CAPACITY-RELATED BENEFITS OF PROPOSED CNS/ATM TECHNOLOGIES

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Abstract

The US National Airspace System (NAS) consists of interrelated elements of communication, navigation, surveillance (CNS), and air traffic management (ATM). Numerous improvements to these elements are currently under consideration which will yield a variety of benefits. This paper focuses on the capacity-related benefits of operations in the extended terminal area, including both transition and terminal airspace. The key benefit mechanism impacting airport capacity is trajectory prediction accuracy used in ATM arrival scheduling and sequencing algorithms. Improved trajectory prediction accuracy will benefit airport operations because it enables: (1) improved airport throughput by reducing excess spacing between successive aircraft; and (2) a more cost-effective distribution of aircraft delay between Air Route Traffic Control Center (ARTCC) and Terminal Radar Approach Control (TRACON) airspaces. Using a previously-developed benefits analysis method, the paper estimates capacity-related time and fuel cost savings of 3 proposed phases of future CNS/ATM technologies, using the current operating system as the baseline for comparison.

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US Government research and technology development efforts are underway which will improve existing Communication, Navigation, and Surveillance (CNS) systems as well as implement advanced Air Traffic Management (ATM) decision support tools (DSTs) in the National Airspace System (NAS).[1-2] A key requirement in the implementation of such technologies is a careful analysis of expected benefits, weighed against system costs. This paper assesses the airport capacity-related benefits of a subset of the CNS/ATM technologies currently proposed for the NAS. The focus is on ATM systems and user-ATM data exchange.

Initially, in Section 1, three scenarios of future CNS/ATM technology deployment in the NAS are proposed. These evolutionary phases reflect future implementation of current or under-development programs. Section 2 discusses the specific capacity-related benefit mechanisms under study in the context of other potential benefits. The analysis methodology is summarized briefly in Section 3. The model inputs and resulting benefit estimates appear in Section 4. Section 5 offers conclusions and remarks.

1. Assumed Technology Scenarios

A three phase evolution of CNS/ATM technology enhancements are proposed in Table 1. These phases represent steps toward implementation of proposed technologies.[3-6] In this study, benefits will be calculated by comparing these scenarios to a baseline of current system operations.

The three phases include deployment of proposed ATM DSTs, widespread use of FMS flight control and Required Time of Arrival (RTA) capability in the terminal area, use of current data link to exchange non-time critical data and future data link to negotiate user preferred trajectories (UPT) to meet ATM DST-calculated RTAs.

Table 1 Evolutionary CNS/ATM Scenarios

	CNS/ATM Technologies				
Scenario	ATM DST	Comm.	Nav.	Surv.	CDM
Current System	None	voice	Non-FMS	radar	None
Phase 1	TMA PFAST	voice	Non-FMS	radar	None
Phase 2	EDA AFAST	ACARS	FMS (LNAV/ VNAV)	radar	Basic DX
Phase 3		ATN	RTA	ADS-B	UPT DX

Specifically, the technologies assumed in the three proposed CNS/ATM phases are discussed below:

Phase 1 focuses on near-term deployment of the Center-TRACON Automation System (CTAS) Build 2. This includes the Passive Final Approach Spacing Tool (P-FAST) in the TRACON and the Traffic Management Advisor (TMA) in the ARTCC transition airspace. These tools assist controllers in the sequencing and scheduling of arrival traffic into congested airports, both at arrival fixes and landing runways. Prototypes of both tools are operational at Dallas-Ft. Worth.

Phase 2 enhances the Phase 1 ATM DSTs with Active-FAST (A-FAST) in the TRACON and En Route Descent Advisor (EDA) in the ARTCC transition airspace. Beyond Phase 1 DSTs, these tools provide controllers with maneuver advisories to meet the CTAS sequences and schedules. These tools are currently under development at NASA Ames. Phase 2 also assumes the widespread use of aircraft FMS flight control, including lateral and vertical navigation (LNAV/VNAV), in the extended terminal airspace, reducing flight variability. Basic user-CTAS data exchange is also assumed. This includes the passive exchange of calibration data, including aircraft weight, planned threshold crossing speed, and wind/temperature measurements/forecasts. The exchange of these data will improve the airborne and ground trajectory prediction models.

Phase 3 is a far term vision of a four-dimensional user-ATM arrival trajectory negotiation in the extended terminal area. This requires a far term data link such as the proposed Aeronautical Telecommunications Network (ATN) to host the exchange of time-critical ATM clearance and route negotiation. Additionally, the aircraft must be equipped with RTA capabilities and traffic avoidance equipment such as Broadcast Automatic Dependent Surveillance (ADS-B).

The study was limited to the ATM/CNS improvements shown in Table 1 as these tools will have a significant impact on capacity-related benefits of terminal operations. It is recognized, however, that there are numerous additional ATM DSTs (e.g., Surface Management Advisor, and Initial Conflict Probe), Collaborative decision making (CDM) tools (e.g., Flight System Monitor), and aircraft avionics (e.g., Global Positioning Systems) under study that could also be included in such an analysis. In fact, the included ATM/CNS improvements may have additional benefits, not herewith addressed. As such, this study is a first-cut estimate at a much larger realm of possible ATM/CNS benefits. The larger world of benefits is discussed in Section 2.

2. Capacity-Related Benefits Defined

Implementation of future CNS/ATM technologies in the NAS may allow a number of benefits to accrue to various NAS stakeholders in multiple domains, as identified in Table 2.

Table 2 Possible ATM/CNS Benefits

Benefit Type	Stakeholder	Domain/Airspace
Delay	Users/Airlines	Terminal
Flight Efficiency	ATM Service Provider (FAA)	Transition
Productivity	Flying Public	En Route
Safety		Oceanic
ATM interruptions		Airport Surface

As discussed in Section 1, this study is limited to capacity-related benefits of the terminal/transition airspace, accrued to users in the form of reduced delay and flight efficiencies, measured in direct operating costs of time and fuel. In the remainder of this section, these two benefit mechanisms are discussed in more detail.

Increased Airport Throughput

Airport throughput is a function of the spacing achieved between successive aircraft at the runway threshold. Actual spacings, as implemented by air traffic controllers, are generally larger than the minimum separation requirements.[7] Observations indicate that the extra spaces can be assumed to be intentional spacing buffers which serve in part to assure that separation minima are not violated because of trajectory uncertainties. Excess spacing is also generated by uncertainty in the delivery of arrival aircraft at the inbound metering fixes. Deviations from the ATM metering fix crossing schedule, due to timing delivery inaccuracies, require subsequent trajectory adjustments by downstream ATM to prevent violations of separation minima and eliminate extraneous gaps at downstream merge points and the runway threshold. With reductions in predicted trajectory uncertainty under proposed future technologies, the size of the excess spacing buffer needed to compensate for trajectory variances can be reduced. A smaller buffer would reduce the spacing applied between successive aircraft, thereby increasing the throughput of the runway system. The increased throughput would reduce aircraft delays and associated user fuel and time direct operating costs.

ARTCC/TRACON Delay Distribution Fuel Savings

In the terminal area, a delay distribution function, formalized in future ATM automation, is employed to allocate aircraft delay between ARTCC and TRACON airspace during busy traffic periods. The allocation process works to achieve an optimum balance between fuel burn savings and runway system throughput. The delay distribution function performs a trade-off between the advantage of absorbing delay at the higher en route altitudes, where fuel efficiency is greater, versus the advantage of packing more aircraft in the terminal airspace to ensure that aircraft are continually available to use the runway system. As trajectory prediction and control accuracy is improved with improved trajectory prediction under proposed technologies, less delay is needed to be absorbed in the TRACON airspace to maintain high runway system throughput. This provides savings as a result of more fuel-efficient arrival trajectories. Whereas excess spacing buffers determine the runway system throughput and the associated total amount of delay, delay distribution determines where and how efficiently delay is to be absorbed.

3. Analysis Methodology Overview

One way to significantly increase airport throughput is through the optimal scheduling and sequencing of aircraft trajectories in congested terminal airspace.[8] Such algorithms are dependent upon accurate predictions of when aircraft will cross downstream waypoints. Thus, a key requirement of advanced terminal area ATM DSTs, is a highly accurate prediction of trajectory waypoint crossing times. Other analyses which focus on the benefits of a conflict detection and resolution tool, would find trajectory prediction *position* accuracy of paramount interest, providing reliable future aircraft locations to a conflict probe tool.

Trajectory prediction accuracy can be improved through high fidelity trajectory modeling of flight trajectories in the terminal airspace, as found in the proposed ATM DSTs and aircraft FMSs. Additionally, both the air and ground trajectory models can be improved with the use of more accurate model inputs, such as aircraft weight estimates and wind/temperature forecasts obtained through data exchange. Future avionics may also improve aircraft surveillance and intent information through ADS-B reporting. In the far term, arrival trajectory negotiation using FMS RTA capabilities should allow for highly accurate trajectory prediction and control accuracies. This study analyzes trajectory prediction timing accuracy and its various improvements with future CNS/ATM technologies, and its effects on capacity-related benefit metrics.

Figure 1 shows the overall analysis process used in this study. This analysis process has been used in numerous research efforts [9-12] and is only briefly detailed in the remainder of this section. The analysis process is initiated by identifying the various candidate technologies, and their capabilities., as was done in Section 1. Each technology is then described in terms of parameters that relate to operational factors that affect aircraft trajectories. Figure 1 lists key parameters impacted by CNS/ATM technologies. These parameters are defined by a stochastic distribution which quantitatively describes the accuracy of each parameter for baseline and proposed CNS/ATM scenarios.

The modeling process encompasses three sub-components. Initially, the accuracy with which trajectories can be predicted and controlled is modeled using computer simulation, close-form analytical solutions, and a combination of the two, as appropriate for each phase of flight. The parameter accuracy distributions are inputs to this trajectory modeling process. The outputs include excess spacing buffers applicable to runway system operations and incremental fuel cost due to ARTCC/TRACON delay distribution. Recent CTAS prototype field test observations were used to calibrate the various parameter accuracy distributions in this model.[13-14]

A second computer simulation is used to evaluate airport throughput and determine traffic delay using the threshold excess spacing buffer data and minimum separation requirements as input. The model incorporates data describing daily flight schedules of commercial, general aviation and military aircraft and detailed configurations of the major domestic airports for instrument flight rules (IFR) and visual flight rules (VFR). Modeling parameters describing separation procedures for the IFR and VFR runway configurations at each airport are adjusted to reflect the operating environment of the various scenarios under study. The model produces average daily traffic delay data by arrival and departure operations and instrument and visual meteorological conditions for each airport under study.

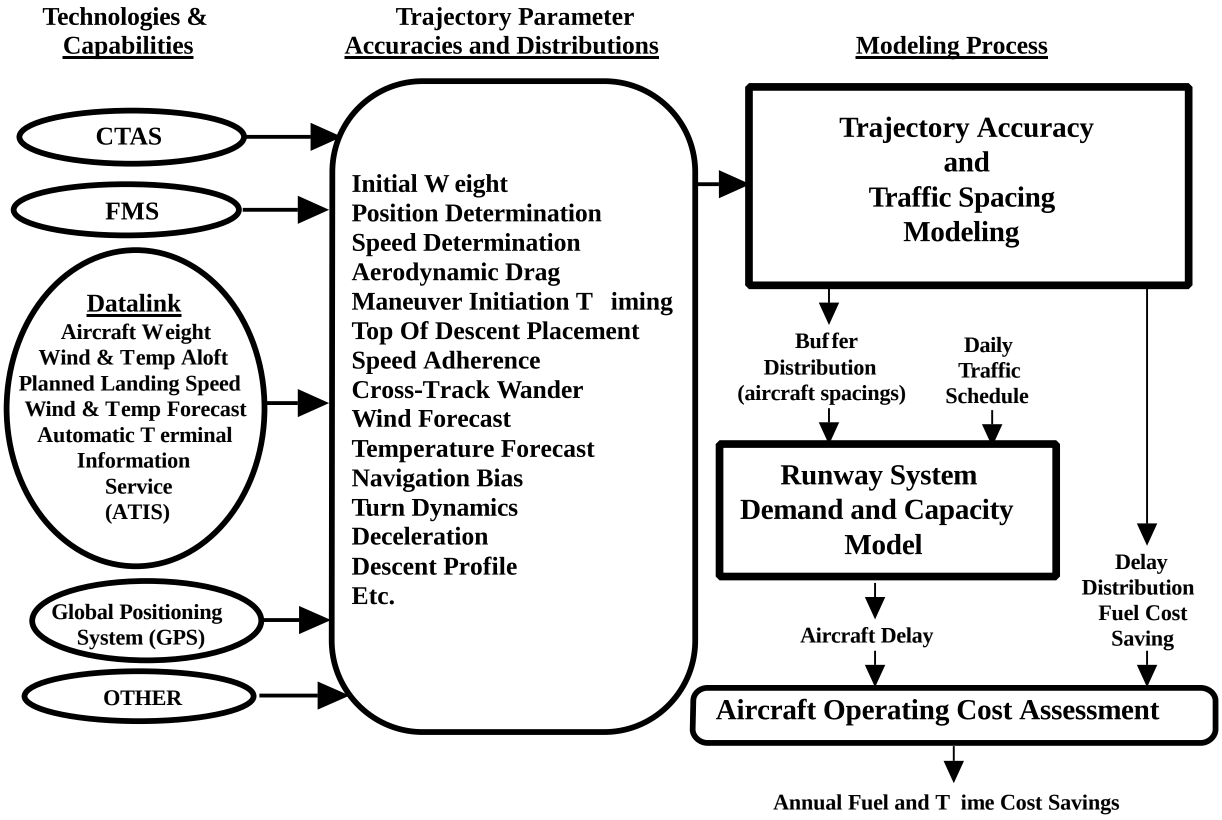

Figure 1 Analysis Process [10-12]

The daily traffic delay data are then extrapolated to annual cost savings by airport using detailed aircraft direct operating cost rates, annual airport traffic forecasts and meteorological factors. The aircraft direct operating costs used, represent fuel, crew and maintenance costs.

The three models are described further in the remainder of this section. For more information, the reader is directed to References 9-12. The chosen model parameter values and resulting benefits are identified in Section 4.

Trajectory Accuracy and Traffic Spacing Model

The interarrival aircraft spacing achieved at the landing runways is the critical metric in analyzing airport arrival throughput. This metric is the output of the Trajectory Accuracy and Traffic Spacing Model of Figure 1. The achieved interarrival spacings consists of the ATM minimum separation requirement,[15] and a buffer imposed by controllers to ensure that these minimums are not violated given the uncertainty associated with an aircraft's predicted trajectory.

Additionally, delivery inaccuracies in aircraft crossings at the metering fixes or TRACON entry point, can contribute to reduced throughput. This results because aircraft may not be in place to fill landing slots, causing gaps in the arrival stream which reduce overall arrival landing throughput. Although these gaps would likely have a duration of several seconds and occur infrequently, their impact can be approximated by averaging the gaps over all interarrival separations. Likewise, suboptimal runway balancing and sequencing would lead to extraneous gaps in runway utilization that can also be approximated in this way. These threshold spacing components: the required minimum separation; controllers' position uncertainty buffer; and buffer due to extraneous gaps; are shown in Figure 2.

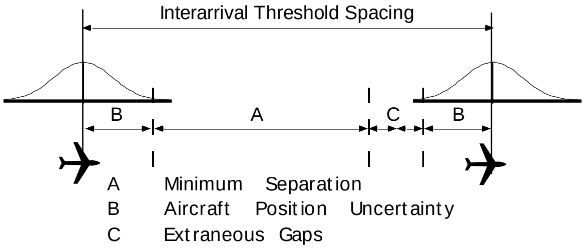

Figure 2 Threshold Interarrival Separation

The Trajectory Accuracy and Traffic Spacing Model calculation of position uncertainty uses fast-time Monte Carlo simulations of nominal arrival trajectories, as shown in Figure 3.

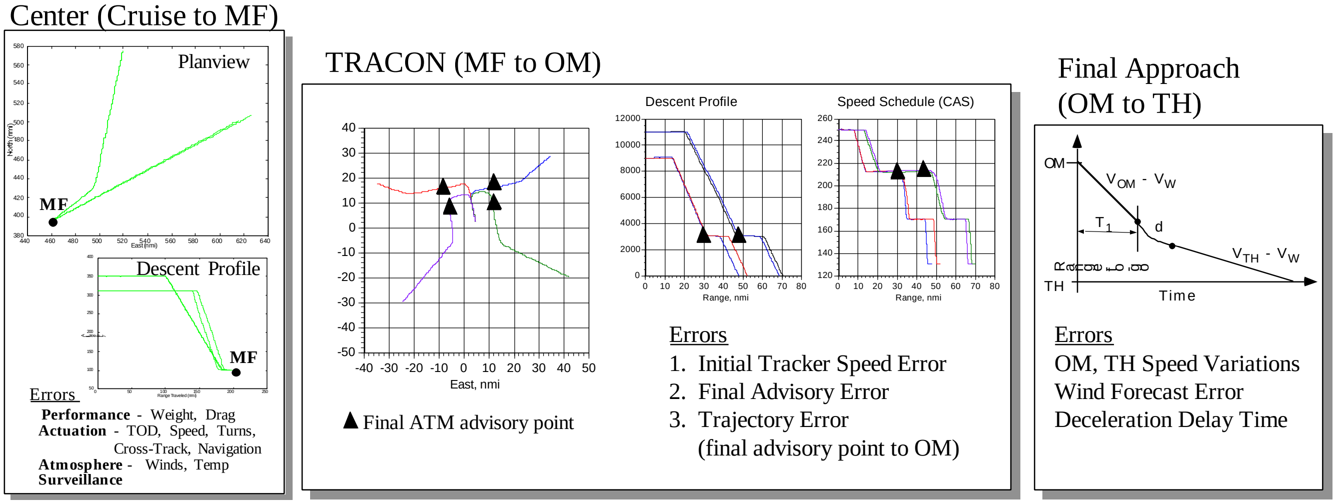

Figure 3 Position Uncertainty Trajectory Simulation

The model simulates the accumulation of an arrival aircraft's position uncertainty from Cruise to the runway threshold. On final approach, the model ensures that aircraft pairs do not violate minimum separation criteria as they decelerate to their final landing speeds and touchdown.

The calculation of threshold buffers due to extraneous gaps utilizes an analytical model of Center/ARTCC contributions to threshold buffer [16] as well as estimates of runway balancing and sequencing impacts from NASA Ames simulations, [8] confirmed by field test results. [13-14]

The Center model derives the optimal relationship between a TRACON Delay Setting and extraneous gaps at the runway threshold. It is based on the premise that scheduling some delay in the TRACON allows TRACON controllers more flexibility to absorb metering fix crossing variability allowing them to maximize airport throughput. However, delay absorbed in the TRACON requires more fuel than if absorbed in the higher elevation ARTCC. Thus fuel efficiency is improved with less TRACON delay, i.e., at lower TRACON Delay Settings. As a result of this trade-off, an optimum TRACON Delay Setting can be derived, one that minimizes the combined cost of lost throughput and fuelburn.

These relationships are plotted in Figure 4. The figure parametrically relates metering fix delivery accuracy to the optimal TRACON Delay Setting and the corresponding extraneous gaps threshold buffer and delay distribution incremental fuel costs. Although the threshold extraneous gap buffer is on the order of a few seconds, the delay actually incurred by an aircraft at the end of the rush could accumulate to 20 to 50 times this value depending on the rush size. As the optimal lines in the figures show, improved metering fix accuracy (moving in the direction of the arrow) would result in a reduction in optimal TRACON Delay Setting with corresponding delay and fuel efficiency savings.

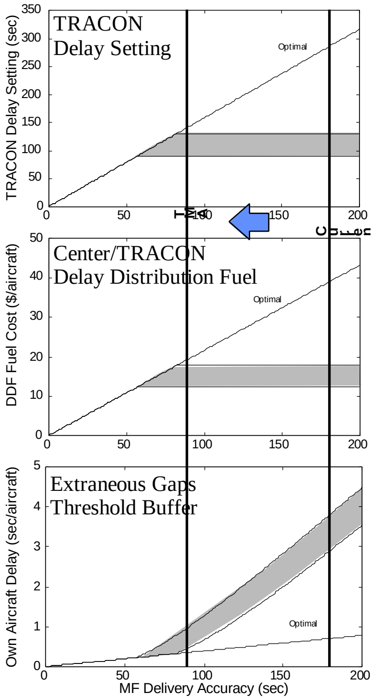

Figure 4 Center Model

Based on previous studies of TRACON flight track data,[17-18] However TRACON airspace can typically absorb only 100 to 200 seconds of delay on average beyond the fastest feasible path to the runway. This is reflective of the airspace geometry and complexity of TRACON air traffic control operations. In this study, we restrict the TRACON delay setting to 100 second. As a result, the buffer and fuel costs change considerably, as shown by the bottom edge of the shaded region in Figure 4. These relationships are used to determine the best TRACON Delay Setting for each modeled CNS/ATM scenario, as well as the corresponding extraneous gap threshold buffer and delay distribution incremental fuel cost.

Runway System Demand and Capacity Model

Once the interarrival separations (rule and buffer) are determined for each scenario from the Trajectory Accuracy and Traffic Spacing Model, they are used in simulations of a full day's traffic at candidate airports. The model generates scheduled takeoff/landing times and any associated delays, by simulating the interactions of traffic demand, the runway use configuration assumed at the airport, and the appropriate aircraft separation procedures for instrument and visual flight rules (IFR and VFR). Figure 5 shows the IFR configuration modeled at DFW and lists appropriate separations required to cover the various DFW operations.

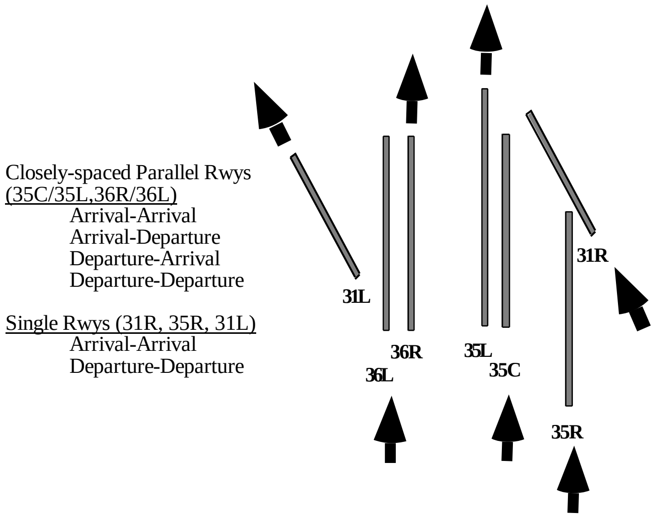

Figure 5 IFR Runway Configuration, DFW

Each simulation run depicts a typical day at the subject airport, imposing VMC conditions for the bulk of the day, with IMC conditions for a 5 hour AM period. The results of each run are used to calculate an average VMC and IMC delay per operation. These average delays take into account the impact of historical IMC persistence on delay severity.[19] Persistence in this case refers to the time duration of continuous IMC. Thus, locations with only intermittent IMC would expect lower delays, because periods of VMC would be able to clear delays accumulated from prior IMC periods. Figure 6 shows sample scheduled operations, realized throughput, and delay results from DFW airport simulation. As noted, significant delays are accrued during the shaded AM IMC period, but dissipate soon after VMC conditions resume.

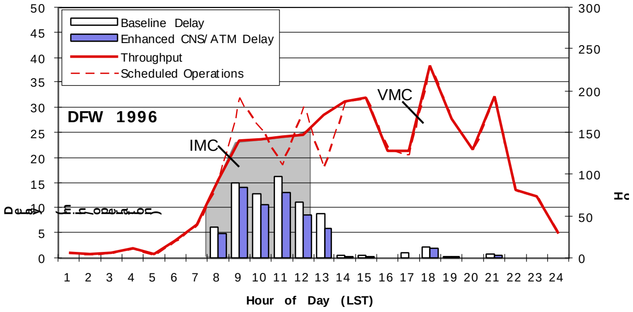

Figure 6 DFW Simulated Throughput & Delay

Aircraft Operating Cost Assessment

The resulting IMC and VMC average delays for each CNS/ATM scenario at each airport are recorded and compared. Equation (1) gives the general formula used to convert these delays into airport cost savings. This equation is evaluated for four operation types: IFR and VFR arrivals and departures.

In the first term of Eq. (1), the delays are used to determine average aircraft delay savings expected from the CNS/ATM enhancements. Average per aircraft delay cost savings are then identified for each scenario by application of aircraft direct operating cost rates (second term in Eq. (1)) to the estimated minutes of aircraft delay savings. These savings estimates account for operating cost differences among aircraft classes, based on the traffic mix at each airport. Finally, these data are extrapolated, using airport-specific annual traffic forecasts and historic meteorological data (third term in Eq. (1)), to estimate the corresponding annual cost savings.

$$\begin{array}{c}\text{Annual Delay}\\\text{Cost Savings}\\\text{(\$/year)}\end{array} = \begin{array}{c}(\text{Delay}_{BL}\ -\\\text{Delay}_{CNS/ATM})\\\text{(minutes/operation)}\end{array} \times \begin{array}{c}\text{Aircraft Cost}\\\text{Rate}\\\text{(\$/minute)}\end{array} \times \begin{array}{c}\text{Airport Annual}\\\text{Traffic Forecast}\\\text{(operations/year)}\end{array} \qquad (1)$$

4. Model Assumptions and Results

Using the models discussed in Section 3, we are able to evaluate the capacity-related benefits of the three evolutionary CNS/ATM phases, described in Section 1 at 11 candidate airports. This section details both the specific parameter values assumed in the modeling the various scenarios as well as the resulting delay and fuel efficiency benefits.

The Trajectory Accuracy and Traffic Spacing Model uses as input, estimates of parameter accuracies, that affect arrival aircraft trajectories. These parameter errors are chosen to reflect the operational environment of the current system and CNS/ATM phases described in Section 1. The choice of these parameter values requires the reconciliation of manufacturer and/or research-based accuracies with actual field performance. Assumptions for future technologies must also assume important operational issues will be addressed to not limit implementation locations. Fortunately, recent 1996 prototype field test results of the CTAS Build 2 baseline ATM DSTs at Dallas-Ft. Worth (DFW) [13-14] provides realistic understanding of the Current System and Phase 1 operations. Future Phases must rely more heavily on manufacturers claims and simulation studies.

The parameter error estimates used to represent the three CNS/ATM technology scenarios are detailed in Table 3, along with the resulting metering fix crossing accuracies, threshold spacing buffers, and Center/TRACON delay distribution fuel costs, expected under each scenario.

Table 3 Assumed Center Trajectory Parameter Accuracies

			Standard Deviation			
		Mean	Current Sys	CNS/ATM Evolution		
Trajectory Error Parameter	Units	Value	Baseline	Phase 1	Phase 2	Phase 3
CENTER						
Initial Weight	%	0	---	10	2.5	2.5
Aerodynamic Drag	%	0	---	7	7	7
Top of Descent (TOD) Placement	nmi	0	---	16	0.5	NA
Speed Adherence	knots (kt)	0	---	20	4	4
Cross-Track Wander	nmi	0	---	5	0.25	0.25
Aircraft Navigation Bias	degrees	0	---	2	2	2
Turn Dynamics	sec	0	---	15	1	1
Wind Forecast	kt	0	---	20	4	4
Temperature Forecast	°C	0	---	10	1	1
Surveillance	kt	0	---	15	15	NA
RTA Open Loop	%	NA	NA	NA	NA	33
RTA Setting	sec	NA	NA	NA	NA	6
TRACON						
Final advisory delay (1)	sec	0	12.12	10.80/9.75	9.4/8.49	NA
Turn variation	sec	35	7.0	7.0	1.0	1.0
Deceleration variation	%	0.52	0.120	0.120	0.108	0.108
Descent rate variation	ft/min	1440	160	160	144	144
Speed adherence	kt	0	4.0	4.0	1.2	1.2
Wind forecast accuracy	kt	0	4.7	4.7	4.0	4.0
Tracker speed accuracy	kt	0	3.5	3.5	3.5	NA
RTA Open Loop	%	NA	NA	NA	NA	16.45
RTA Setting	sec	NA	NA	NA	NA	6
Rwy Balancing/Sequencing (1)	sec	2.3	No	No/Yes	No/Yes	No/Yes
FINAL APPROACH						
Outer Marker Speed	kt	170	5.0	5.0	1.8	1.2
Threshold Speed (2)	kt	120-135	9	9	4	1.2
Deceleration Delay Time	sec	10	12	12	12	NA
Wind Forecast Error	kt	10	10	4.7	4.0	4.0
MF Crossing Accuracy (4)	sec	0	180	90	14	5
Expected Buffer (5) (6)	sec	0	31.44	26.62/23.54	18.91/15.78	7.23/4.93
Incremental Fuel Cost	$/arrival (7)	0	13.67	13.67	3.02	1.08

(1) Parameter varies by number of arrival runways, 1-2/3+ runway values shown. Applied per runway usage at each airport
(2) Speed varies by aircraft size classification, 120, 125, and 135 for small, large, and heavy aircraft, respectively
(3) Not applicable under RTA operations.
(4) Current System and Phase 1 metering fix crossing accuracy observed in TMA prototype field tests. [14]
(5) Average excess spacing buffer value, weighted by airport's aircraft class distribution.
(6) Current System and Phase 1 buffers calibrated from P-FAST prototype field test results [13]
(7) Delay Distribution Fuel Cost Savings applies only to rush period arrivals.
Note: Shading indicates improvements from prior scenario

Table 4 Average Delay Savings

Average Delay Savings (minutes)

	Phase 1				Phase 2				Phase 3			
	IFR		VFR		IFR		VFR		IFR		VFR	
Airport	Dep	Arr	Dep	Arr	Dep	Arr	Dep	Arr	Dep	Arr	Dep	Arr
ATL	1.07	0.94	0.00	1.74	2.78	2.44	0.00	4.51	2.18	2.10	0.15	7.83
BOS	1.89	1.54	1.96	1.83	4.87	3.96	5.06	4.72	8.68	6.95	13.01	12.34
DFW	0.96	1.23	0.00	0.28	1.79	2.32	0.00	0.47	2.67	3.54	0.00	0.53
DEN	0.23	0.50	0.05	0.12	0.50	1.02	0.08	0.21	0.97	1.82	0.11	0.31
DTW	0.26	0.71	0.11	0.71	0.68	1.82	0.28	1.82	1.18	3.41	0.44	3.24
EWR	1.28	1.46	0.12	0.18	3.32	3.78	0.24	0.35	6.79	7.39	0.46	0.56
JFK	0.01	0.08	0.22	0.27	0.01	0.22	0.56	0.69	0.01	0.31	0.97	1.13
LAX	1.55	1.48	0.00	5.80	4.00	3.82	0.00	10.19	7.27	7.57	0.00	12.25
LGA	0.87	1.00	7.95	7.96	2.27	2.59	20.64	20.66	4.64	5.73	30.79	30.68
ORD	0.00	0.00	2.08	3.11	0.00	0.00	3.73	5.59	2.64	3.22	5.05	7.66
SFO	0.78	0.65	1.30	1.21	2.01	1.66	3.35	3.11	4.81	4.57	8.28	8.52

Table 3 parameters reflect Phase 1 improvements due to high-fidelity modeling of TMA and P-FAST over cognitive sequencing and scheduling algorithms of the current system. Phase 2 reduces actuation errors with CTAS-calculated maneuver advisories of EDA and A-FAST, increases maneuver adherence with FMS flight control, and improves aircraft weight and meteorological forecasts through user-CTAS data exchange. Phase 3 reduces mismatches in CTAS-FMS trajectory prediction by allowing an aircraft to fly its preferred trajectory to meet the CTAS-calculated RTA at a very high accuracy.

The results at the bottom of Table 3, show significant reduction in metering fix delivery error, expected threshold buffer, and Center/TRACON delay distribution incremental fuel costs. Interestingly, Phase 1 and 2 reap almost all of the metering fix delivery improvement and corresponding fuel savings, while 45 percent of the threshold buffer savings comes in Phase 3.

The expected buffer results of Table 3 were then used in the Runway System Demand and Capacity model to determine the average delays for arrivals and departures under IMC and VMC conditions. The resulting delays for the three CNS/ATM enhancement phases are shown in Table 4. Typically, larger savings are expected for arrival savings, as the ATM DSTs under study alter primarily arrival sequencing and scheduling. However, as controllers try to keep arrival and departure delays in balance, all operations benefit. because the demand at LaGuardia (LGA) is much larger than its capacity, it incurs the largest delay savings. Because current conditions do not allowing the airport to dissipate the growing delays throughout the day, any improvement in capacity will reduce delays on almost every operation at LGA. Other airports show similar trends.

These delay savings are then used to assess annual aircraft operating cost savings, incorporating the cost rates and annualization factors shown in Table 5. Table 6 details the resulting delay cost savings.

Table 5 Cost Rates and Annualization Factors [20-23]

Airport	Annual IMC Occurrence 7AM-10PM	1996 Annual Ops (000s)	Average Operating Cost ($/min) Departures	Arrivals
ATL	14.2%	855	15.58	22.41
BOS	15.6%	480	11.34	15.92
DFW	8.4%	892	13.30	18.93
DEN	6.0%	499	13.50	19.25
DTW	16.6%	511	13.92	19.82
EWR	16.6%	446	14.12	20.18
JFK	15.0%	348	19.84	28.96
LAX	22.2%	747	15.17	21.82
LGA	16.4%	350	13.05	18.59
ORD	16.1%	914	15.24	21.92
SFO	12.5%	451	15.58	22.47

Note: Analysis also assumes 50% of airport traffic is arrivals

Table 6 Annual Delay Cost Savings

Annual Operating Cost Savings (1998 $ million)

Airport	Phase 1	Phase 2	Phase 3
ATL	16.66	43.25	70.45
BOS	12.21	31.51	78.08
DFW	3.54	6.19	7.99
DEN	0.86	1.63	2.48
DTW	4.08	10.53	18.68
EWR	2.77	6.59	12.55
JFK	1.88	4.82	8.00
LAX	41.35	76.50	100.55
LGA	38.22	99.14	149.02
ORD	38.78	69.66	103.28
SFO	10.23	26.40	69.14

Center/TRACON delay distribution fuel savings use the incremental fuel cost values at the bottom of Table 3 and apply these savings to all peak period rush arrivals. Peak period arrivals account for 30 percent of all operations at DFW. This percentage was assumed to represent rush arrivals at the other large and medium hub airports, under study. As a result, the largest delay distribution fuel savings occur at airports with the highest number of annual operations.

Table 6 Annual Delay Distribution Fuel Savings

Annual Operating Cost Savings (1998 $ million)

Airport	Phase 1	Phase 2	Phase 3
ATL	0	2.40	2.84
BOS	0	1.63	1.93
DFW	0	2.86	3.38
DEN	0	1.64	1.93
DTW	0	1.64	1.94
EWR	0	1.46	1.72
JFK	0	1.15	1.36
LAX	0	2.32	2.74
LGA	0	1.12	1.32
ORD	0	2.86	3.38
SFO	0	1.47	1.73

The combined delay and Center/TRACON delay distribution fuel cost savings are shown in Table 8 and graphically depicted in Figure 7. As these cost components represent two different, but operationally distinct, impacts of CNS/ATM improvements, they were summed. However, the two components were evaluated using different methods (i.e., simulations versus analytical models) and ideally a common methodology would be employed to assure that benefits evaluations are compatible with each other.

Table 8 Total Cost Savings

Annual Operating Cost Savings (1998 $ million)

Airport	Phase 1	Phase 2	Phase 3
ATL	16.66	45.98	73.68
BOS	12.21	33.05	79.90
DFW	3.54	9.04	11.36
DEN	0.86	3.22	4.37
DTW	4.08	12.16	20.61
EWR	2.77	8.01	14.23
JFK	1.88	5.93	9.31
LAX	41.35	78.88	103.37
LGA	38.22	100.26	150.34
ORD	38.78	72.58	106.73
SFO	10.23	27.84	70.85

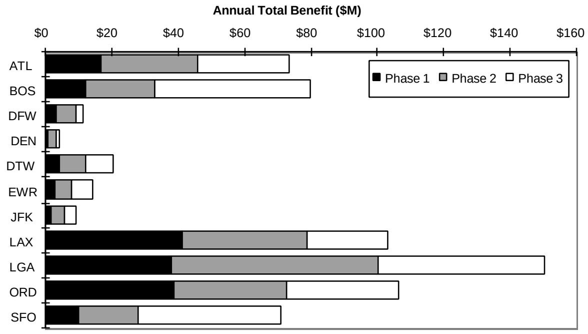

Figure 7 Total Annual Cost Savings

5. Conclusions

This report assess the capacity-related benefits of proposed CNS/ATM enhancements at 11 major US airports. These enhancements were broken into three evolutionary phases of NAS improvements to current system operations:

Phase 1 - CTAS TMA and P-FAST ATM DSTs are deployed to improve arrival trajectory scheduling and sequencing.

Phase 2 - CTAS EDA and A-FAST ATM DSTs are deployed, providing controllers CTAS-calculated maneuver advisories to meet Phase 1 schedules. Additionally, FMS flight control is employed in the terminal area and user-CTAS exchange of basic calibration data is exercised for use in air and ground trajectory prediction calculations.

Phase 3 - User-CTAS negotiation of 4D arrival trajectories to meet CTAS-calculated RTAs becomes operational. This requires ATN data link and ADS-B surveillance technologies.

The study assessed capacity-related benefits for these scenarios, including: (1) reduced delay due to increases in runway system throughput; and (2) increased fuel efficiency with improved distribution of delay between Center and TRACON flight segments. These are two of many potential benefits achievable with these proposed CNS/ATM technologies. The discussed methodology should be extended to cover other potential benefits mechanisms for a more complete benefits picture of these technologies.

The resulting capacity-related benefits of the proposed CNS/ATM enhancements are significant, and vary considerably by airport. The estimated 1996 operating cost savings associated with runway throughput and delay benefits were found to range from $1-38, $2-99, and $3-149 million annually at the 11 airports in Phases 1, 2, and 3, respectively.

Better distribution of delay between Center and TRACON airspace resulted in no fuel savings in Phase 1, due to the limitation that each airport can only absorb a maximum of 100 seconds of delay in the TRACON. In phases 2 and 3, when this restriction is non-binding, the savings range from $1-3 million annually per airport.

When the two capacity-related benefits are combined, the benefits range from $1-41, $3-100, and $4-150 million annually in Phases 1, 2, and 3, respectively. Total benefits at all 11 airports is estimated at $170, $397, and $575 million annually in each Phase, with over 90 percent resulting from delay savings. The benefits were relatively equal between phases, although Phase 2 had the highest incremental benefit.

The largest overall savings occurred at severely capacity-constrained airports including NY LaGuardia (LGA), Chicago O'Hare (ORD) and Los Angeles International (LAX) airports. These are closely followed by Boston Logan (BOS), Atlanta Hartsfield (ATL), and San Francisco (SFO). As the current capacity restrictions at the remaining airports are lower they are predicted to have fewer capacity-related benefits.

This paper has demonstrated a methodology to quantify specific benefits of proposed CNS/ATM technologies. Combined with costs, such analyses are a necessary step in evaluating the overall economic value of these proposed technologies. Such studies can be useful at several stages of NAS development: to optimally direct scarce research moneys, assist in deployment decisions, and evaluate in-field tool performance.

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