Preliminary Assessment of Future Operational Concepts Using the Airspace Concept Evaluation System

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The Airspace Concept Evaluation System (ACES) is a non-real-time, computer simulation of local, regional and nationwide factors covering aircraft operations from gate departure to arrival. ACES' overarching objective is to provide a flexible National Airspace System (NAS) simulation and modeling environment that can assess the impact of new NAS tools, concepts, and architectures, including those that represent a significant departure from the existing NAS operational paradigm. The first release of ACES was completed in March 2003 and in May 2003 ACES' potential as an analysis tool was evaluated by using it to assess three future NAS operational concepts: the Advanced Airspace Concept for improved en-route airspace capacity and two notional concepts for improved terminal area capacity. This paper presents an overview of that assessment exercise and shows that ACES has great potential as an analysis tool for the evaluation of future NAS operational concepts.

I. Introduction

THE National Aeronautics and Space Administration (NASA) has established the Virtual Airspace Modeling and Simulation (VAMS) Project to examine proposed operational concepts for increasing the capacity of the National Airspace System (NAS). As part of this effort, VAMS is developing the Airspace Concept Evaluation System (ACES) to simulate NAS operations. ACES is a non-real-time, computer simulation of local, regional, and nationwide factors covering aircraft operations from gate departure to arrival. ACES' overarching objective is to provide a flexible NAS simulation and modeling environment that can assess the impact of new NAS tools, concepts, and architectures, including those that represent a significant departure from the existing NAS operational paradigm. To meet this objective, ACES utilizes the High Level Architecture (HLA) and an agent-based modeling paradigm to create the large scale, distributed simulation framework necessary to support NAS-wide simulations.[1,2]

ACES development follows a periodic build cycle. Each major build adds models or increases model fidelity, provides bug fixes, and improves usability and performance. The first build, Build 1, was delivered to NASA in March 2003. Build 2 was delivered in October 2003 and Build 3 was delivered in July 2004. ACES Build 1 had models for Air Traffic Management (ATM) encompassing Air Traffic Control (ATC) and Traffic Flow Management (TFM) operations, aircraft dynamics, and en route winds. The modeling accounted for airspace and airport designs and procedures, including airport visual flight rules (VFR) and instrument flight rules (IFR). Agents represented NAS operations and included strategic traffic management, regional traffic management, approach and departure control, surface control, and aircraft entities.

In May 2003, NASA Headquarters asked the VAMS Project to provide a preliminary, high-level assessment of the NAS-wide impacts of at least two future operational concepts using ACES. This principle goal of this exercise was to evaluate ACES as an assessment tool for future NAS operational concepts. At that time, given the level of fidelity of both ACES and the VAMS' operational concepts, it was unreasonable to expect that the assessment

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would give absolute results, but relative trends were a reasonable expectation. A secondary benefit of the assessment exercise was the additional experience the NASA analysts would gain in running ACES.

The first official release of ACES, Build 1.1, was delivered to NASA Ames by its contractors in March 2003. Although this initial release was operational, numerous code improvements were already underway for the Build 1.2 release that would be of significant value in performing the concept assessments. Therefore, the decision was made to conduct the assessment experiment using Build 1.2, which was delivered to NASA Ames at the end of June 2003.

This report presents the results of six simulation runs including current and future reference conditions as well as the addition of proposed future concepts. Metrics in categories such as capacity, throughput, efficiency, predictability, costs and environment were evaluated.

II.   ACES Build 1.2 Model Descriptions

ACES is a large-scale, fast-time computer simulation of flights through the NAS multi-sector, multi-airport network. The simulation accounts for terminal gate pushback and arrival, taxi, runway system takeoff and landing, local approach and departure, climb and descent transition, and cruise operations. ACES employs a multi-trajectory based modeling approach that currently models TFM, ATC and flight operations, en route winds, and airport operating conditions. Software agents that exchange messages to relay information represent TFM, ATC and flight operations. This type of representation was chosen to provide a one-to-one matching of major real world activities to their software representations. The ACES tool applies a continual feedback, hierarchical modeling process to capture actions and responses among scheduling and trajectory planning, flight deck trajectory management, TFM strategic trajectory planning, and ATC tactical trajectory management operations. The intent is to quantitatively describe air traffic movement resulting from the interaction of the operational and technological constructs. By this process, TFM modeling agents in ACES assess projected demand over planning horizons, develop traffic flow plans and issue traffic restrictions to ATC agents. ACES simulates the propagation of TFM constraints through the NAS. ATC agents manage tactical flight movement by applying standard operating procedures subject to the TFM restrictions. Advanced four-degree of freedom trajectory modeling emulates the movement of each aircraft along a four-dimension trajectory in conformance with its current flight plan and clearance. A detailed description of the current ACES modeling capabilities is presented in reference 3. The model descriptions that follow are extracted from reference 3 with minor changes that reflect the ACES build and set up used in this study.

ACES Build 1.2, used for this assessment exercise, performs a gate-to-gate simulation of each flight. Figure 1 depicts the agent communications that occur for a single flight as it progresses from gate departure to gate arrival
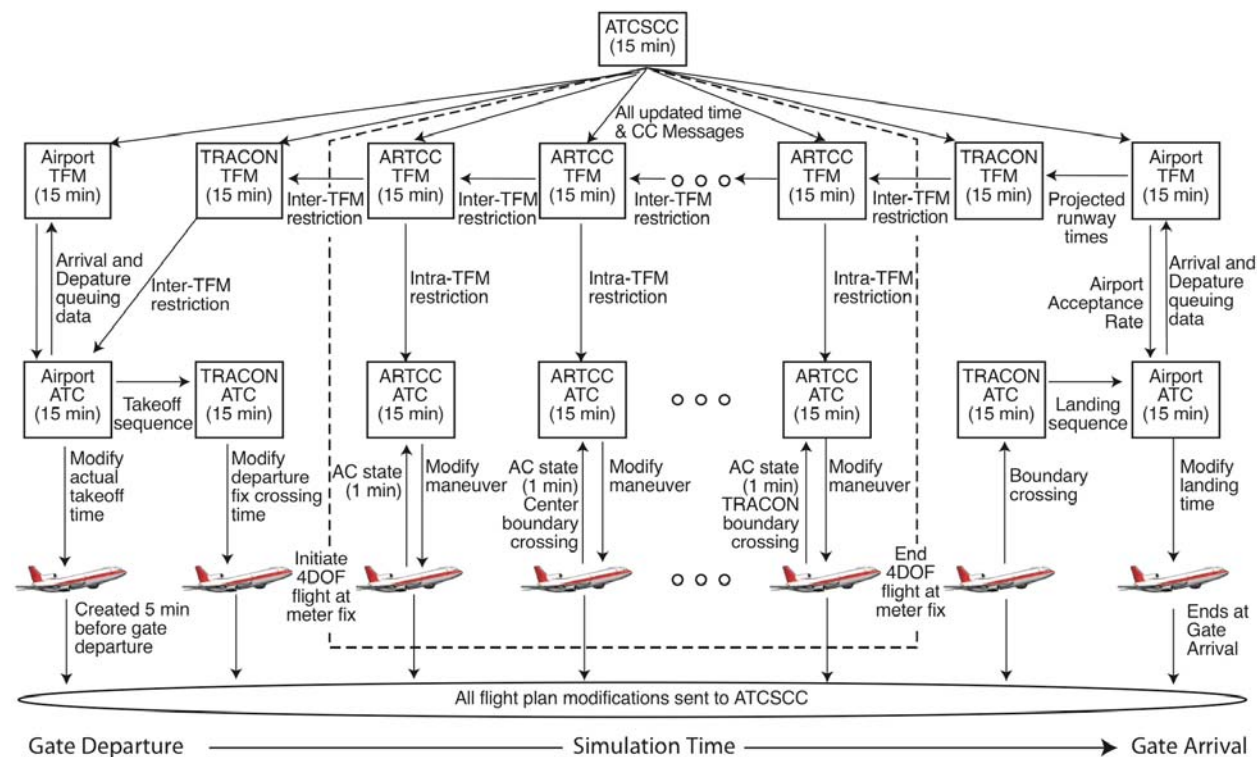

Figure 1. Gate-to-gate modeling.

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within the simulation. Messages between agents occur based on events (e.g. a gate departure event) or based on periodic update cycles. (Default message update rates are shown in parentheses.) Aircraft movement is modeled from the departure airport terminal gate, through the departure airport surface taxi system to and through the takeoff runway system, and through the terminal airspace to a departure fix. Then the aircraft goes through a series of en-route Air Route Traffic Control Centers (ARTCCs) and their sectors to an arrival fix on a terminal airspace boundary, through the terminal airspace, to and through the landing runway system, and through the arrival airport surface taxi system to the arrival airport terminal gate. An agent representing the Air Traffic Control System Command Center (ATCSCC) communicates with TFM agents and receives flight plan modification messages.

ACES Build 1.2 provides various levels of modeling fidelity. En route operations currently are simulated with higher fidelity than terminal. A four-dimensional (4D) aircraft trajectory model is used to simulate detailed, time-stepped flight dynamics in en route airspace, whereas node-to-node transit times are used to simulate terminal flight movement. The boundaries of the 20 domestic ARTCCs and all en route sectors are encoded in ACES databases. Terminal operations are modeled by nodes representing the terminal gate system, runway system and arrival and departure fixes (see Figure 2). These fixes demarcate the terminal-en route airspace boundary.

ACES currently applies a generic terminal area design to represent the Terminal Radar Approach Control (TRACON). This generic design assigns four arrival and four departure fixes to each TRACON where the fixes are evenly spaced on a 40-nautical mile (nmi) radius circle centered on the airport, aligned and interleaved as shown in Figure 2. The arrival fixes are assigned only to flights landing at the airport and departure fixes are assigned only to flights taking-off from the airport. One TRACON is associated with each airport.
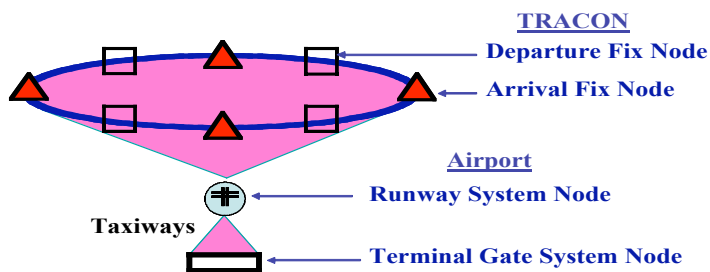

Figure 2. Generic terminal modeling structure.

A. Airport TFM Model

ACES Build 1.2 treats the runway system node as the critical factor in modeling each terminal operation. In this modeling structure, each Airport TFM agent invokes its model to examine projected takeoff and landing traffic loading at the runway system based on the flight schedule (see Figure 3). This model sets runway system arrival and departure acceptance rates over a TFM planning horizon based on airport capacity descriptors. The acceptance rates can vary over time depending on arrival versus departure mix and airport operating conditions, however this study was run with IFR or VFR acceptance rates that remained fixed at each airport for the entire simulation. Concurrently, the Airport TFM model also determines planned landing times, which include any delays needed to meet the acceptance rates. The Airport TFM agent transmits the planned acceptance rates to its Airport ATC agent, and transmits planned landing time to its TRACON TFM agent. The Airport TFM agent also relays to its Airport ATC agent any planned flight takeoff time restriction received from its TRACON TFM agent. Such a restriction is due to an en route constraint at a departure fix set by an ARTCC TFM agent.
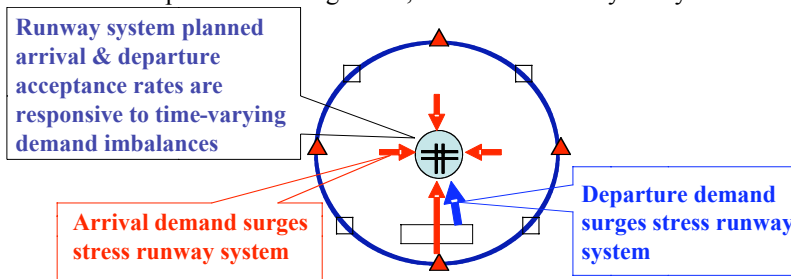

Figure 3. Airport TFM operations modeling.

B. Airport ATC Model

Each Airport ATC agent in ACES Build 1.2 simulates the management of actual flight operations through the surface and runway systems (see Figure 4). The Airport ATC model generates each flight's actual departure time from the terminal gate system based on the schedule. The Airport ATC model constructs a takeoff schedule of flights based on the terminal gate system departure times and originally scheduled (un-delayed) taxi-out time. Concurrently, the Airport ATC model constructs a landing time schedule of flights based on projections received from the TRACON ATC agent. The Airport ATC model assigns actual takeoff and landing times based on comparative analyses of the flight schedule versus the arrival and departure acceptance rates. The model spaces

successive takeoffs and successive landings to conform to the arrival and departure acceptance rates. The actual takeoff and landing times include delays induced by the acceptance rate-based traffic overloads, which result in runway system departure queues on the airport surface and airborne arrival delays. The Airport ATC model assigns each flight's terminal gate arrival time based on its actual landing time and originally scheduled (un-delayed) taxi-in time. The Airport ATC model transmits the actual takeoff times to its TRACON ATC agent and the Air Traffic Control System Command Center (ATCSCC) agent.
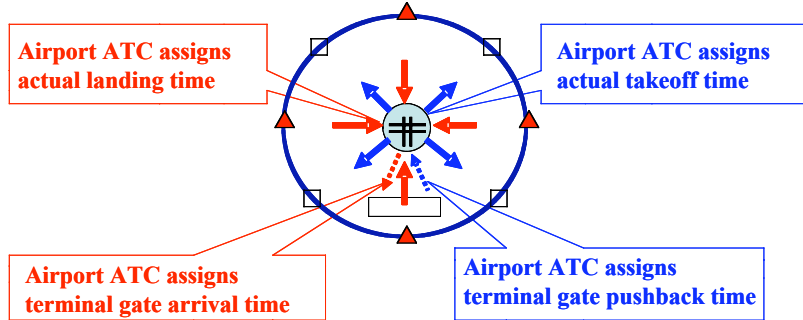

Figure 4. Airport ATC operations modeling.

C. TRACON TFM Model

In Build 1.2, each TRACON TFM agent relays traffic restrictions, subject to local adjustments, between its Airport TFM agent and its adjoining ARTCC TFM agents. The TRACON TFM model determines flight restrictions to be applied at each arrival fix over the TFM planning horizon in conformance with the runway system planned acceptance rates. The TRACON TFM model processes planned landing times received from the Airport TFM model, applies originally scheduled (un-delayed) terminal airspace inbound transit times, and assigns planned arrival fix crossing times. The TRACON TFM model also determines flight restrictions to be applied to airport departure flights over the TFM planning horizon in conformance with constraints imposed by ARTCC agents. The TRACON TFM model processes planned departure fix crossing times received from an ARTCC TFM agent, applies originally scheduled (un-delayed) terminal airspace outbound transit times, and assigns planned takeoff times. The TRACON TFM agent transmits the inbound planned crossing time at each arrival fix to the ARTCC TFM agent handling that fix, and transmits planned takeoff time restrictions to its Airport TFM agent.

D. TRACON ATC Model

Each TRACON ATC agent in ACES Build 1.2 simulates management of actual flight operations through the terminal airspace. The TRACON ATC model determines a scheduled departure fix crossing time based on the actual takeoff time and originally scheduled (un-delayed) terminal airspace outbound transit time. The TRACON ATC model assigns actual departure fix crossing times based on comparative analyses of the flight schedule versus pair wise aircraft separation procedures (see Figure 5). The model spaces successive crossings at each fix in altitude-separated traffic streams (i.e., representing turbojet, turboprop and piston-powered aircraft) to conform to minimum separation requirements. Concurrently, the TRACON ATC model constructs a projected landing time schedule of flights based on actual times of arrival fix crossings received from the ARTCC ATC agent and the originally scheduled (un-delayed) terminal airspace inbound transit time. The TRACON ATC agent transmits the projected landing times to its Airport ATC agent, and the actual crossing times at each departure fix to the ARTCC agent handling that fix and the ATCSCC agent.
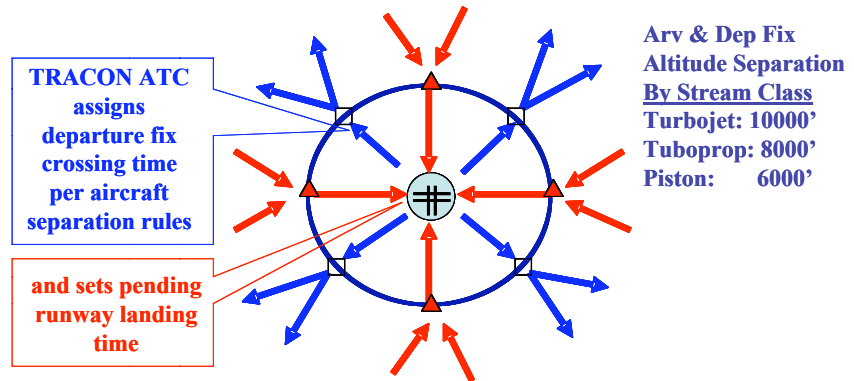

Figure 5. TRACON ATC operations modeling.

E. ARTCC TFM Model

The ARTCC TFM agents generate and propagate TFM traffic restrictions through the en route network. Each ARTCC agent plans traffic restrictions for its multi-sector airspace. The ARTCC TFM model in Build 1.2 receives planned exit boundary crossing time requirements from adjacent TFM agents (e.g., ARTCC or TRACON TFM agents) and relays the exit time requirement to its ARTCC ATC agent. The ARTCC TFM model examines its capability to absorb delays and adjusts planned flight times accordingly to delay flights in its own airspace, to the

extent possible, to meet TFM exit time requirements. Otherwise, planned delays are propagated upstream by assigning planned ARTCC entry time requirements for delayed flights. The ARTCC TFM model sets a plan (see Figure 6) for flights requiring outbound delay that either adsorbs the delay, transposes the delay upstream, or a combination thereof. Hence, all or part of a planned arrival delay due to runway system acceptance rate may be absorbed en route (in one or more ARTCCs) or propagated to the origin airport and absorbed prior to takeoff.

In Build 2 of ACES, the ARTCC TFM model receives Monitor Alert-based projected sector overload advisories from the ATCSCC TFM agent, which lead to TFM actions to enforce sector capacity constraints. This feature was not functional in Build 1.2, so sector capacities were not limited.
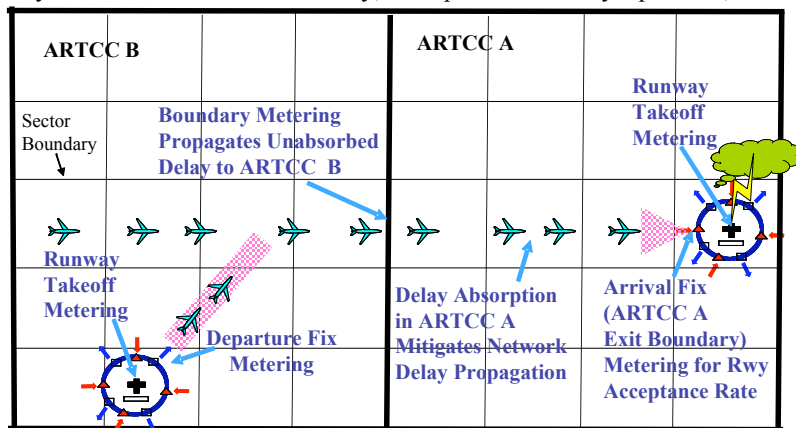

Figure 6. ARTCC TFM Operations Modeling.

F. ARTCC ATC Model

The ARTCC ATC model in ACES Build 1.2 manages traffic to maintain compliance with the TFM restrictions. The ARTCC ATC model maintains a list of all aircraft within the airspace and it receives TFM restriction messages specifying which aircraft are to be delayed and their required ARTCC exit boundary crossing time. For these TFM restrictions, the ARTCC ATC agent implements path stretching by turning the aircraft off-route temporarily to fly one or more dogleg turns about its nominal route. It rejoins the nominal route approximately as it exits the ARTCC. The dogleg turn model is an approximate solution. It uses a local flat-earth reference frame and accounts for wind and finite turn rates.

G. ATCSCC TFM Model

An ATCSCC TFM agent in ACES Build 1.2 oversees gate-to-gate flight movement, receiving and passing traffic movement information from and to other agents. The ATCSCC TFM model simulates a Monitor Alert function by examining the predicted trajectories of all aircraft and computing sector traffic loadings. The sector traffic loadings are compared to the sector capacity to identify predicted overloaded sectors. The ATCSCC TFM agent transmits sector congestion alert messages to ARTCC TFMs. As mentioned previously, Monitor Alert function was not enabled for this study.

H. Airline Operations Center Model

An Airline Operations Center (AOC) agent is used in ACES Build 1.2 to implement a traffic demand model. This model assigns flight plans for all flights for the given ACES simulation run. The output of the traffic demand model is a set of flights, where each flight is defined by a city pair, planned departure and arrival times, aircraft type, and route details.

I. Flight Model

The ACES Build 1.2 Flight model flies the aircraft forward in time to generate a four dimensional (4D) trajectory. The model uses a 4-degree-of-freedom dynamics model including the aircraft roll angle for realistic turn maneuver modeling in the en route airspace (i.e., between the departure and arrival meter fixes). It uses airframe and propulsion models to construct a free body diagram and solve the aircraft equations of motion. For guidance it uses route following and route capture logic for the horizontal plane maneuvers, and realistic energy-management logic for capturing a speed-altitude state. A lower fidelity approach is applied in the terminal area using transit time input data. Here, nominal (un-delayed) flight times specific to the stream class (i.e., jet, turbojet, piston) of the aircraft are assigned to define terminal airspace transit times. Similarly, nominal (un-delayed) inbound and outbound surface taxi times are assigned by airport. The TRACON TFM may apply delay to these un-delayed flight times.

J. Wind Model

ACES Build 1.2 uses the Rapid Update Cycle (RUC) nationwide hourly wind estimates to model wind as two horizontal vector components in the north-south and east-west directions, respectively, at the aircraft location. These data appear in the equations of motion of flight, which are used to propagate the aircraft trajectories. Wind forecast error is not currently modeled. The RUC data are interpolated to the aircraft position and time for all aircraft. This

four-dimensional interpolation (three spatial coordinates and one temporal coordinate) is done using a sequence of four one-dimensional interpolation steps. This capability was not used for this study due to unexpected complications in specifying RUC data for future dates within the simulation. This problem has been addressed in subsequent ACES builds.

III.   EXPERIMENTAL PLAN

K. Concept Identification

Three concepts were selected for use in the demonstration of ACES. The ACES Team had committed to delivering a preliminary, high-level assessment of the system-wide impact on the NAS of two or more VAMS concepts. Selection of the particular VAMS demonstration concepts for this exercise was based on two factors. First, the ACES team needed to determine whether the concept could be integrated into the current ACES environment, in a time sensitive manner. Second, the ACES team wanted to demonstrate concepts representing as many of the various phases of a flight as possible. One en-route and two terminal area concepts were selected.

The Advanced Airspace Concept (AAC) under development by NASA Ames Research Center was selected as the en-route concept. The Terminal Area Capacity Enhancement Concept (TACEC) being developed by Raytheon and the Wake Vortex Avoidance System (WakeVAS) being developed by NASA Langley Research Center were chosen as the terminal area concepts. Unfortunately, only very rough preliminary estimates of the airport capacity benefits were available for the two terminal area concepts. To avoid the potential for an unfair comparison of the two terminal area concepts on the basis of preliminary estimates, two generic terminal area concepts were generated that had airport capacity benefits of comparable magnitude to some of the preliminary benefit estimates for TACEC and WakeVAS. These two generic concepts are referred to as the Good Weather Terminal Area Concept for Visual Meteorological Conditions (VMC) and the Bad Weather Terminal Area Concept for Instrument Meteorological Conditions (IMC).

1.   AAC En-Route Concept

The AAC concept[4] has both en-route and terminal area applications. For this study, only the en-route benefits are considered. The AAC utilizes a ground-based component, the Advanced Airspace Computer System (AACS), that generates efficient and conflict–free traffic clearances and associated trajectories that are sent directly to aircraft via data-link. Another ground-based component, the Tactical Separation Assisted Flight Environment (TSAFE), provides a safety net to ensure that safe separations are maintained in the event of failures in the AACS or in certain on-board aircraft systems. TSAFE independently monitors the clearances and trajectories sent by the AACS to each equipped aircraft, monitors aircraft conformance to those trajectories, and issues warnings and resolution advisories to pilots and controllers when appropriate. Because the AAC will reduce controller workload associated with tactical problem solving, controllers will be able to safely shift their focus to more strategic problems, such as traffic flow management and pilot requests. The reduced controller workload and improved trajectory and schedule conformance should lead to en-route capacities that are two to three times greater than current capacities.

2.   Good Weather Terminal Area Concept (GWTAC)

The notional GWTAC concept utilizes improved scheduling and trajectory accuracies in the terminal area to improve airport capacities. This concept is assumed to be applicable to all terminal areas and it is assumed that its benefits are independent of capacity improvements obtained via other methods. Since this concept is a notional one intended to exercise the capabilities of ACES, the capacity benefit to airport arrival and departure rates was arbitrarily assumed to be an across-the-board increase of 15%. This is believed to be a reasonable and possibly even overly conservative capacity benefit for such a concept. All airports are considered potential candidates for this type of improvement.

3.   Bad Weather Terminal Area Concept (BWTAC)

The capacity increasing benefits of the notional BWTAC concept are loosely based on preliminary TACEC and WakeVAS estimates that were available at the time of this study. Capacity improvements are estimated for each airport individually based on capacity restrictions for closely spaced parallel runways and the airport's overall Instrument Flight Rules (IFR) capacities. Although there is potential for increased capacity for some airports with closely spaced parallel runways under VMC conditions using these type of concepts, the estimated improved IFR capacity increases are limited to values no greater than the airport's VFR capacities. Again, the assumed benefits are believed to be reasonable and possibly overly conservative.

L. Assessment Plan

The development of the assessment plan was constrained by several factors: the capabilities of ACES Build 1.2, the availability of scenario data; the availability of key VAMS team members to prepare and conduct the

experiment; and the availability of the ACES computer system (also used to perform acceptance tests of new or updated ACES software components.) These factors, combined with the time frame available for the study, would only allow a few simulation scenarios to be prepared, executed and analyzed. Ideally, each concept would be evaluated over a variety of conditions, representative of possible NAS operational states. As this was not possible, it was decided to test the concepts under extreme NAS conditions.

The number of flights that are scheduled for a single day represents NAS demand. Two demand extremes were chosen, a flight schedule representative of current demand and one for a possible future where demand is double current day demand. The airport condition extremes were chosen, a perfect weather day, where all airports operated under VMC for the entire simulation period, and a bad weather day, where all major airports operated under IMC for the entire simulation period. The combination of these variations results in four simulation runs.

Two en-route conditions were originally considered, one with current sector capacities and one with tripled sector capacities that might be achieved by implementing AAC. This was contingent upon Build 1.3 of ACES being available in time for the study. As this was not the case, all scenarios were run with unlimited sector capacities, a condition simulating the use of AAC in the en-route environment. This had the advantage that the two terminal area concepts were evaluated in the absence of en-route capacity limits, which would provide an upper limit on the benefits they could provide.

It was decided to evaluate the two terminal area concepts under the future demand scenario, as this would be more representative of the demand levels for which they are targeted. The good weather day scenario was chosen for the GWTAC concept and the bad weather day was chosen for the BWTAC concept.

Although only six scenarios were chosen, they do represent a set of extreme conditions, which should provide an adequate, early test of the modeling capabilities of ACES in evaluating future NAS concepts.

M. Input Data

Input data are necessary to drive an ACES simulation. These data include environmental descriptions of the airspace, traffic demand schedules, operational conditions and capacities, and various simulation system files. The input data are located in several data files described below. The files are modified as necessary to best represent the operational concept being simulated.

1. Environment Data Files

The environmental data files describe the virtual airspace in the form of boundaries for the continental United States, air route traffic control centers and sectors. The airspace is described both by latitude/longitude values as well as altitude stratification. Completing the environment description are the definitions of terminal area airspace and airports. The terminal airspace defines the boundary around an airport and the associated departure and arrival meter fixes. Surface reference points define the airports. These values are described by latitude/longitude. The environmental input files used for the six test cases studied in this effort were defined using the current airspace system.

2. Traffic Demand Schedule Data Files

A traffic demand schedule in this context defines the number of aircraft operations and their distribution over a given time period. More specifically it includes the planned service between origin and destination airports, departure times, and the providing air carrier and associated flight equipment. The demand schedule is the air transportation system's response satisfying the demand of the traveling public. The flying public establishes the demand schedule defining the origins and destinations for the desired travel and the time of day the travel will take place. Air carriers satisfy the demand, scheduling flights between city-pairs at appropriate times and frequencies. The demand schedule is the prime input necessary to drive an ACES simulation. For this study cargo, general aviation and military flights are not included in the demand schedules.

The demand schedule is an independent component of an operational day's scenario. The scenario additionally includes the occurrence of events that perturb the execution of the scheduled demand. This may include variations in weather, and/or strategic and tactical decisions made by air transportation service providers. But demand exists no matter what the perturbations are.

Due to daily variations in the operational demands of the NAS throughout the week and seasonal variation throughout the year, a simulation demand schedule must represent a "typical" day capturing an average view.

To evaluate the added value of a proposed NAS operational concept, a baseline demand schedule and a future demand schedule are the required minimum set. The baseline demand schedule for this effort is defined as a "current-day" demand. It describes a typical NAS operational day in the present time frame, 2002. The future demand schedule is established as an estimate of a typical NAS operational day in the future year 2022. This estimate is formulated from both economic and transportation demand projections.[5]

The current and future traffic demand schedules use the existing hub and spoke system (where several airlines operate multiple stage flights that connect at centralized "hubs") as the primary operating structure of the air transportation system.

3. General Development

Modifications to existing current and future traffic demand data sets were required so ACES could use them and so that simulation results could be properly compared. The first modification was to filter the data sets to a common set of 98 airports. (The reason for this was that the available future demand schedule[5] only included 98 airports.) The second was to filter flights to a common set of domestic commercial passenger flights. Flights not designated as such were eliminated. These included international, military, general aviation, air taxi, life flight, helicopter, and cargo flights. Third, flights departing from and arriving at the same airport were eliminated. And finally, flights between airports that are separated by less than 90 nautical miles were removed. The last two modifications were made because ACES does not currently support these types of flight plans.

A significant amount of work went into making the data sets' flight trajectories functional within the ACES system. A tool, FlightGen, was developed to automate much of this effort. This tool performs the following tasks. (1) It eliminates lat/lon pairs that exist within the ACES defined terminal area extending out to a radius of 40 nautical miles around each airport. (2) It ensures that a minimum of 5 lat/lon pairs exist for each trajectory and the distance between consecutive pairs is greater than 1 arc minute but less than 500 nautical miles. (3) It tests that the first and last lat/lon pairs represent the departure and arrival airports and corrects them if they do not. (4) It provides trajectories in three forms: the original flight trajectory truncated at the terminal areas; an optimized Great Circle (GC) trajectory from departure airport to arrival airport; and an optimized GC trajectory from ACES departure meter fix to ACES arrival meter fix. Airspace data is referenced from the Digital Aeronautical Information and National Flight Database published by the Federal Aviation Administration (FAA) National Aeronautical Charting Office.

4. Current Demand

The current demand data set was developed from an ACES Build 1.0 validation input file. The date selected was Friday May 17, 2002. This was defined as a "high traffic" operational day. The FAA's Enhanced Traffic Management System (ETMS) provided the original source data for this demand schedule. The ETMS data for May 17, 2002 had a total of 41,358 operations. The ACES validation data set represented operations at 250 domestic airports reducing the number of operations to 30,237. After applying the modifications described above, the resulting data set representing domestic commercial passenger flights at 98 major US airports contains 17,875 operations. Of these, 16,468 are processed and flown in ACES. ACES reject the remaining 1,407 flights because of existing errors in sector and center boundary data, and the inability of the flight model to negotiate these errors. Solutions to correct this have been implemented in more recent versions of ACES.

5. Future Demand

The future demand data set was developed from a transportation demand and economic analysis forecast for the year 2022. This forecasted scenario assumed economic growth and airline recovery. Specifically, Gross Domestic Product growth is relatively high, aviation system growth is restricted, and substitutes for commercial aviation services do not significantly materialize. It was also assumed that there would be "further growth in the hub and spoke system" and "growth by low cost carriers and others serving low yield sectors at secondary airports". Passenger flight data were derived from Official Airline Guide data for Monday, May 12, 1997. A flight-growth multiplier was calculated from the economic forecast assumptions. This multiplier was applied to the baseline data set of 1997 to arrive at the forecasted operational demand. It was assumed that all domestic airports have the same passenger demand growth rate from 1997 to 2022.[5]

The future demand data set began with a total of 37,879 operations at 102 airports. In addition to applying the modifications described above missing data had to be constructed to arrive at a complete ACES input file. These constructed data are currently of low fidelity; subsequent demand generation efforts have improved upon this. First, generic flight identification numbers, AOC and aircraft type assignments were made. Flight ID's are a simple series of numbers. AOC assignments are distributed among 21 generic airlines evenly distributing ACES computational loads. The most common aircraft type for a given weight class in the current demand data set was used to populate the future demand set. Second, each scheduled operation was mapped to a flight trajectory, nominal cruise altitude, and speed. The resulting future demand data set representing domestic commercial passenger flights at 98 major US airports contains 36,252 operations. Of these, 33,167 are processed and flown in ACES. The rejected flights are again due to sector and center boundary issues as discussed above.

6. Operating Conditions and Capacity Data Files

In Build 1.2, ACES' greatest flexibility to simulate Airspace Concept resides in the operating conditions and capacity input files. Included here are definitions for airports, terminal areas, and en-route sectors.

Airport operating conditions are defined as being under VFR or IFR. Optimum airport operating conditions exist during VFR status. IFR places the airport in a reduced operating state. The operating condition can be modified in quarter-hour increments for each individual airport throughout the simulation run time. Airport capacity input data defines the maximum number of departures, arrivals, and total operations accommodated per hour at each airport. Operating capacities are inter-related with operating conditions. Highest capacities are achieved during VFR conditions. Capacity is reduced for IFR conditions. Airport surface transit time from gate to runway and visa versa is also defined at each airport.

Terminal area transit times are defined for each type of aircraft. These times describe how long a vehicle type will take to maneuver from the runway takeoff point to the terminal area departure fix, or from the terminal area arrival fix to the landing point on the runway.

En-route sector capacity can be defined for each sector in the simulated airspace. Because of limitations in ACES Build 1.2, sector capacities were all set to a significantly high value during this assessment. Later software releases provide the functionality to use individual sector capacity values.

Settings for operating conditions and capacities are described in the test cases discussed below.

7. Simulation System Data Files

The final category of input data files includes the aircraft modeling files and simulation control data. The aircraft modeling files include data that drive the four degree-of-freedom aircraft trajectory models through the en-route airspace. The simulation control data files manage simulation resources through assignment of models to different processors in the distributed simulation system.

8. Test Case Reference Data

Table 1 summarizes the capacities and conditions used in the construction of the input data files.

The current VFR and IFR arrival and departure rates for the 30 Benchmark 2001 airports were based on the maximum optimal and reduced rates published in the FAA "The Airport Capacity Benchmark Report 2001."[6] The VFR rates for the remaining airports were obtained, if available, from the FAA's Aviation System Performance Metrics (ASPM) database.[7] For airports not listed in ASPM database, VFR arrival and departure rates were based on estimates derived from an FAA Advisory Circular."[8]

The Operational Evolution Plan[9] (OEP) VFR and IFR arrival and departure rates for the 30 Benchmark 2001 airports were based on the maximum optimal and reduced rates published in Benchmark report assuming that all potential technology and runway improvements are implemented for each airport.

Preliminary GWTAC benefit estimates were not available in time for this report; therefore a rough estimate of a 15% improvement, over the OEP values, was assumed for the VFR arrival and departure rates at the 30 Benchmark 2001 airports.

Rough estimates of the BWTAC improvements to arrival and departure rates were available for 20 of the Benchmark 2001 airports. These improvements were applied to the OEP IFR rates for the 20 airports. For airports where the improved rates would exceed the assumed OEP VFR rates, the OEP VFR rates were used.

N. Evaluation Metrics

Six categories of evaluation metrics were selected for the preliminary assessment of future operational concepts using ACES. The air transportation community routinely uses these categories for airspace system performance evaluations. The categories and their associated metrics were chosen from a superset of metrics assembled and developed by the System Evaluation and Assessment element of the Virtual Airspace Modeling and Simulation Project. ACES Build 1.2 is capable of producing the data necessary to calculate these metrics.

The categories include capacity, throughput, efficiency, predictability, costs and environment. There is at least one metric within each of these. Because the assessed future concepts are being developed primarily for increased national airspace capacity, the capacity category is more heavily weighted.

1. Capacity

Capacity metrics provide information about the total number of operations occurring within the national airspace system. Included are metrics for the overall system and metrics for individual airport operations.

Total system metrics:
  - Total Commercial Passenger Flights Flown per Day
  - Total Passenger Trips per Day
  - Total Revenue Passenger Miles Flown per Day
  - Total Aircraft Travel Time

Airport level metrics:
  - Flight Arrivals per Hour per Airport
  - Flight Departures per Hour per Airport
  - Passenger Arrivals per Hour per Airport
  - Passenger Departures per Hour per Airport

Table 1 Test Case Scenario Summary

Test Case	Demand	Capacity	Condition	Condition Implementation
Current Demand, All VFR	Current	Current Airport Operating Capacities	VFR	VFR at all airports
Current Demand, VFR & IFR	Current	Current Airport Operating Capacities	VFR & IFR	IFR at 30 Benchmark airports, VFR at all other airports
Future Demand, All VFR	Future	Current Airport Operating Capacities + Improvements at 30 benchmark airports due to proposed runways and technologies as published in the Airport Capacity Benchmark Report 2001	VFR	VFR at all airports
Future Demand, VFR & IFR	Future	Current Airport Operating Capacities + Improvements at 30 benchmark airports due to proposed runways and technologies as published in the Airport Capacity Benchmark Report 2001	VFR & IFR	IFR at 30 Benchmark airports, VFR at all other airports
Future Demand, All VFR + GWTAC	Future	Current Airport Operating Capacities + Improvements at 30 benchmark airports due to proposed runways and technologies as published in the Airport Capacity Benchmark Report 2001 + improvements estimated by GWTAC concept applied at 30 benchmark airports	VFR	VFR at all airports
Future Demand, VFR & IFR + BWTAC	Future	Current Airport Operating Capacities + Improvements at 30 benchmark airports due to proposed runways and technologies as published in the Airport Capacity Benchmark Report 2001 + improvements estimated by BWTAC concept applied at 20 benchmark airports	VFR & IFR	IFR at 30 Benchmark airports, VFR at all other airports

2. Throughput

Throughput metrics provide information about the maximum number of operations occurring within the system.
- Peak Airport Throughput
- Peak En-route Throughput
- Sector Loading
- Number of Overloaded Sectors

3. Efficiency

Two metrics were chosen to assess the gross efficiency of the operational concepts.
- Total Flight Travel Time
- Total Flight Miles Flown

4. Predictability

Predictability metrics measure the operational concept's ability to provide the necessary capacity to satisfy the traffic demand.
- Flights more than 15 minutes late from Scheduled Arrival Time
- Passengers more than 15 minutes late from Scheduled Arrival Time
- Average Minutes Late per Flight
- Total Delay

5. Cost and Environment

The last two metric categories use the same metric: total fuel burned. This value can be interpreted to provide gross fuel cost and environmental pollution comparisons between operational concepts.
- Total fuel burned

IV.   RESULTS ANALYSIS

O. Simulation Scenario Assessments

Operational concept assessments have been made for the following combination of the six simulation cases. The evaluation metrics described above were the basis for these assessments.

- Current All VFR vs. Current VFR & IFR
- Current All VFR vs. Future All VFR
- Current VFR & IFR vs. Future VFR & IFR
- Future All VFR vs. Future All VFR + GWTAC
- Future VFR & IFR vs. Future VFR & IFR + BWTAC

The number of flights, passenger trips, revenue passenger miles and miles flown for all current demand test cases and all future demand test cases are constant for the respective traffic demand. This is because ACES Build 1.2 does not have the functionality to cancel flights and consolidate passengers in response to system delays. As shown in Figure 7, the number of flights, passenger trips, and travel time double between the current and future demand. Total miles flown and revenue passenger miles increase 85% in the future demand cases because the average number of miles flown per flight is equivalently reduced in the future demand. Though the number of flights and miles traveled are the same, and the total travel time is relatively the same within each demand case, total delays and the distribution of the delay between the different phases of travel very greatly between simulation runs.

The delay metrics for the current demand case are shown in Figure 8, which indicates that total delay increases 210% when the 30 benchmark-airports operate in the IMC state. The greatest proportion of this increase is seen in the gate departure delay. In the VMC test case, very little gate departure delay occurs. Under mixed VMC/IMC, this delay increases 8285% as flights are held at the gate prior to departure by TFM restrictions forecasted at arrival airports. Takeoff delay, which is the delay experienced between gate push-back and takeoff, increases approximately 130%, as does the in-flight delay. When comparing the current demand case total delays with future demand case total delays, the doubling of traffic demand results in a 584% increase in total delay for the VMC run and an incredible increase of 1095% for the mixed VMC/IMC case. Adding GWTAC and BWTAC operational improvements results in dramatic reductions in total delays for the future demand case. With GWTAC improvements added to the VMC
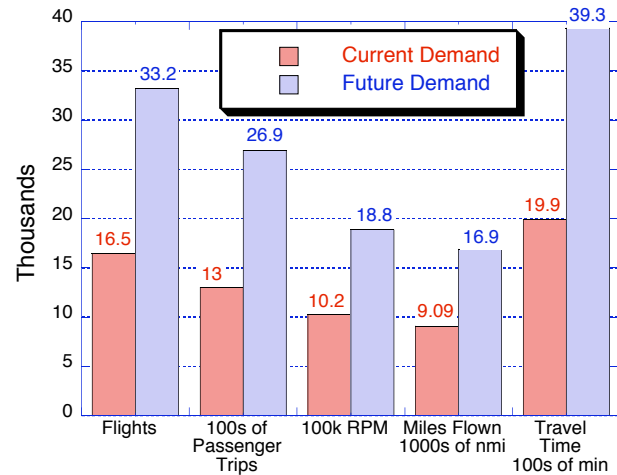
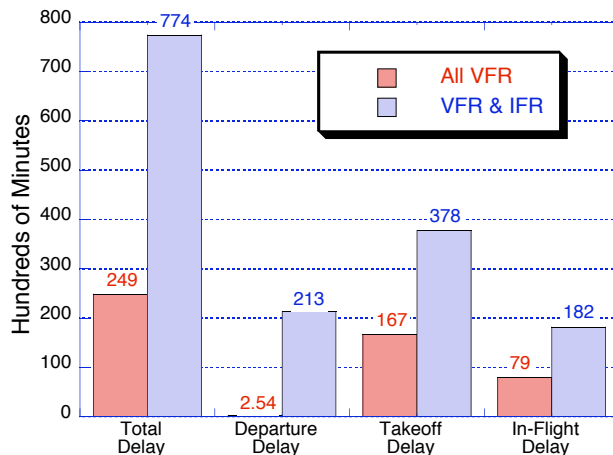**Figure 7. System-wide demand metrics.**

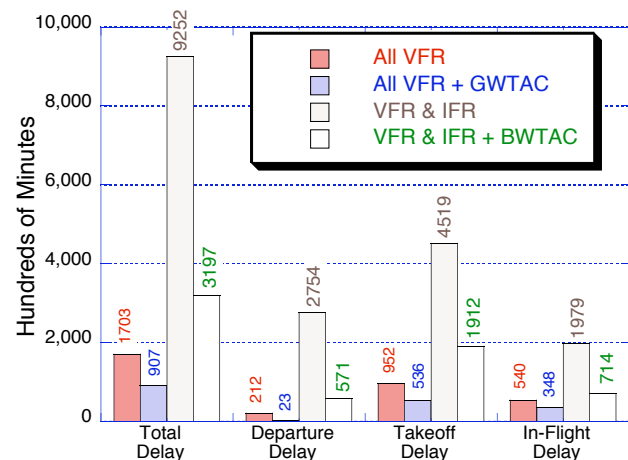**Figure 8. Delay metrics for current demand.**

Figure 9. Delay metrics for future demand.

case, there is only a 264% increase above the current delay, an improvement in total delay of 46% for the future case. Adding BWTAC concept improvements to the mixed VMC/IMC case results in a total system delay of 313%; an improvement in total delay of 65% for the future case.

In all test cases, takeoff delay is proportionally greater than gate departure delay and in-flight delay. Further investigation into this is required, but potential reasons may be due to the low-fidelity surface queuing model, and/or the functionality of the Airport TFM model. Improvements to the airport TFM model may be required to further delay gate push-back until there is sufficient space for them to maneuver on the surface (in the queue) with minimal delays. Future ACES improvements to the surface modeling might also have an effect on this. Also, these delays should be further analyzed at each airport to determine if certain airports are experiencing more takeoff delay that others and the possible reasons for this.

As would be expected, trends for flights and passengers recorded late by more than 15 minutes are similar to those seen in the above discussion. Increasing the traffic demand results in significant increase in late flights and passengers, as shown in Figure 10. Adding future operational concept improvements reduces the level, but it is still above the values recorded for the current demand case. Of interesting note, when viewing delay using the "average minutes late" metric, the future demand runs, with improvements from GWTAC and BWTAC included, result in average minutes late being twice the value of the current demand.
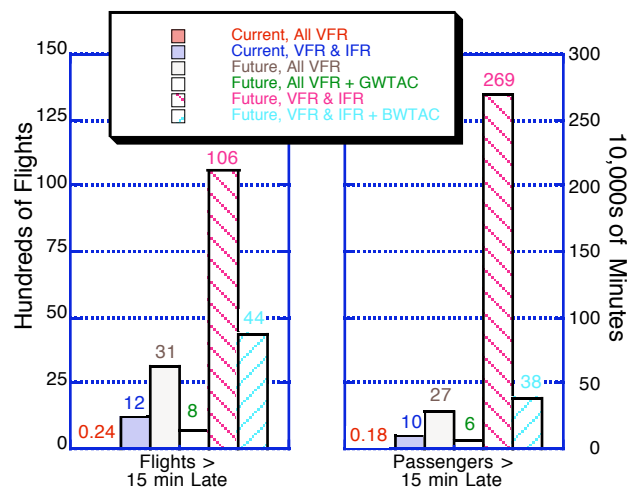

Figure 10. Excessive passenger and flight delay.

P. AAC Assessment

Due to limitations of ACES Build 1.2, the AAC concept was implicitly modeled by placing no restriction on sector capacity. Although not directly modeled, an examination of the aircraft counts in each sector can be used to assess the need for enhanced sector capacity in each scenario. Two sector counts metrics were used; the first was enumeration of the number of times that sectors reported a count greater than 15 aircraft. Sector counts were reported based on the largest aircraft in each sector count during each quarter hour of the simulation. This further was broken down into the number of occurrences for each count value over 15. The second metric was the identification of the number of sectors that exceeded their currently assigned sector capacities for any quarter hour period during the simulation. The maximum number of aircraft by which the sector capacity was exceeded was also recorded for each over capacity sector.

1. Current Demand: All VFR vs. VFR & IFR

The maximum reported sector count is 31 for the Current Demand All VFR scenario and 30 for the Current Demand VFR & IFR scenario. There are no significant differences between the distribution or number of high sector counts reported for each scenario. A total of 33 sectors exceeded their capacity for the Current Demand All VFR scenario and 35 exceeded their capacity for the Current Demand VFR & IFR scenario. No significant differences between the two scenarios were noted for either the distribution or the number of over capacity sectors reported for each scenario. There was no clear trend linking the number of high sector count occurrences and airport capacity, suggesting that airport throughput was not strongly dependant on the en-route capacity for the current demand scenarios. It should be noted that the impact of en-route weather systems limiting sector capacity and availability was not evaluated in either scenario. Under such conditions, the capacity in available sectors is likely to be a significant factor in achievable airport throughput.

2. Future vs. Current Demand: All VFR

Histograms of sector count occurrences above 15 counts are shown in Figure 11.The maximum reported sector count is 31 for the Current Demand All VFR scenario and 38 for the Future Demand All VFR scenario. Overall, the Future Demand All VFR scenario has a seven-fold increase in the number of high sector count occurrences as compared to the Current Demand All VFR scenario.

There are 33 sectors that exceed their capacity for the Current Demand All VFR scenario and 120 that exceed their current capacity for the Future Demand All VFR scenario. There is a significant increase in both the number of sectors exceeding current capacity and the in number of sectors that exceed their capacity by 8 or more aircraft.

The need for AAC is very obvious for the Future Demand scenario. Although the future demand is only twice the current demand, there is a seven-fold increase in the number of high sector count occurrences and a four-fold increase in the number of sectors exceeding current capacity. The relationship between overall demand and sector capacities is clearly non-linear and sector capacity needs are likely to be very sensitive to local demand fluctuations under the future scenario.

3. Future Demand: All VFR vs. VFR & IFR

Sector counts for good and bad weather scenarios are presented in Figure 12. The maximum reported sector count is 38 for the Future Demand All VFR scenario and 34 for the Future Demand VFR & IFR scenario. In general, the Future Demand All VFR scenario has a noticeably greater number of high sector count occurrences as compared to the Future Demand VFR & IFR scenario.

There are 120 sectors that exceed their capacity for the Future Demand All VFR scenario and 105 sectors that exceed their current capacity for the Future Demand VFR & IFR scenario. There is not a significant difference in the number sectors that are over capacity or in the maximum number of aircraft by which capacity is exceeded between the two scenarios.

The trend that the number of high sector count occurrences decreases as airport capacity decreases indicates that the need for en-route capacity is strongly linked to airport throughput. In other words, for the future demand scenarios, airport throughput is dependent on the availability of en-route capacity.

4. Future Demand with GWTAC and BWTAC

The results for the scenarios with GWTAC and BWTAC are not presented in this paper, however they follow the same trend that was noted for Figure 12, that greater airport capacity is directly dependent on greater en-route sector capacity.

5. AAC Summary

The sector count results presented indicate that the NAS, under future demand levels, is a system with strongly linked constraints. It is evident that a system like AAC, that eliminates or reduces en-route capacity constraints, is needed in order to realize benefits of concepts that increase airport capacities. Future assessments, using later versions of ACES, should be able to confirm the impact of limited sector capacities on airport throughputs.
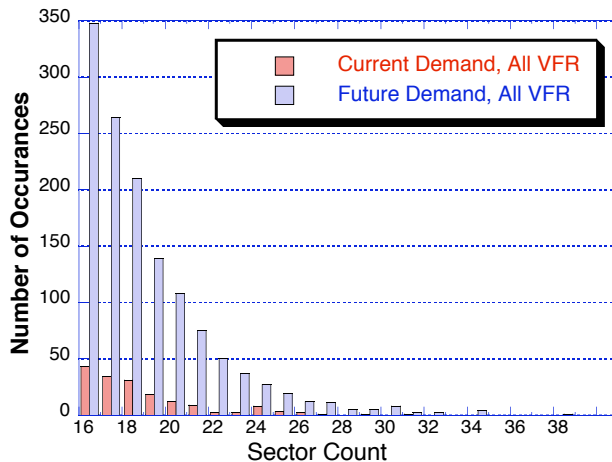

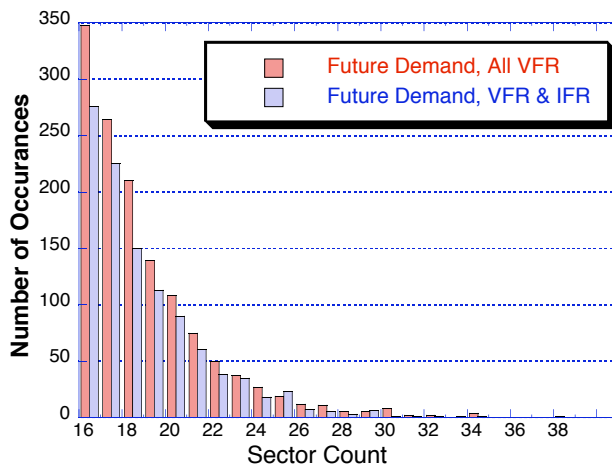
Figure 11. Sector counts: current and future demands.

Figure 12. Sector counts: future demand for all VFR and mixed VFR and IFR operations.

V.   DISCUSSION

ACES is a brand new airspace operations modeling tool that is still under aggressive development. The version used in this study was limited in both model scope and fidelity. The initial development focus was on the simulation engine and the initial set of models. Little effort was given to the development of preprocessing and post-processing tools. Given these limitations, the expectations for what could be accomplished in this study were modest.

The scenario data used in this study was gathered from numerous sources that were not always in agreement when there was data overlap. Some required scenario data was not available and had to be estimated. The scenario data used was the best that could be found or estimated given data availability, time and resources. Although this

data should not be considered adequate for a quantitative assessment of NAS concepts, it does serve the primary goals of this assessment exercise, which was to provide an early evaluation ACES' analysis capabilities.

Despite the modest expectations for this early version of ACES, the results of this study indicate that it is a promising NAS simulation tool. The generic BWTAC and GWTAC concepts were both shown to provide a significant reduction in delay under the future demand scenarios. The fact that resulting delays are still large when compared to the delays predicted for the current demand scenarios, shows that the doubled demand of the future scenarios will be a challenging problem to address.

The ability to model NAS behavior with and without AAC-enabled sector capacities was not available in ACES Build 1.2. However, the ability to monitor sector capacities provided a means to assess the need for AAC-enabled sector capacities. The results indicate that under the future demand profile, en-route sector capacities need to increase in order to enable increases in airport throughput. Furthermore, the magnitude of the sector capacity increases indicates that AAC would be required in order to realize the airport throughput gains that were achieved by the BWTAC and GWTAC concepts.

Two promising aspects of ACES are the scope and detail of the results it provides, particularly with respect to the interaction of NAS agents. This type of detail is much more than a node and link model of the NAS could possibly provide. The ability to analyze the need for the AAC concept through the examination of detailed sector count data is an example of this. The analyzed data presented in this report represents a modest subset of information that could be mined from this data set, and more recent versions of ACES greatly expand upon both the modeling and the analysis capabilities presented in this paper.

Acknowledgments

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