Jianzhong Jay Wang, Paul Chang, and Koushik Datta, bd Systems Inc., NASA Ames Research Center, Moffett Field, CA. Contract NAS2-98074, Task Order 4242-001. September 23, 2003.

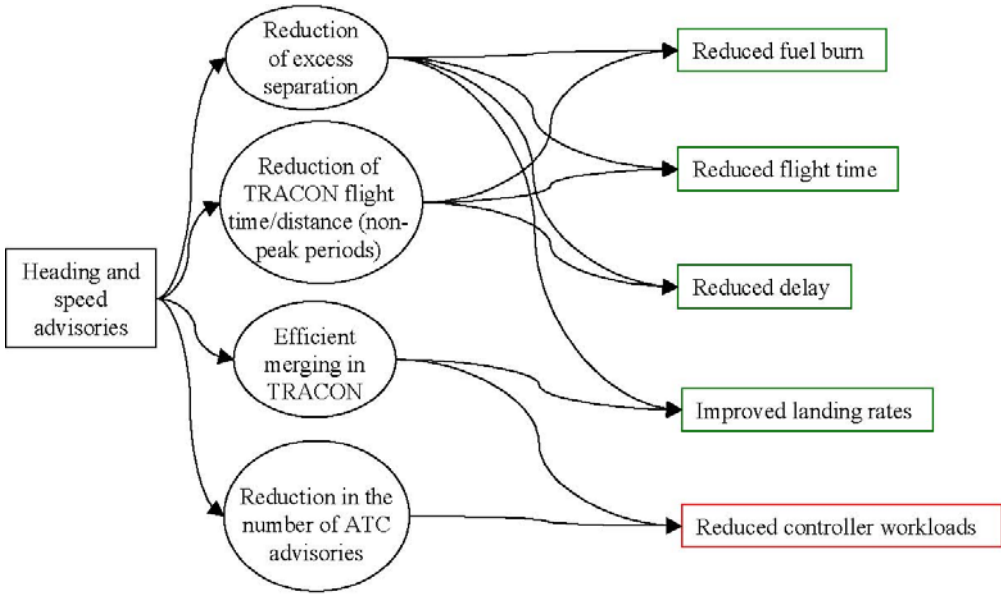
The report documents single-year benefit estimates for aFAST deployment at the Dallas/Fort Worth (DFW) and Atlanta (ATL) airports. The estimates are based on year 2000 traffic flow, and benefits are estimated in year 2000 constant dollars. Only the reduction of excess inter-arrival separation at the runway was evaluated in the report.

[1] TRACON: Terminal Radar Approach Control.

FUNCTIONS, BENEFIT MECHANISMS, AND METRICS

Figure 17-1 shows the functions, benefit mechanisms, and metrics of aFAST.

Figure 17-1. aFAST Key Functions, Benefit Mechanisms, and Direct Benefits



MODELING AND ANALYSIS APPROACH

The benefits of aFAST are based on the basic assumption that aFAST will allow reductions in both aircraft pair interarrival distances (IADs) and in the uncertainties of those distances (σ_{IADs}). The specific estimating assumptions made (and corresponding scenarios evaluated) include:

1. aFAST will match the best-observed visual meteorological conditions (VMC) inter-arrival distance separation (mean and standard deviation), provided that the mean does not violate the wake turbulence separation standard.

2. aFAST will match the observed proportions below the wake turbulence standard while maintaining the best-observed VMC standard deviation, provided that the mean does not violate the wake turbulence separation standard.

3. aFAST will match the mean from scenario 2 while maintaining half of the best-observed VMC standard deviation, provided that the mean does not violate the wake turbulence separation standard.

4. aFAST will maintain half of the best-observed VMC standard deviation while matching the observed proportions below the wake turbulence standard, provided that the mean does not violate the wake turbulence separation standard. This assumption is a combination of assumptions 2 and 3.

The statistics for DFW and ATL are derived from 6 days (3 VMC and 3 instrument meteorological conditions, or IMC) of radar data from each airport. Specifically, the IADs and σ_{IADs} used to calculate aFAST benefits are derived from Large-Large aircraft pair data during peak throughput operating conditions. Based on the number of arrivals during peak periods on an average day, and the fraction of VMC and IMC days, the average savings per peak time is extrapolated to find the annual benefits.

Airline direct operating costs (DOCs) are used to convert time saving into dollar savings. The dollar value of DOC used is $38.55 per minute in year 2000 dollars.

Specific individual steps of the analysis include:

1. Analysis of radar data and extraction VMC of IADs and σ_{IADs}.

2. Use of a simulation to calculate the differences in approach flight times that result when the IADs and σ_{IADs} are reduced in accordance with the four assumed benefit conditions listed above.

3. Extrapolation of the savings to a full year.

4. Economic evaluation of the time savings.

The following section discusses these steps.

Radar Data

The radar data used in this study had been previously collected for CTAS development (at DFW) and Surface Management Advisor (SMA) development (at ATL). The data were analyzed and reformatted to extract the information needed for the aFAST analysis. Table 17-1 shows the data fields extracted for each airport.

Table 17-1. aFAST Radar-Derived Analysis Data

DFW	ATL
Aircraft ID	Aircraft ID
X Coordinates	X Coordinates
Y Coordinates	Y Coordinates
Altitudes	Altitudes
Ground Speeds	Ranges
Headings	Azimuths
Times of Recording	Times Received

Generation of Interarrival Distance Statistics

The extracted radar data were combined with runway and TRACON geometries to derive TRACON entry times and threshold for each data set. IAD and σ_{IAD} statistics were calculated as functions of arrival gates and weight classes for each airport, with in-trail and merging approaches analyzed separately. The throughput rates were used to identify the "at capacity" periods for VMC and IMC conditions. The best-observed Large-Large "at capacity" IADs for each airport were used to represent aFAST performance.

Table 17-2 shows the arrival pair (or "doublet") counts for one IMC day's arrivals at ATL. The first number in each cell is the total pair count, and the second is the Large-Large pair count. Only the Large-Large pairs are used to calculate the IAD statistics. A leader-follower pair both from the same gate, such as DALAS-DALAS, represents an in-trail approach, and a leader-follower pair from different gates, such as DALAS-LOGEN, represents a merged approach.[2]

Table 17-2. Doublet Count Example for ATL

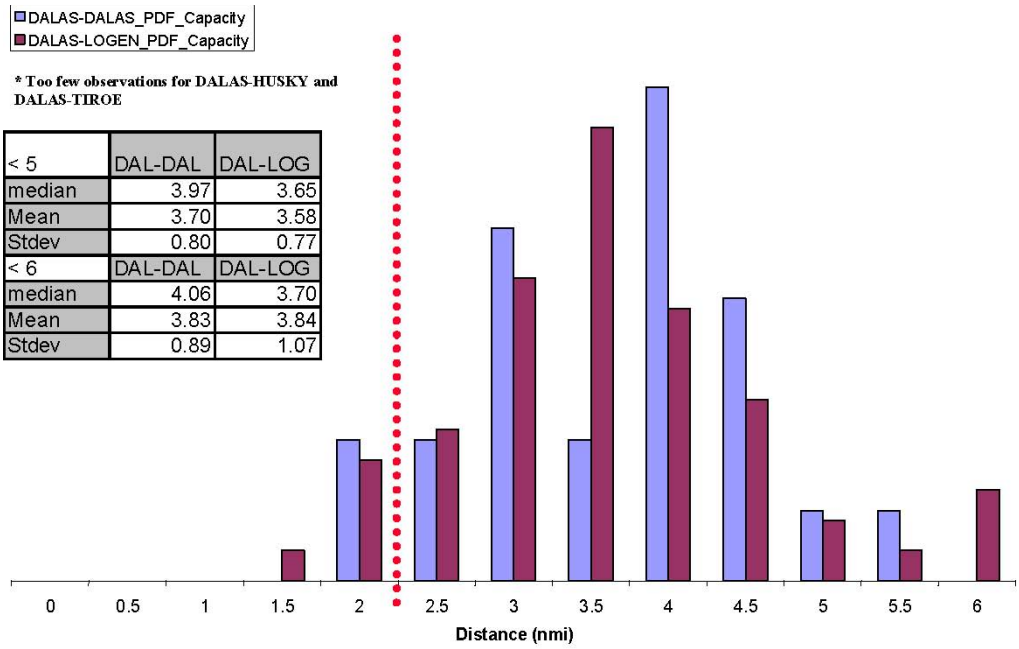
ATL doublet counts for October 20, 1999 (IMC)				
Leader aircraft gate	Follower aircraft gate			
	DALAS	HUSKY	LOGEN	TIROE
DALAS	30/24	18/13	67/56	28/23
HUSKY	21/17	66/46	9/6	53/37
LOGEN	73/61	8/4	82/69	14/11
TIROE	21/19	57/47	18/15	34/29

[2] DALAS and LOGEN are the northwest and northeast arrival gates, respectively, for ATL. TIROE and HUSKY are the southwest and southeast gates.

Figure 17-2 shows the IAD statistics corresponding to the DALAS-DALAS and DALAS-LOGEN Large-Large arrivals in Table 17-2. Note that there is no ordinate in Figure 17-2. This is because the bars for each gate pair have different scales. As shown in Table 17-2, there are 24 flights in the DALAS-DALAS data set and 56 flights in the DALAS-LOGEN data set. The DALAS-DALAS data bars at 5.0 and 5.5 nautical miles (nm) in Figure 17-2 each represent one flight. The DALAS-LOGEN data bar at 1.5 nm. also represents one flight. The statistical information in the figures is not affected by the scale difference.

Note that in all the separation charts, the vertical dotted line represents the 2.5 nm ATC minimum separation.

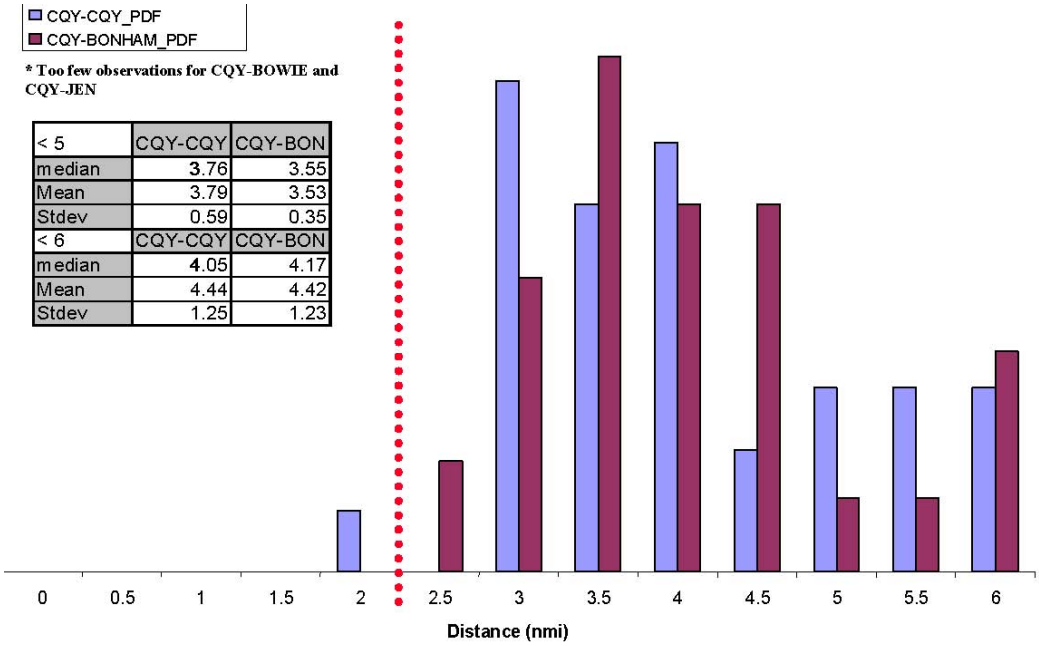
Figure 17-2. Worst Observed IMC Inter-Arrival Separations at ATL



< 5	DAL-DAL	DAL-LOG
median	3.97	3.65
Mean	3.70	3.58
Stdev	0.80	0.77
< 6	DAL-DAL	DAL-LOG
median	4.06	3.70
Mean	3.83	3.84
Stdev	0.89	1.07

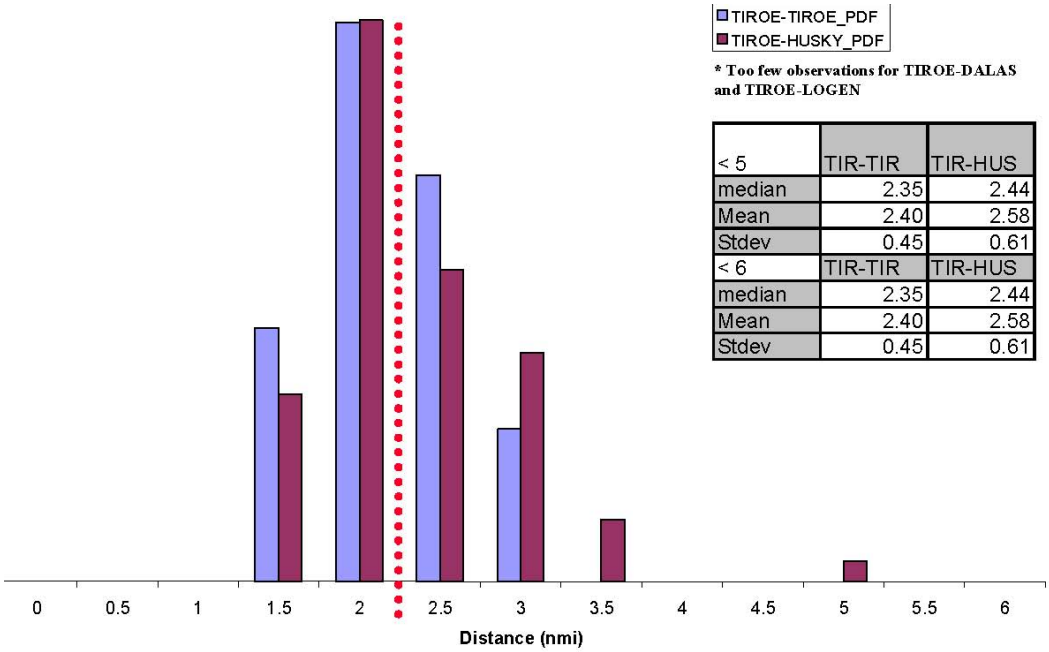
Figures 17-3 and 17-4 show the best observed VMC interarrival separations for DFW and ATL. These are used as the basis for expected aFAST performance.

Figure 17-3. Best Observed VMC Interarrival Separations at DFW



< 5	CQY-CQY	CQY-BON
median	3.76	3.55
Mean	3.79	3.53
Stdev	0.59	0.35
< 6	CQY-CQY	CQY-BON
median	4.05	4.17
Mean	4.44	4.42
Stdev	1.25	1.23

Figure 17-4. Best Observed VMC Interarrival Separations at ATL



< 5	TIR-TIR	TIR-HUS
median	2.35	2.44
Mean	2.40	2.58
Stdev	0.45	0.61
< 6	TIR-TIR	TIR-HUS
median	2.35	2.44
Mean	2.40	2.58
Stdev	0.45	0.61

Tables 17-3 and 17-4 show the IADs and σ_{IAD}s used to calculate DFW and ATL aFAST benefits for the cases described above. Note that the best ATL VMC IAD of 2.4 nm. is less than the 2.5 nm. ATC minimum separation, so 2.5 nm. is used for the benefit analysis. Note also for ATL that there is no improvement possible in IAT from Case 1, so Case 2 is moot. The same is true for Case 4.

Table 17-3. DFW Analysis Scenario Parameters

aFAST scenario	Mean separation (nm)	Standard deviation (nm)
Case 1	3.5	0.4
Case 2	3.2	0.4
Case 3	3.2	0.2
Case 4	2.9	0.2

Table 17-4. ATL Analysis Scenario Parameters

aFAST scenario	Mean separation (nm)	Standard deviation (nm)
Case 1	2.5	0.4
Case 2	-	-
Case 3	2.5	0.2
Case 4	-	-

RESULTS, FINDINGS, AND CONCLUSIONS

Simulation and "At Capacity" Benefit Results

The simulation model replaces actual IADs and σ_{IAD}s with those corresponding to the aFAST cases and calculates the differences in total TRACON travel times. For each airport and each of the four cases, 10 simulation runs are made for each of the three days of data. This amounts to $2 \times 4 \times 10 \times 3 = 240$ simulation runs. The runs are made for the "at capacity" periods of the day.

Tables 17-5 through 17-8 show the basic time differences for the cases. Note in Table 17-7 that the IAT differences for VMC cases at ATL on January 14, 2000, are negative. This is because the actual IAT was 2.4 minutes, which was increased to 2.5 minutes for the aFAST case.

Table 17-5. DFW VMC Simulation Results

	Date of data	Actual flight time (hours)	Simulated flight time (hours)	Difference (hours)
Case 1	2/6/00	238.50	227.36	11.14
	5/29/00	220.46	216.84	3.62
	9/11/00	218.97	214.10	4.87
Case 2	2/6/00	238.50	225.63	12.87
	5/29/00	220.46	215.74	4.72
	9/11/00	218.97	212.54	6.43
Case 3	2/6/00	238.50	225.48	13.02
	5/29/00	220.46	215.68	4.78
	9/11/00	218.97	212.44	6.53
Case 4	2/6/00	238.50	224.06	14.44
	5/29/00	220.46	214.70	5.75
	9/11/00	218.97	211.21	7.76

Table 17-6. DFW IMC Simulation Results

	Date of data	Actual flight time (hours)	Simulated flight time (hours)	Difference (hours)
Case 1	4/10/00	79.76	67.41	12.35
	4/13/00-1	43.76	39.57	4.19
	4/13/00-2	17.34	16.67	0.67
	4/14/00	204.75	185.60	19.15
Case 2	4/10/00	79.76	66.46	13.3
	4/13/00-1	43.76	39.44	4.32
	4/13/00-2	17.34	16.64	0.70
	4/14/00	204.75	184.41	20.34
Case 3	4/10/00	79.76	66.42	13.34
	4/13/00-1	43.76	39.43	4.33
	4/13/00-2	17.34	16.65	0.69
	4/14/00	204.75	184.38	20.37
Case 4	4/10/00	79.76	65.69	14.08
	4/13/00-1	43.76	39.28	4.48
	4/13/00-2	17.34	16.64	0.70
	4/14/00	204.75	183.22	21.52

Table 17-7. ATL VMC Simulation Results

	Date of data	Actual flight time (hours)	Simulated flight time (hours)	Difference (hours)
Case 1	1/11/00	310.19	295.06	15.13
	1/14/00	287.06	287.56	-0.50
	11/14/9	288.54	277.28	11.26
Case 2	1/11/00	-	-	-
	1/14/00	-	-	-
	11/14/9	-	-	-
Case 3	1/11/00	310.19	294.08	16.11
	1/14/00	287.06	287.45	-0.39
	11/14/9	288.54	277.24	11.30
Case 4	1/11/00	-	-	-
	1/14/00	-	-	-
	11/14/9	-	-	-

Table 17-8. ATL IMC Simulation Results

	Date of data	Actual flight time (hours)	Simulated flight time (hours)	Difference (hours)
Case 1	1/16/00-1	15.16	12.01	3.15
	1/16/00-2	48.89	40.54	8.35
	1/24/00	56.98	47.20	9.78
	10/20/99	204.53	159.59	44.94
Case 2	1/16/00-1	-	-	-
	1/16/00-2	-	-	-
	1/24/00	-	-	-
	10/20/99	-	-	-
Case 3	1/16/00-1	15.16	12.00	3.16
	1/16/00-2	48.89	40.55	8.34
	1/24/00	56.98	47.16	9.82
	10/20/99	204.53	159.58	44.95
Case 4	1/16/00-1	-	-	-
	1/16/00-2	-	-	-
	1/24/00	-	-	-
	10/20/99	-	-	-

The results for the individual days are averaged to find the "at capacity" delay per arrival for each case. The DOC of $38.55 per minute is used to calculate the corresponding "at capacity" dollar savings per arrival. Tables 17-9 and 17-10 show the results for DFW and ATL.

Table 17-9. DFW "At Capacity" Per-Flight Savings

		Flight time savings (minutes/arrival)	Flight $ savings ($/arrival)
VMC	Case 1	0.65	25.20
	Case 2	0.80	30.85
	Case 3	0.81	31.24
	Case 4	0.93	35.91
IMC	Case 1	2.32	89.58
	Case 2	2.47	95.17
	Case 3	2.47	95.38
	Case 4	2.61	100.44

Table 17-10. ATL "At Capacity" Per-Flight Savings

		Flight time savings (minutes/arrival)	Flight $ savings ($/arrival)
VMC	Case 1	0.67	25.65
	Case 2	-	-
	Case 3	0.68	26.09
	Case 4	-	-
IMC	Case 1	4.06	156.48
	Case 2	-	-
	Case 3	4.06	156.55
	Case 4	-	-

Extrapolation and Annual Results

The data for "at capacity" benefit per minute are extrapolated to the full year based on throughput information. Detailed throughput for the days under study is shown in Tables 17-11 and 17-12. These results are averaged to provide the results in Table 17-13.

Table 17-11. DFW Throughput Characteristics Data

	Date of data	Total flights	Flights "At Capacity"	% "At Capacity"	Total hours	Total hours "At Capacity"
VMC	2/6/00	1023	585	57.18	15.15	4.29
	5/29/00	1016	621	61.12	15.32	4.50
	9/11/00	984	594	60.37	13.46	4.16
IMC	4/10/00	286	214	75.86	5.12	2.16
	4/13/00-1	174	130	74.71	3.03	1.18
	4/13/00-2	79	43	53.16	1.85	0.46
	4/14/00	818	552	67.48	12.00	4.62

Table 17-12. ATL Throughput Characteristics Data

		Total flights	Flights "At Capacity"	% "At Capacity"	Total hours	Total hours "At Capacity"
VMC	1/11/00	1290	837	64.88	23.08	9.05
	1/14/00	1281	819	63.93	22.60	8.48
	11/14/99	1181	678	57.41	21.14	7.24
IMC	1/16/00-1	52	44	80.77	1.58	0.79
	1/16/00-2	178	145	80.34	4.14	1.90
	1/24/00	212	178	87.03	4.96	2.36
	10/20/99	679	612	90.13	13.74	9.04

Table 17-13. Average Arrivals Per Hour During "At Capacity" Periods

	VMC	IMC
DFW	139	111
ATL	94	69

The annual benefit is calculated using the following relationships:

VMC Benefit = $365 \times 24 \times (\%VMC) \times (VMC\ @Cap\ throughput) \times (time\ savings\ per\ arrival) \times (DOC\ per\ minute)$

IMC Benefit = $365 \times 24 \times (\%IMC) \times (IMC\ @Cap\ throughput) \times (time\ savings\ per\ arrival) \times (DOC\ per\ minute)$

Total Annual Benefit = VMC Benefit + IMC Benefit

The year 2000 benefits for DFW and ATL are shown in Table 17-14 (in year 2000 dollar amounts).

Table 17-14. Potential aFAST Annual Benefits in 2000 (year 2000$)

		aFAST case 1		aFAST case 2		aFAST case 3		aFAST case 4	
		Hours	$M	Hours	$M	Hours	$M	Hours	$M
DFW	VMC	3,558	$8.23	4,356	$10.08	4,411	$10.20	5,071	$11.73
	IMC	977	$2.26	1,039	$2.40	1,041	$2.40	1,096	$2.54
	Total	4,535	$10.49	5,395	$12.48	5,452	$12.61	6,167	$14.26
ATL	VMC	2,884	$6.67	-	-	3,010	$6.79	-	-
	IMC	3,564	$8.24	-	-	3,567	$8.25	-	-
	Total	6,448	$14.91	-	-	6,577	$15.03	-	-

Chapter 18
Advanced Air Transportation Technologies (AATT) Project—Summary of Single-Year, NAS-Wide Integrated Benefits Assessment

INTRODUCTION

Since 1997, the AATT Project has been the focal point of NASA's research into air traffic management DSTs and innovative operational concepts. With the project concluding at the end of fiscal year 2004, a final summary assessment incorporating as many of the project's research products as possible was desired to provide a unified depiction of its contributions.

The objective of this study was to estimate the single-year benefits under a hypothetical scenario in which all the AATT DSTs reach fruition and are deployed across the NAS. The DSTs modeled for this summary benefits assessment include:

- Active Final Approach Spacing Tool (aFAST)
- Passive Final Approach Spacing Tool (pFAST)
- Traffic Management Advisor (TMA)
- Multi-Center Traffic Management Advisor (McTMA)
- Regional Metering (RM) arrival metering
- Surface Management System (SMS)
- Surface Management Advisor (SMA)
- Expedite Departure Path (EDP)
- En Route Data Exchange (EDX)
- Distributed Air/Ground Traffic Management Concept Element 11 (DAG-TM CE-11)

In addition, NASA provided an estimate of the airspace capacity increase (19.6 percent), based on a controller workload modeling study of en route DSTs.[1] This increase was incorporated into the integrated benefits assessment. The increase is due to the following en route DSTs:

- En Route/Descent Advisor (EDA)
- Regional Metering (RM) en route metering
- Direct-To (D2).

The study estimated the operational benefits by the capacity increases at airport runways, taxiways, and the en route sectors, in various operating and meteorological conditions. These operational benefits were then translated to economic benefits, estimated by the savings resulting from reduction in flight delays and the value of enabling more traffic.

The economic benefits are functions of the operational benefits and air traffic demand. The study was based on two levels of demand: 1997, representing the initial year of the AATT Project; and 2015, representing a future year with increased demand and a correspondingly greater need for capacity-enhancing DSTs.

Several AATT DSTs were not modeled in this study:

- Traffic Flow Management Research and Development (TFM R&D) (System-Wide Evaluation and Planning Tool and Future Air Traffic Management Concepts Evaluation Tool-Airline Operations Center [SWEPT and FACET-AOC])
- Traffic Flow Automation System (TFAS)
- Collaborative Arrival Planner (CAP)
- Conflict Prediction and Trial Planning (CPTP)
- Distributed Air/Ground Traffic Management Concept Element 5 (DAG-TM CE-5)
- Distributed Air/Ground Traffic Management Concept Element 6 (DAG-TM CE-6).

Regarding the DAG-TM concept elements that were explored under AATT, the benefits of Terminal Arrival Self-Spacing (CE-11) are included in the study, while the concepts of En Route Free Maneuvering (CE-5) and En Route Trajectory Negotiation (CE-6) are not in the study. The en route concept elements were not included because their benefits cannot be realized without the deployment of

[1] *Task Order 74 Final Report, Sub-tasks 1 and 4: Analysis of En Route Descent Advisor Key Functional Capabilities*, Ken Leiden et al., Micro Analysis & Design Inc., May 3, 2004.

particular enabling technologies prior to their own implementation. For instance, Controller Pilot Data Link Communications (CPDLC) must be fielded before DAG-TM. Because the study baseline is a 1997 state of the NAS (in which technologies such as CPDLC are not in place), DAG-TM CE-5 and CE-6 were not included in the analysis.

The full citation for this assessment is:

> *Single-Year, NAS-Wide Integrated AATT Benefits Assessment,* Shahab Hasan, Dou Long, Robert Hemm, and Jeremy Eckhause, LMI Report NS356T1, September 2004.

MODELING AND ANALYSIS

The integrated benefits of TMA, McTMA, EDX, EDA, pFAST, aFAST, and CE-11 of DAG-TM were analyzed directly using the LMINET model. In addition, the benefits of EDA, D2, and RM in increasing airspace capacity were provided by NASA and incorporated in the LMINET modeling.

In general terms, LMINET is an NAS-wide model which models flights among a set of airports by linking queuing network models of the airports with sequences of air traffic control (ATC) sectors. The demands, delays, and capacities at airports and sectors are determined by the flight schedules, flight trajectories, airport runway configuration, and airport weather conditions. The model considers all flights, both commercial and general aviation, in the United States, including the international flights that originate or terminate in the United States. The arrival and departure delays are computed for the top 102 airports; these airports comprise roughly 95 percent of all U.S. enplanements. All ATC sectors are considered.

Two different LMINET benefit methodologies were used. The first measures the delay reductions for the socio-economic based traffic demand in 1997 and 2015, respectively, where the demand is as predicted by the FAA Terminal Area Forecast (TAF), and is unconstrained by airport and airspace congestion. The second method takes the view that the baseline traffic without AATT DSTs will not be able to reach the level predicted by the socio-economic demand forecast due to unacceptable congestion caused by airport and airspace capacity scarcity.

Using the second method, there are two kinds of benefits: one is the value of additional enabled traffic that the air carriers can schedule and fly; and the second is variable operating cost savings from delay reduction for all traffic. The first methodology can be applied to traffic in both 1997 and 2015, but the second applies only to 2015, because the technologies cannot make more historical traffic. The study authors believe the second methodology is more realistic, while the first was retained because it is commonly used. For both methods, delay is calculated by running LMINET for 1 entire year of traffic and weather.

Separate from the LMINET analysis, the benefits of SMA, SMS, and EDP were estimated using the results of previous studies.[2] Benefits per departure were derived and applied to 2015 demand estimates. According to the studies, SMA/SMS/EDP will reduce taxi-out delay, enhance the efficiency of runway use, and reduce TRACON airspace congestion. These delays are not closely coupled to the delay mechanisms affected by the DSTs that were analyzed using LMINET; thus, the benefits of SMA/SMS/EDP were considered to be additive to those estimated for the other AATT DSTs using either LMINET methodology.

RESULTS, FINDINGS, AND CONCLUSIONS

Runway Capacity Benefit at 32 Large Hub Airports

Table 18-1 lists the maximum arrival, maximum departure, and equal arrival and departure capacities and their percentage increases from AATT for the 32 large hub airports, under VFR, MVFR, and IFR configurations.[3] Although the capacity increases were calculated for 102 airports, the 32 large hub airports matter most in the benefits assessment and thus are the only ones reported.

MAXIMUM ARRIVALS AND MAXIMUM DEPARTURES

For the VFR configuration, the maximum arrival capacities increase 7–8 percent, and the maximum departure capacities increase 1–2 percent. For the MVFR configuration, the maximum arrival capacities increase 23–29 percent, and the maximum departure capacities increase up to 2 percent. For the IFR configuration, the maximum arrival capacities increase 21–29 percent, and the maximum departure capacities increase up to 2 percent. The variation of capacity increases among airports is due to their differences in runway configurations and local traffic mixes.

Most of the capacity increases are from the increase in arrivals, because most of the AATT DSTs are designed to solve the arrival congestion problem. Even though the maximum departure capacities are not increased much, the airports can increase the departure capacity by shifting the operation point in their capacity Pareto frontier, i.e., by “trading” arrival capacity for departure capacity along the Pareto curve.

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[2] *Surface Movement Advisor (SMA) Benefit Analysis*, Wilma Rada, MCA Research Corp., Prepared for FAA ASD-420, October 14, 1997.

Air Traffic Management System Development and Integration (ATMSDI) CTO-05, Surface Management System (SMS), Initial Life-Cycle Benefits/Cost Assessment, Raytheon Corp., NASA Ames Contract Number NAS2-00015, March 31, 2004.

Life-Cycle Cost/Benefit Assessment of Expedite Departure Path (EDP), Jianzhong Jay Wang et al., bd Systems Inc., NASA Ames Task Order 24242-001, August 29, 2003.

[3] An airport with more than 1 percent of total domestic enplanements is categorized as a large hub by the Federal Aviation Administration.

Table 18-1. Percentage Increases in Maximum Arrivals, Maximum Departures, and "Even" Operations Capacity for 32 Large Hub Airports

	VFR			MVFR			IFR		
Airport	Maximum arrivals increase	Maximum departures increase	"Even" operations increase	Maximum arrivals increase	Maximum departures increase	"Even" operations increase	Maximum arrivals increase	Maximum departures increase	"Even" operations increase
ATL	8.0	2.0	4.8	23.0	2.0	11.6	21.0	2.0	10.6
BOS	7.0	1.0	2.9	25.0	1.0	8.1	22.0	1.0	11.9
BWI	7.0	1.0	4.0	25.0	1.0	13.4	22.0	1.0	9.4
CLT	7.0	1.0	5.0	25.0	1.0	17.9	22.0	1.0	9.4
CVG	7.0	1.0	2.4	25.0	1.0	12.8	22.0	1.0	8.3
DCA	7.0	1.0	4.2	25.0	1.0	14.0	22.0	1.0	12.8
DEN	7.0	1.0	3.6	25.0	1.0	12.6	22.0	1.0	10.3
DFW	7.0	1.0	3.5	25.0	1.0	11.5	22.0	1.0	10.1
DTW	7.0	1.0	3.0	25.0	1.0	7.8	22.0	1.0	7.2
EWR	7.0	1.0	3.9	25.0	1.0	11.7	22.0	1.0	11.1
FLL	7.0	1.0	2.8	29.0	1.0	19.2	22.0	1.0	7.8
HNL	8.0	2.0	2.6	23.0	2.0	6.2	21.0	2.0	4.7
IAD	7.0	1.0	3.0	25.0	1.0	9.9	22.0	1.0	9.3
IAH	7.0	1.0	2.2	25.0	1.0	12.1	22.0	1.0	14.9
JFK	8.0	2.0	5.6	23.0	2.0	14.2	21.0	2.0	11.6
LAS	7.0	1.0	2.7	25.0	1.0	8.8	22.0	1.0	9.1
LAX	8.0	2.0	4.9	23.0	2.0	11.6	21.0	2.0	10.7
LGA	7.0	1.0	3.9	25.0	1.0	8.8	22.0	1.0	8.2
MCO	7.0	1.0	3.9	25.0	1.0	12.7	22.0	1.0	10.9
MDW	7.0	1.0	4.2	25.0	1.0	13.7	22.0	1.0	12.8
MIA	8.0	2.0	3.4	23.0	2.0	11.2	21.0	2.0	12.9
MSP	7.0	1.0	3.1	29.0	1.0	15.2	29.0	1.0	8.6
ORD	7.0	1.0	4.0	25.0	1.0	7.3	22.0	1.0	6.9
PHL	7.0	1.0	3.1	25.0	1.0	6.9	22.0	1.0	9.0
PHX	7.0	1.0	3.6	29.0	1.0	8.5	29.0	1.0	0.0
PIT	7.0	1.0	3.6	25.0	1.0	15.5	22.0	1.0	12.5
SAN	7.0	1.0	1.0	25.0	1.0	1.1	22.0	1.0	9.1
SEA	7.0	1.0	3.3	25.0	1.0	9.0	22.0	1.0	6.0
SFO	8.0	2.0	3.6	23.0	2.0	6.1	21.0	2.0	6.5
SLC	7.0	1.0	3.3	25.0	1.0	10.7	22.0	1.0	11.1
STL	7.0	1.0	2.9	25.0	1.0	10.3	22.0	1.0	9.5
TPA	7.0	1.0	4.3	25.0	1.0	14.5	22.0	1.0	13.5

EQUAL OR MIXED ARRIVALS AND DEPARTURES

Often airports do not operate at either their maximum arrival or departure capacities, but at some mix in between. The mixed operating points are fundamentally dependent on the runway configuration and use.

Using the two-point Pareto curves of airport capacity, it is often possible to draw an "even" arrival/departure 45-degree line to intersect the capacity curves of interest. Then, comparing the total operations at each intersection, it is possible to calculate a percentage increase in capacity.

SMA/SMS/EDP Benefits

As explained above, this integrated AATT benefits assessment relied on previously published studies of SMA, SMS, and EDP for the benefits estimation of these DSTs. Those studies predict time savings benefits for SMA, SMS, and EDP of roughly 1 minute per departure, 3 to 64 seconds per departure, and 37 seconds per departure, respectively. SMS is also predicted to provide 640 to 1,066 minutes per day per airport of taxi fuel savings. These benefits are not completely additive; SMA and SMS address similar problems, and EDP requires integration with SMS for approximately half of its benefits.

As noted in the studies, the direct translation of departure time savings to delay savings is not straightforward, because time saved in one phase, such as taxi, may show up in later phases, and thus have no impact on total delay. Based on review of the combined studies, the integrated AATT benefits study assumed that the *combined* SMA and SMS technologies will provide *delay* reductions equal to the airport-specific *time* reductions predicted in the SMS study. The study further assumed that EDP will additionally reduce departure *delay* 30 seconds per departure. The economic benefits were calculated by multiplying the predicted delay reductions by the estimated departure demand.

Table 18-2 shows the total benefits for the three scenarios.

Table 18-2. Combined SMA, SMS, and EDP Total Benefits

Scenario	Delay savings (minutes per year)	Taxi fuel savings (minutes per year)
1997 demand	9,470,916	14,634,011
2015 unconstrained demand	12,139,992	18,478,955
2015 constrained demand	11,228,656	17,289,776

Economic Benefits Results

1997 Demand—Benefits Measured by Delay Reduction

Even if the AATT DSTs had been deployed across the NAS in 1997, they would not have induced more traffic, and therefore their benefit is measured only by the delay reduction they would enable. The AATT benefits are measured by the difference between the delays at the 102 airports with and without the DSTs. LMINET calculates the delays using the real flight schedules in 1997, and the weather in 1994.[4] Table 18-3 summarizes the annual benefits corresponding to the 1997 level of air traffic demand. As discussed above, SMA, SMS, and EDP delay reductions are estimated by post-processing and are not reflected here.

Table 18-3. Delay Reduction Benefits, 1997 Demand

Benefit	Value
Arrival/departure delay reduction (millions of minutes)	16.99
Percentage delay reduction	12%
Average delay reduction per arrival (minutes)	1.04
Average delay reduction per departure (minutes)	0.36
Economic value	$577 M

2015 Unconstrained Demand—Benefits Measured by Delay Reduction

This is the traditional method of benefit evaluation—which the study authors consider unrealistic—in which the unconstrained forecast demand for 2015 is fed to LMINET. The benefit of AATT is measured by the reduction of the flight delays relative to the baseline. The benefits, based on the unconstrained demand in 2015, are summarized in Table 18-4.

Table 18-4. Delay Reduction Benefits, 2015 Unconstrained Demand

Benefit	Value
Arrival/departure delay reduction (millions of minutes)	87.80
Percentage delay reduction	16%
Average delay reduction per arrival (minutes)	4.4
Average delay reduction per departure (minutes)	1.5
Economic value	$3,085 M

[4] The fact that traffic demand and weather data came from different years is of no consequence to the analysis. Data from 1994 was used as representative “normal” weather.

2015 Constrained Demand—Benefits Measured by Enabled Traffic and Delay Reduction

The study authors contend that the benefit estimate based on the 2015 unconstrained demand, in Table 18-4, is unrealistic because the average delays at some airports are too large to be tolerable. A more realistic estimate is based on constrained traffic demand, where the DST benefits are derived from both the enabled traffic and delay reduction.

Flight schedules are based on NAS operations under good weather conditions. Commercial traffic follows a weekly pattern (7 days), and the GA traffic follows a seasonal pattern (winter, summer, spring/fall). The study, therefore, developed $7 \times 3 = 21$ good weather traffic files for LMINET. Enabled traffic benefits are based on the weighted average of improvements for the 21 days. The enabled traffic benefits are shown in Table 18-5 and discussed below.

Table 18-5. 2015 Enabled Traffic Benefits

	Baseline RPM reduction (%)	AATT RPM reduction (%)	AATT improvement (%)	Consumer surplus
Domestic	6.70	5.00	1.70	$1,181.6 M
International	1.12	0.81	0.31	$105.4 M
GA	2.32	0.91	1.41	$31.6 M
Total				$1,318.8 M

In Table 18-5, the revenue passenger mile (RPM) percentage reductions, relative to the unconstrained traffic, are based on the LMINET outputs, weighted for the selected 21 days. The percentage AATT improvement is the difference between the percentage RPM reductions between the AATT and the baseline. The consumer surpluses are the dollar values of the additional traffic enabled by AATT.

GA benefit is estimated based on the value of a passenger mile ($0.1084) times the enabled traffic. The forecast GA passenger miles for 2015 is 20.7 billion, and the consumer surplus attributable to AATT is given by $\$0.1084 \times 1.41\% \times 20.7$ billion = $31.6 million.

Once the constrained traffic schedules are constructed for both the baseline and AATT scenarios, they are fed back to LMINET for the delay calculation with 1 year of weather. The purpose is to estimate the delay reduction from AATT DSTs. The total flight delay reduction benefits are summarized in Table 18-6.

Table 18-6. Delay Reduction Benefits, 2015 Constrained Demand

Benefit	Value
Arrival/departure delay reduction (millions of minutes)	15.94
Percentage delay reduction	7%
Average delay reduction per arrival (minutes)	1.01
Average delay reduction per departure (minutes)	0.13
Economic value	$560 M

Under this methodology, the benefits from the enabled traffic and from the delay reduction are additive because they apply to two distinct traffic measures. The enabled traffic benefits come from the increase of scheduled traffic, while the delay reduction come from the scheduled traffic under all weather conditions. The total AATT DSTs benefits, including the enabled traffic, are 0.56 + 1.32 = $1.88 billion. This figure does not, however, include the benefits of SMA, SMS, and EDP.

SMA, SMS, and EDP Benefits Results

Table 18-2 reported the delay savings and taxi-fuel savings estimated for SMA, SMS, and EDP for the 1997, unconstrained 2015, and constrained 2015 demands. Table 18-7 shows the economic benefits for these technologies based on the economic values of delay and taxi fuel published by the Federal Aviation Administration.[5]

Table 18-7. SMA, SMS, and EDP Annual Benefits

Scenario	Annual dollar savings in millions (2002 constant dollars)			Average time savings in minutes per departure	
	Delay (VOC)	Taxi fuel	Total	Delay (VOC)	Taxi fuel
1997 demand	$322	$29	$351	1.02	1.58
2015 unconstrained demand	$427	$37	$464	1.03	1.57
2015 constrained demand	$394	$35	$430	1.03	1.58

VOC = airline variable operating costs.

[5] FAA-APO-98-8, *Economic Values for Evaluation of FAA Investment and Regulatory Decisions*, June 1988. The latest version of this document with the 2002 values in the executive summary can be found on the Internet at http:\\www.apo.faa.gov\economic\execsumm.pdf.

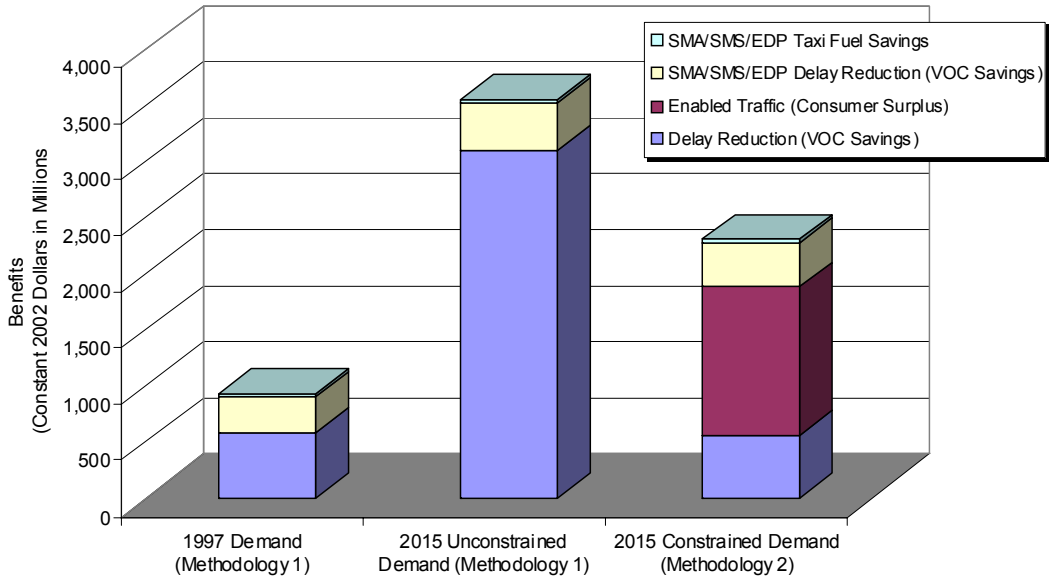
SUMMARY OF BENEFITS

Table 18-8 and Figure 18-1 show the combined benefits for all the modeled AATT DSTs for the three scenarios.

Table 18-8. AATT Benefits Summary

Scenario	Benefit ($millions, constant 2002 dollars)				
	Enabled traffic (consumer surplus)	Delay reduction (VOC savings)	SMA/SMS/EDP delay reduction (VOC savings)	SMA/SMS/EDP taxi fuel savings	Total benefit
1997 demand	N/A	557	322	29	928
2015 unconstrained demand	N/A	3,085	427	37	3,549
2015 constrained demand	1,319	560	394	35	2,308

Figure 18-1. AATT Benefits Summary



1997 UNCONSTRAINED DEMAND

If the AATT DSTs had been deployed across the NAS in 1997, they would not have induced more traffic, and therefore their benefit is measured only via the delay reduction stemming from higher NAS capacities. The annual benefit is estimated to be $929 million, in 2002 constant dollars.

2015 Unconstrained Demand

If it is assumed that all the forecast traffic will indeed be scheduled and flown through the NAS, the annual AATT benefit is estimated to be $3.55 billion in 2015 based on the delay reduction. The study authors do not believe the estimate based on this assumption is accurate, because the airlines would not tolerate a baseline schedule with unacceptable delays. These results are included because unconstrained growth is a widely used, albeit unrealistic, methodology.

2015 Constrained Demand

The constrained methodology assumes that the airlines will only operate with schedules whose integrity can be maintained during good weather operations. The AATT economic benefits are then assessed via both enabled traffic and delay reduction. Under this methodology, the enabled traffic benefits are estimated to be $1.32 billion, and the delay benefits to be $0.99 billion, in 2015. The total benefit is the sum of the two ($2.31 billion), because these benefits are believed to be additive.

Caveats

This analysis includes many necessary assumptions and generalizations. Three particular items, discussed below, should be considered when evaluating the results.

- LMINET can be run to analyze sector loading and terminal area congestion, but it does not track tail number itineraries. Thus, delays that disrupt schedules may have larger impacts than the basic delay reductions contained in this report, and thus their reduction would glean larger benefits. On the other hand, the model does not model airline responses to delay, such as rescheduling during bad weather events, that could reduce the total delay.

- The benefits for departure delay and taxi fuel reductions from SMA, SMS, and EDP are significant. Because the benefits reported in the integrated AATT assessment are based on the results of AATT benefit studies performed by other analysts, one should refer to those studies to evaluate foundations of the benefits.

- Lastly, estimated benefits are functions of model input data. The most important among them is the traffic forecast. Because of the nonlinear relationship between capacity and delay, a small change in predicted traffic demand can cause quite a large change in the benefits. In this study, the traffic in 2015 is based on the TAF released in March 2003.

Appendix A
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Appendix B
Abbreviations

AAR	Airport Acceptance Rate; average acceptance rate
AATT	Advanced Air Transportation Technologies
ABQ	Albuquerque International Sunport Airport
AC	air carrier
ADS-B	Automatic Dependent Surveillance Broadcast
ADW	Andrews Air Force Base
aFAST	Active Final Approach Spacing Tool
AIAA	American Institute of Aeronautics and Astronautics
ANC	Ted Stevens Anchorage International Airport
AOC	Airline Operations Center
APO	FAA Office of Aviation Policy and Procedures
APREQ	Approval Request
ARTCC	Air Route Traffic Control Center
ASP	Arrival Sequencing Program
ASPM	Aviation System Performance Metrics
ASQP	Airline Service Quality Performance
ASRC	ASRC Aerospace Corporation
AT	Arrival/Departure Trade-Off; air taxi/commuter
ATC	air traffic control
ATCSCC	Air Traffic Control System Command Center
ATCT	air traffic control tower
ATL	Hartsfield-Jackson Atlanta International Airport
ATM	air traffic management
ATMSDI	Air Traffic Management System Development and Integration
ATSP	air traffic service provider
BEP	breakeven point
BNA	Nashville International Airport
BOS	General Edward Lawrence Logan International Airport (Boston)

BTS	Bureau of Transportation Statistics
BWI	Baltimore-Washington International Airport
CAP	Collaborative Arrival Planner
CCLD	core capability limited deployment
CDTI	Cockpit Display of Traffic Information
CE	concept element
CLE	Cleveland-Hopkins International Airport
CLT	Charlotte/Douglas International Airport
CONUS	continental United States
CPTP	Conflict Prediction and Trial Planning
CSC	Computer Sciences Corporation
CT	Controller Tools
CTA	Controlled Time of Arrival
CTAS	Center-TRACON Automation System
CVG	Cincinnati/Northern Kentucky International Airport
D2	Direct-To
DAG-TM	Distributed Air/Ground Traffic Management
DCA	Ronald Reagan Washington National Airport
DEN	Denver International Airport
DFW	Dallas-Fort Worth International Airport
DOC	direct operating cost
DP	Departure Prediction
DST	decision support tool
DTW	Detroit Metropolitan Wayne County Airport
EDA	En Route Descent Advisor
EDCT	Expected Departure Clearance Time
EDP	Expedite Departure Path
EDX	En Route Data Exchange
EPNL	effective perceived noise level
ES	Efficient Spot
ESL	economic service life
ETA	estimated time of arrival

ETMS	Enhanced Traffic Management System
EWR	Newark Liberty International Airport
FAA	Federal Aviation Administration
FACET	Future Air Traffic Management Concepts Evaluation Tool
FAST	Final Approach Spacing Tool
FCA	Flow Constraint Area
FFP	Free Flight Phase
FLL	Fort Lauderdale/Hollywood International Airport
FMA	False Monitor Alert
FMS	Flight Management System
GA	general aviation
GDP	ground delay program
GPS	Global Positioning System
HAP	horizontal anchor point
HNL	Honolulu International Airport
HOU	William P. Hobby Airport (Houston TX)
HPN	Westchester County Airport (White Plains, NY)
IAD	Washington Dulles International Airport
IAH	George Bush Intercontinental Airport (Houston TX)
IDU	initial daily use
IFR	Instrument Flight Rules
IMC	instrument meteorological conditions
IND	Indianapolis International Airport
IPE	Integrated Predictive Error
JFK	John F. Kennedy International Airport (New York)
LAS	McCarran International Airport (Las Vegas)
LAX	Los Angeles International Airport
LCC	life-cycle cost
LCCBA	life-cycle cost/benefit assessment
LGA	LaGuardia Airport (New York)
MA	missed alert

MCI	Kansas City International Airport
MCO	Orlando International Airport
McTMA	Multi-Center Traffic Management Advisor
MDW	Chicago Midway International Airport
MEM	Memphis International Airport
MIA	Miami International Airport
MIT	miles in trail
MMA	Missed Monitor Alert
MSP	Minneapolis-St. Paul International/Wold-Chamberlain Airport
MVFR	Marginal Visual Flight Rules
N90	New York TRACON
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NPV	net present value
OAK	Metropolitan Oakland International Airport
OEP	FAA Operational Evolution Plan
OOOI	Out, Off, On and In
ORD	Chicago O'Hare International Airport
PAX	passenger
PBI	Palm Beach International Airport
PCA	planned capability available
PCT	Potomac TRACON
PDX	Portland International Airport
pFAST	Passive Final Approach Spacing Tool
PHL	Philadelphia International Airport
PHX	Phoenix Sky Harbor International Airport
PIT	Pittsburgh International Airport
PS	Pushback Scheduling
PV	present value
R&D	research and development
RA	Runway Allocation; Route Analyzer
RDU	Raleigh-Durham International Airport

RM	Regional Metering
RPM	revenue passenger mile
RTA	required time of arrival
RUC	Rapid Update Cycle
SAN	San Diego International Airport
SAT	San Antonio International Airport
SEA	Seattle-Tacoma International Airport
SFB	Orlando Sanford Airport
SFO	San Francisco International Airport
SJC	Norman Y. Mineta San Jose International Airport
SJU	Luis Munoz Marin International Airport (San Juan PR)
SLC	Salt Lake City International Airport
SMA	Surface Management Advisor
SMS	Surface Management System
SNA	John Wayne Airport-Orange County Airport (Santa Ana CA)
SRC	Systems Research Corporation
STAR	Standard Terminal Arrival Route
STL	Lambert-St. Louis International Airport
SWEPT	System-Wide Evaluation and Planning Tool
TAF	Terminal Area Forecast
TBM	time-based metering
TEB	Teterboro Airport (Teterboro NJ)
TFAS	Traffic Flow Automation System
TFM	traffic flow management
TIS-B	Traffic Information Service Broadcast
TM	traffic management
TMA	Traffic Management Advisor
TMA-MC	Multi-Center Traffic Management Advisor
TMA-SC	Single-Center Traffic Management Advisor
TMC	Traffic Management Coordinator
TMU	traffic management unit
TOD	top of descent

TPA	Tampa International Airport
TRACON	Terminal Radar Approach Control
TRL	Technology Readiness Level
TS	Trajectory Synthesis
TSAFE	Tactical Separation Assured Flight Environment
TUS	Tucson International Airport
URET	User Request Evaluation Tool
VAP	vertical anchor point
VFR	Visual Flight Rules
VMC	visual meteorological conditions
ZAB	Albuquerque ARTCC
ZAU	Chicago ARTCC
ZBW	Boston ARTCC
ZDC	Washington DC ARTCC
ZDV	Denver ARTCC
ZFW	Fort Worth ARTCC
ZHU	Houston ARTCC
ZID	Indianapolis ARTCC
ZJX	Jacksonville ARTCC
ZKC	Kansas City ARTCC
ZLA	Los Angeles ARTCC
ZLC	Salt Lake City ARTCC
ZMA	Miami ARTCC
ZME	Memphis ARTCC
ZMP	Minneapolis ARTCC
ZNY	New York ARTCC
ZOA	Oakland ARTCC
ZOB	Cleveland ARTCC
ZSE	Seattle ARTCC
ZTL	Atlanta ARTCC