Terminal Area Modeling Complexity Alternatives in a NAS-wide Simulation

George J. Couluris, Ph.D., and Gregory C. Carr
Seagull Technology, Inc., Campbell, CA 95008-6902

Larry Meyn and Karlin Roth, Ph.D.
NASA Ames Research Center, Moffett Field, CA 94035-1000

and

Anna Dabrowski and James Phillips
Seagull Technology, Inc., Campbell, CA 95008-6902

The Airspace Concepts Evaluation System (ACES) is a distributed fast-time computer simulation used for design and trade-off studies of system level concepts for the National Airspace System (NAS). ACES employs multi-trajectory modeling in an agent-based software structure to describe the behavior and interactions of Traffic Flow Management, Air Traffic Control, Flight Deck, and Airline Operational Control functions and associated technologies. ACES modules include airport, terminal, en route and system-wide traffic management and controller agents, dispatcher agents, and flight agents; individual aircraft flight dynamics; and airport, airspace, meteorological, and related infrastructure components. ACES simulates gate-to-gate flight operations through the multi-sector, multi-Center, multi-airport NAS network.

This paper focuses on the design and implementation of enhanced terminal area modeling capabilities in ACES Build 3. Previous builds of ACES have implemented a nodal model to describe runway system utilization at each airport with nominal terminal airspace transit times. The Build 3 capabilities provide improved modeling fidelity by accounting for individual runway operations and enabling the specification of additional detail in terminal airspace network operations. The Runway Modeling capability simulates individual aircraft operations on individual runways based on user-specified runway use configurations and runway interactions at an airport. The Simplified Terminal Airspace Network Modeling capability simulates irregular terminal airspace boundaries, variable terminal transit times and multiple airport operations in a terminal area. ACES Build 3 introduces capabilities to apply more complex terminal area modeling to selected airports while retaining the less-complex nodal model at other airports. ACES also supports variable complexity modeling by enabling users to define the time span over which Traffic Flow Management agents have accurate knowledge of upcoming airport operating conditions (versus inaccurate knowledge based on extrapolated forecasts) and to define the mode by which traffic flow restrictions are simulated (i.e., determined by runway system operating dynamics versus manually-defined static acceptance rates). These features support the modeling of decision support tools of variable levels of sophistication, enabling ACES users to assess the relative value of alternative advanced tool development efforts.

Nomenclature

ACES	=	Airspace Concepts Evaluation System
AOC	=	Airline Operational Control
ATC	=	Air Traffic Control
ATCSCC	=	Air Traffic Control System Command Center
ATM	=	Air Traffic Management
ARTCC	=	Air Route Traffic Control Center
EDT	=	Eastern Daylight Time
IFR	=	Instrument Flight Rules
NAS	=	National Airspace System
nmi	=	Nautical Miles
TAS	=	True Airspeed
TFM	=	Traffic Flow Management
TRACON	=	Terminal Radar Approach Control
VFR	=	Visual Flight Rules

I. Introduction

The Airspace Concepts Evaluation System (ACES) is a large-scale, fast-time, computer simulation of gate-to-gate flight operations through the National Airspace System (NAS). ACES is being developed by the NASA Virtual Airspace Modeling and Simulation project to assess future Air Traffic Management (ATM) concepts of operation. The simulation employs multi-trajectory modeling in an agent-based software structure to describe the behavior and interactions of Traffic Flow Management (TFM), Air Traffic Control (ATC), Flight Deck, and Airline Operational Control (AOC) entities. ACES models both terminal and en route operational domains, covering the multi-sector, multi-Center, multi-airport NAS network. This paper focuses on the design and implementation of enhanced terminal area modeling capabilities in ACES Build 3.

Previous builds[1] of ACES have implemented a Nodal Model to describe terminal operations at each airport. The Nodal Model treats an airport as a traffic source/sink point and analyzes delays based on user-defined airport acceptance rates (to represent traffic flow through an airport's runway system without modeling individual runways) and nominal terminal airspace transit and surface taxi times. The new ACES Build 3 introduces capabilities to apply more complex terminal area modeling to selected airports while retaining the less-complex Nodal Model at all other airports. The Build 3 capabilities provide improved modeling fidelity by accounting for individual runway operations and enabling the specification of additional detail in terminal airspace network operations. The ACES Build 3 enhancements are encapsulated in the:

(1) Runway Model; and

(2) Simplified Terminal Airspace Network Model.

These capabilities consist of software utilities that model various components of terminal operations. The utilities include: user-input mechanisms for describing local runway systems, airspace operating structures, and procedures and rules corresponding to airport operating conditions (e.g., visual versus instrument operations).

The Runway Model incorporates software utilities to support simulation of individual aircraft operations on individual runways at an airport, based on user-specified runway use configurations and runway interactions. The Runway Assignment utility determines takeoff and landing runways for each flight according to boundary fix and aircraft type specifications. The Runway Aircraft Spacing utility determines takeoff and landing times by individual runway in conformance with airport operating procedures, runway configurations, and airport operating conditions. This utility uses pair-wise aircraft spacing rules (based on minimum wake-vortex separation requirements and excess spacing buffers) to assign runway operations and delays.

The Simplified Terminal Airspace Network Model incorporates a linkage structure and software utilities to support simulation of variable terminal airspace transit times and multiple airports in a terminal area. The linkage structure connects nodes representing boundary fixes with nodes representing runway thresholds or airports. The network modeling capability applies aircraft separation rules at the link end points (nodes) but not along the link, nor at link crossings. The Flexible Terminal Airspace Boundary utility determines the configuration and use of arrival and departure fixes on the terminal airspace boundary, which may be circular or irregularly shaped in Build 3. The Runway-Boundary Fix Linkage utility determines flight transit times between specific fixes and an airport. The Multiple Airports utility enables modeling interactions among the different runway systems, arrival and departure paths and boundary fixes servicing a common terminal area. The utility synchronizes traffic flow planning and movement in a multi-airport terminal environment.

This paper describes the runway-specific and terminal airspace network modeling structure implemented in ACES Build 3 to improve the fidelity of its terminal area analysis. This structure is defined by the simulation capabilities of the Runway Model and Simplified Terminal Airspace Network Model. Their mutual application as a relatively complex terminal area simulation tool is described relative to the simpler airport nodal model. The capability of the runway-specific modeling to distinguish capabilities of alternative decision support tools is described with respect to two modes for conducting Airport TFM assessment: (1) Airport Automated TFM planning which projects and assesses dynamic takeoffs and landing requirements by individual aircraft; and (2) Airport Manual TFM planning which applies static acceptance rates. (The Manual TFM planning mode currently is modeled in an ACES internal development version as a Build 3 enhancement). We also address the ACES capability to examine NAS performance impacts due to variability in time horizons over which TFM agents have accurate information describing future airport operating conditions.

II. ACES Modeling Process

A. General Modeling Process

The ACES NAS-wide 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 emulates Air Traffic Management (ATM) operations encompassing TFM and ATC components, flight dynamics, en route winds, and airport operating conditions. ACES accounts for airspace and airport designs and procedures, including airport visual flight rules (VFR) and instrument flight rules (IFR). Agent modeling structures represent NAS entities and operations including the Air Traffic Control System Command Center (ATCSCC), the en route Air Route Traffic Control Center (ARTCC), the Terminal Radar Approach Control (TRACON), the Airport Traffic Control Tower, and aircraft entities. ACES Build 3 (by default input data) simulates 250 airports, 20 ARTCC's and all en route sectors for current conterminous U.S. domestic operations.[1]

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. By this process, TFM modeling agents in ACES assess projected demand over planning horizons, develop traffic flow plans, and issue traffic restrictions to ATC and other TFM agents. ACES then propagates these TFM constraints or restrictions through the NAS. ATC agents manage tactical flight movement by applying standard operating procedures to resolve the TFM restrictions and potential violations of aircraft separation minima. An advanced four-degree of freedom trajectory model emulates the movement of each aircraft along a four-dimensional trajectory in conformance with its current flight plan and clearance.[1]

B. Airport Modeling Process

In the ACES airport nodal modeling mode[1], the Airport TFM model governs runway system operations (see Figure 1). The Airport TFM Nodal Model sets runway system arrival and departure acceptance rates based on assessments of departure versus arrival traffic loading (i.e., scheduled and currently queued fights), airport operating conditions and throughput limit parameters (i.e., maximum acceptance rates). Each Airport TFM agent issues the runway system arrival and departure acceptance rates to its Airport ATC agent, and issues landing time restrictions to its TRACON agent (for subsequent propagation to upstream agents). The Airport ATC Nodal Model applies the acceptance rates to assign takeoff and landing times.

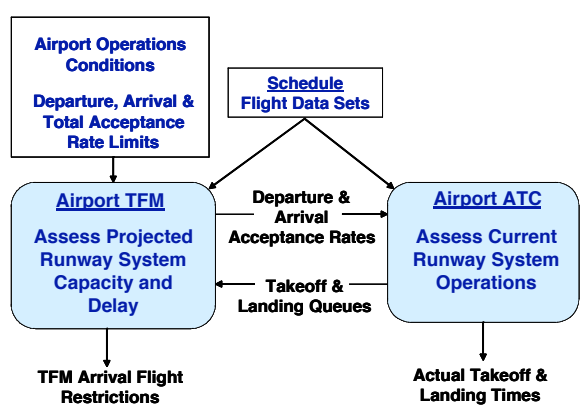

Figure 1. ACES Airport Nodal Modeling

In the ACES runway modeling mode (a Build 3 feature), the Airport Automated TFM and Airport ATC models use a common set of parameters to determine operations (see Figure 2). These parameters define the rules and procedures for using individual runways and separating individual aircraft (rather than gross

airport throughput limit parameters). This process enables representation of specific operating requirements at an airport corresponding to an operational concept under study. ACES allows the user to specify a schedule of airport operating conditions that is used by the Airport ATC model as well as the Airport Automated TFM model (as opposed to the nodal modeling in which these data are provided only to the Airport TFM model). The Airport ATC model applies the runway operating rules and procedures (corresponding to the airport operating conditions schedule) to determine and assign takeoff and landing times by flight by runway. Separately, the Airport Automated TFM model uses the same operating conditions schedule, rules and procedures to determine TFM restrictions to delay arrival flights. The Airport ATC and Airport TFM models are logically consistent, but differ in that the Airport ATC model operates in current simulation time (e.g., in steps of 5-minute time scans) while the Airport TFM model operates in a "look-ahead" planning mode (e.g., in steps of 15-minute time frames over a user specified TFM planning horizon). ACES invokes a TFM assessment for each airport according to a schedule (default: hourly) or upon a change to airport operation conditions (e.g., a switch from VFR to IFR operations at a specific site).

In both nodal and runway modeling, ACES applies nominal inbound and outbound taxi times by airport to represent surface traffic movement between terminal gate and runway/airport nodes. The Surface Traffic Limitations function assigns taxi delay based on user-definable parameters describing surface traffic congestion conditions and constraints.

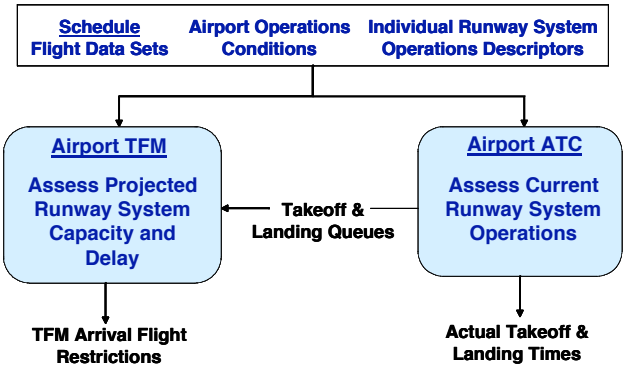

Figure 2. ACES Airport Runway Modeling

ACES Build 3 provides the user with the option to apply a Manual TFM mode in conjunction with the runway modeling mode. In the Manual TFM mode, the Airport TFM agent applies pre-defined arrival and departure acceptance rates (that do not vary with arrival versus departure traffic loading mix as in nodal modeling), and do not depend on aircraft separation rules (as in the Automated TFM mode). The Airport TFM agent issues TFM landing restrictions to its TRACON agent based on these static acceptance rates. The corresponding Airport ATC agent continues to apply pair-wise minimum separation rules regardless of TFM acceptance rates.

The ACES Nodal Model of any airport uses user-defined input parameters specifying the departure, arrival, and total acceptance rate limits for user-defined airport operating conditions. The Runway Model maintains this functionality, but adds the capability to model individual runway operations for one or more special study airports as defined by the user. Hence, ACES Build 3 simultaneously models different airports at either of two levels of complexity (per user specification): (1) nodal airport runway system throughput is governed by acceptance rate limits; and (2) throughput for airports with individual runways is determined by descriptions of local operating procedures.

C. Terminal Airspace Modeling Process

ACES Build 3 defines the terminal operation using nodes to represent the terminal gate system, runways, and arrival and departure fixes. As a default, ACES assigns a generic nodal model (see Figure 3) to each airport unless otherwise specified by the user. In this generic assignment, one node represents a complete airport runway system. One TRACON is associated with each generic airport. Eight generic nodes represent four arrival fixes and four departure fixes equally-spaced on a circle of a 40-nmi radius from the airport node (i.e., the boundary between the TRACON and ARTCC).

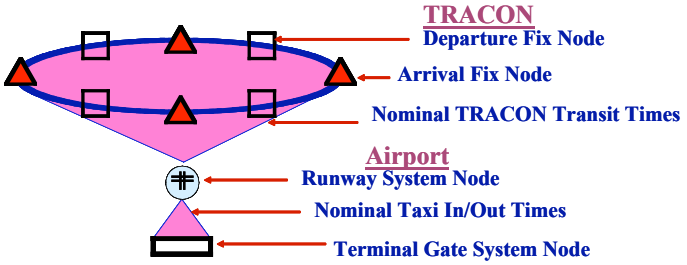

Figure 3. ACES Terminal Area Generic Nodal Modeling

ACES Build 3 enables application of a simplified network concept to connect TRACON boundary fixes with nodal airports as well as individual runway thresholds of runway-modeled airports. To support this concept, ACES

provides the user with the ability to define the terminal area model for any airport and TRACON (see Figure 4). The user has the ability to specify the radius and the number and location of TRACON fixes for any airport when in nodal modeling mode. The user has the ability to define an irregularly shaped TRACON boundary associated with either a nodal-modeled or runway-modeled airport, and to define linkages between fixes and the airport nodes. In the case of the airport runway model, a node represents the landing or takeoff threshold of a runway. Each runway node may be linked with user-specified boundary fixes. In the case of a TRACON with a single nodal modeled airport, ACES automatically links the node of each arrival and departure fix with the airport node.

The user also has the ability to specify multiple airports within a terminal area serviced by a single TRACON. ACES associates boundary fix nodes with runway threshold nodes or nodal airports (see Figure 5). A terminal area model may contain any number of nodal and runway modeled airports, or exclusively nodal modeled airports, or exclusively runway modeled airports.

Aces Build 3.0 automatically calculates terminal area transit times flight-by-flight for specific boundary fix-and-runway/airport pairings using representative aircraft speeds (speeds are based on aircraft type). This calculation distinguishes distances between an airport and various fixes.

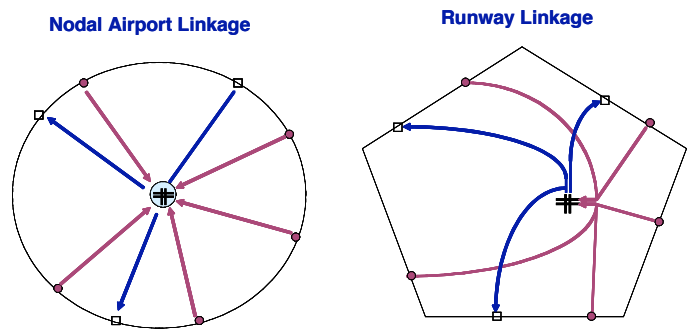

Figure 4. ACES Single-Airport Terminal Area Simplified Terminal Airspace Networks

The network structure supports simulation of special terminal airspace operations and concepts, specifically synchronized concurrent landing operations (i.e., closely-spaced, side-by/near-by/simultaneous runway approaches and landings). This and other runway and terminal airspace modeling features are described in the following sections.

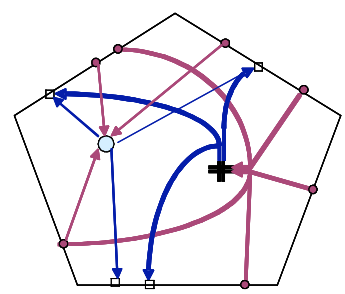

Figure 5. ACES Multiple-Airport Terminal Airspace Network

III. Runway System Modeling

ACES Build 3 supports application of either the Nodal Model or the Runway Model (if specified by the user) to an airport.

A. Nodal Model

ACES nodal modeling treats the runway system node as the critical constraint, and has no need to simulate each takeoff and landing operation by individual runway. Instead, the Airport TFM and ATC Nodal Models process takeoffs and landings through the airport node in a coordinated manner. The Airport TFM Nodal Model develops and provides acceptance rates to the Airport ATC Nodal Model which uses these inputs to determine runway system utilization.

1. Airport TFM Nodal Modeling

Each Airport TFM model examines projected takeoff and landing traffic loading at the runway system based on the flight schedule. The ACES Airport TFM Nodal Model sets runway system arrival and departure acceptance rates over a TFM planning horizon (default: 6 hours) based on airport capacity descriptors. The acceptance rates vary over time depending on arrival versus departure mix and airport operating conditions (VFR procedures generally provide higher rates than IFR procedures). Concurrently, the Airport TFM model also determines planned landing times, including any delays needed to meet the acceptance rates. The Airport TFM model transmits the planned acceptance rates to its Airport ATC model, and transmits planned landing times to its TRACON TFM model. The Airport TFM agent also relays to its Airport ATC model any planned flight takeoff time restriction received from its TRACON TFM model. Such a restriction is due to an en route constraint at a departure fix set by an ARTCC TFM model.

2. Airport ATC Nodal Modeling

Each Airport ATC model simulates the processing of actual flight operations through the runway system (where the system is a single node). The Airport ATC model examines requested takeoff and landing traffic loading at the runway system derived from the flight schedule. The ACES Airport ATC Nodal Model assigns actual takeoff and landing times based on comparative analyses of the flight schedule versus the arrival and departure acceptance rates (determined by the ACES Airport TFM Nodal Model). The model spaces successive takeoffs and successive landings to conform to the overall airport 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.

B. Runway Model

The Airport TFM and Airport ATC models operate separately from each other in the runway modeling mode in ACES Build 3. Both the Airport TFM and Airport ATC models selectively invoke common utilities that are the core of the runway modeling function. The utilities determine runway assignment for each flight and valid aircraft spacing required between successive runway operations as described in the following paragraphs. Using the runway modeling utilities, the Airport TFM model projects properly-spaced takeoff and landings over a TFM planning horizon (default: 6 hours) and issues TFM landing time restrictions to its TRACON agent to accommodate projected arrival delays. The Airport ATC model uses the runway modeling utilities to assign actual takeoff and landing times independently of the TFM projections.

1. Runway Assignment

The Runway Assignment utility applies fix-to-runway mappings defined by the user for a given airport operating condition. The mappings are encoded in a Runway Assignment Table for an airport that specifies the takeoff and landing runway identities based on boundary fix and airport operating condition. The parameters, shown in Table 1, include:

- Airport Id: Airport identifier (Id) 3 or 4 letter code
- Operating Condition: Name of the airport operating condition
- Fix Id: Fix identifier code (alphanumeric) of each eligible fix for the operating condition
- Flight Operation: Arrival (A) or Departure (D) operation for the fix and runway
- Aircraft Engine Type: Jet (J), turbojet (T) and/or piston (P) engine type for the fix and runway
- Default Runway Assignment Id: Identifier (alphanumeric) of the default runway associated with each fix for the operating condition.

Table 1. Illustrative Runway Assignment Table (Partial)

		Runway Assignment Parameters			
Airport Id	Operating Condition	Fix Id	Flt Op-era-tion	Aircraft Engine Type	Default Runway Assign-ment Id
KEWR	VFR SW 22L/R-11	SHAFT	A	J	22L
KEWR	VFR SW 22L/R-11	SWEET	A	J	22L
KEWR	VFR SW 22L/R-11	BREZY	A	T/P	11
KEWR	VFR SW 22L/R-11	HAARP	D	J/T/P	22R
KEWR	VFR SW 22L/R-11	SPARTA	D	J/T/P	22R
KEWR	IFR SW 22L/R	SHAFT	A	J	22L
KEWR	IFR SW 22L/R	SWEET	A	J	22L
KEWR	IFR SW 22L/R	BREZY	A	T/P	22L
KEWR	IFR SW 22L/R	HAARP	D	J/T/P	22R
KEWR	IFR SW 22L/R	SPARTA	D	J/T/P	22R

Runway assignments for departure (or arrival) flights are determined as follows for a given airport and operating condition:

1. Determine the aircraft operation, aircraft engine type, and departure fix from the Flight Data Set.
2. For aircraft operation and aircraft engine type, search the Runway Assignment Table for the fix that matches the departure (or arrival) fix in the Flight Data Set
3. Select the corresponding default departure (or arrival) runway assignment from the Runway Assignment Table.

The Flight Data Set for each flight describes origin and destination airports, aircraft type and flight trajectory updates, including fix and runway assignments.

2. Runway Aircraft Spacing

The Runway Aircraft Spacing utility determines the time separation required between two successive runway operations (landings, takeoffs or combinations thereof) for specific runways at a selected airport given pair-wise aircraft minimum separation requirements (depicting FAA rules[2]), pair-wise aircraft separation buffer matrices (representing excess spacing required for trajectory prediction uncertainties) and time-varying airport operating conditions and associated runway use configurations. For each airport modeled with individual runway operations, the utility applies user-defined data encoded in the Runway Interaction Table, Minimum Separation Tables, and Separation Buffer Tables described in the following paragraphs.

Runway Interaction Table -- For each airport, one user-defined Runway Interaction Table defines the valid runway interactions and pair-wise runway operations for the operating condition (see Table 2 example). This table also identifies the Minimum Separation Table and Buffer Table for each valid runway interaction.

Table 2. Illustrative Runway Interaction Table

Operating Condition	Runway 1	Operation 1	Runway 2	Operation 2	Separation Table	Buffer Table
VFR SW 22L/R-11	22L	A	22L	A	S23	B0
VFR SW 22L/R-11	22L	A	22R	D	S2	B0
VFR SW 22L/R-11	22L	A	11	A	S16	B0
VFR SW 22L/R-11	22R	D	22R	D	S1	B0
VFR SW 22L/R-11	22R	D	22L	A	S2	B0
VFR SW 22L/R-11	11	A	11	A	S1	B0
VFR SW 22L/R-11	11	A	22L	A	S18	B0

The Runway Interaction Table includes the following parameters:

- Operating condition: name of the airport operating condition
- Runway 1: Runway identifier code for the first runway for a pair of aircraft operations
- Operation 1: Operation type – arrival (A) or departure (D) - of the first (lead) aircraft of a pair of aircraft operations
- Runway 2: Runway identifier code for the second runway for a pair of aircraft operations
- Operation 2: Operation type of the second (following) aircraft of a pair of aircraft operations
- Separation Table Name: Identification name of the appropriate Minimum Separation Table for the runway interaction and aircraft operations pair
- Buffer Table Name: Identification Name of the Buffer Table for the runway interaction and aircraft operations pair

In the above illustration, the first line in table identifies the separation table and buffer table to be used to determine spacing requirement between a pair of successive landings on Runway 22L.

Minimum Separation Tables -- Minimum Separation Tables contain matrices that define the minimum allowable time separation between pairs of successive runway operations for a given runway geometry and interaction. These matrices account for wake turbulence spacing as well as runway occupancy characteristics.

ACES Build 3.0 provides default Minimum Separation Tables for various generic runway geometries or interactions for nominal VFR and IFR operating conditions. The separation tables are generic in that they represent nominal, commonly-used runway geometries and interactions, not individual runways or operations at specific airports. Based on knowledge of airport operations, the user specifies (see Table 2 above) which generic separation tables best represent runway interactions at a specific airport for a given airport operating condition. In this manner the user can 'build' a model of a specific airport and operating condition using the generic separation tables. ACES enables the user to modify the default separation tables or define new tables as needed.

The ACES default separation tables account for two types of aircraft operations: departure (DEP) and arrival (ARR). In this case, four possible pairs of aircraft operations form the basis for each separation matrix: (1) arrival followed by an arrival, (2) arrival followed by a departure, (3) departure followed by an arrival, and (4) departure followed by a departure. These respectively are designated arrival1–arrival 2, arrival1 – departure2, departure1 - arrival2, and departure1 - departure2. For each aircraft operation pair, there is a corresponding matrix of sixteen values reflecting the FAA required separation minima[2] for leading-trailing aircraft pairs for four default weight/size-dependent aircraft separation classes: Small, Large, Boeing 757 and Heavy. Each default Minimum Separation Table is then comprised of four symmetric matrices, each with sixteen values representing the separation minima

based on runway operation pair and weight class. An example of a Minimum Separation Table for the case of a single runway and VFR operating is shown in Table 3.

Minimum separations table values are set so as to preclude situations in which arrival aircraft may overtake slower aircraft on final approach. The overtaking event is prevented by adjusting the runway separation matrix entries to compensate for typical speed differences between aircraft classes. The aircraft class designations in the separation tables are used as surrogates for speed class.

ACES enables the user to specify an unlimited number of operating conditions. In order to support this capability, each separation table can accommodate n^2 symmetric [mxm] matrices where n is the number of operation types defined by the user, and m is the number of aircraft separation classes defined by the user.

Buffer Tables -- ACES Build 3.0 enables user specification of inter-aircraft time buffers in a format identical to that of the Minimum Separation Tables. The buffer or excess spacing value is added to the Minimum Separation Table value to determine the total minimum spacing required between aircraft in a pair. The ACES Build 3 implementation provides a single default Spacing Buffer Table comprised of four symmetric matrices, each with sixteen values representing the separation buffer based on runway operation pair and weight class. Note that the default value for all Spacing Buffer Table entries is zero.

Table 3. Illustrative Minimum Separation Table

	Aircraft Separation (seconds)			
	SML	LRG	757	HVY
ARR1-ARR2				
SML	58.0	54.0	54.0	50.0
LRG	84.0	54.0	54.0	50.0
757	84.0	54.0	54.0	50.0
HVY	140.0	108.0	108.0	72.0
	SML	LRG	757	HVY
ARR1-DEP2				
SML	44.0	44.0	44.0	44.0
LRG	52.0	52.0	52.0	52.0
757	52.0	52.0	52.0	52.0
HVY	58.0	58.0	58.0	58.0
	SML	LRG	757	HVY
DEP1-ARR2				
SML	60.0	58.0	58.0	54.0
LRG	60.0	58.0	58.0	54.0
757	60.0	58.0	58.0	54.0
HVY	60.0	58.0	58.0	54.0
	SML	LRG	757	HVY
DEP1-DEP2				
SML	40.0	46.0	46.0	50.0
LRG	46.0	56.0	56.0	60.0
757	120.0	120.0	120.0	90.0
HVY	120.0	120.0	120.0	90.0

3. Runway Model Application

The Airport TFM and Airport ATC modeling logic assigns projected or actual takeoff and landing times based on requested times (derived from the flight schedule) and spacing requirements. The modeling logic determines an allowable time slot and assigns a valid takeoff or landing time for a current target flight. The Airport TFM and Airport ATC invoke the Runway Assignment and Aircraft Spacing utilities to obtain the allowable time slot, which is the earliest runway time that satisfies the spacing required between all pairs of aircraft runway operations involving the target flight. The valid time is one that satisfies the allowable time slot and the requested runway time (i.e., the latest of these times).

The utility identifies a valid runway operation time by table-lookup using the runway interactions defined by the user in combination with minimum separation and excess spacing tables. Recall the minimum separation matrices are a function of leading-trailing aircraft pairs, aircraft separation class, and runway interactions. Given the requested takeoff or landing time and associated descriptive data for the current target flight and data describing the previous (most-recent) assigned takeoff/landing flight and time for each runway, the utility identifies the allowable time slot and the takeoff or landing time assignable to the target flight by performing the following steps:

1. Pair the current operation (i.e., the next flight requiring an actual takeoff or landing assignment) with the previous (most-recent) operation on each runway.
2. Identify the takeoff or landing time of the previous (most-recent) operation on each runway.
3. Compare each operation pair with operation pairs defined in the Runway Interaction Table. The current operation is the second operation in the operation pair. Select the corresponding Minimum Separation Table and Buffer Table.
4. Select the value from the Minimum Separation Table based on the operation pair and the separation class of each aircraft.
5. Select the value from the Buffer Table corresponding to the operation pair and the separation class of each aircraft.
6. Assign the allowable time slot (i.e., the earliest "legal" candidate takeoff or landing time) by adding the minimum separation and buffer value to the previous takeoff or landing time for each operation pair.
7. Assign the valid takeoff or landing time as the maximum of the allowable time slot (earliest legal takeoff or landing time) or the original requested takeoff or landing time.

Illustrative Example of Runway Model Application

For the purposes of illustration consider the sixth flight in Table 4 depicting a sequence flights for a three-runway (Rwy) configuration:

Assume that Flights 1-5 have been assigned takeoff or landing times and Flight 6 is the current flight requiring a landing time assignment. Flight 6 is an arrival with a default runway assignment of Rwy1. Flight 6's landing operation on Rwy1 can form 3 possible operational pairs with preceding flights on the same or other runways. The preceding operations are Flight 1 on Rwy1, Flight 5 on Rwy2 and Flight 4 on Rwy3 as shown in Table 5. For each operational pair, the spacing logic selects the minimum separation and buffer from the corresponding table. The logic computes the three candidate landing times for Flight 6 by adding the minimum separation and buffer to the previous event time for the three possible operational pairs:

- Flight 6 Allowable Landing Time Slot 1 = Flight 1 Landing Time + Minimum Separation + Buffer
- Flight 6 Allowable Landing Time Slot 2 = Flight 5 Takeoff Time + Minimum Separation + Buffer
- Flight 6 Allowable Landing Time Slot 3 = Flight 4 Landing Time + Minimum Separation + Buffer

The assigned landing time for Flight 6 is the maximum of the original Flight 6 Requested Landing time or the three Allowable Landing Time Slot 3 candidates:

Table 4. Illustrative Flight Sequence

Flight	Rwy1	Rwy2	Rwy3
1	A		
2		D	
3			A
4			A
5		D	
6	A		

Table 5. Illustrative Interacting Flights

Preceding Operation			Subject Operation		
Run-way	Opera-tion Id	Flight Id	Run-way	Opera-tion Id	Flight Id
Rwy1	A	1	Rwy1	A	6
Rwy2	D	5	Rwy1	A	6
Rwy3	A	4	Rwy1	A	6

Flight 6 Assigned Valid Event Time = MAXIMUM {Flight 6 Requested Event Time, Flight 6 Slot Time 1, Flight 6 Slot Time 2, Flight 6 Slot Time 3}

Taking the maximum of the candidate landing times and the original requested landing time ensures that the separation requirements are met between successive operations. The Flight 6 Landing Time now becomes the latest event time for Rwy1.

IV. Simplified Terminal Airspace Network Modeling

The ACES Build 3 terminal airspace modeling function operates in conjunction with the airport modeling function regardless of airport modeling mode (nodal or runway). ACES provides the user with the option to implement the default arrival and departure fix structure (described above in Section II.C) and associated fix-airport linkages for any or all airports, or to define the airspace modeling structure for specific TRACONs. The user is able to specify the following TRACON parameters in tabular format: circular or irregularly-shaped terminal airspace boundaries, fix utilization, fix spacing procedures, terminal airspace transit times, synchronized/simultaneous landing procedures, and multiple airports as described in the following paragraphs.

A. Flexible Terminal Airspace Boundary Specification

ACES Build 3 constructs the terminal boundary fixes based on user specifications. Airports that do not have user-defined terminal boundary fixes are automatically assigned the default generic terminal area design. The user specifies the following parameters defining the identity and location of each terminal boundary fix:

- TRACON Id: TRACON identifier code
- Fix Name: Boundary fix formal identification text
- Fix Id: Boundary fix identifier code
- TRACON's Airport Reference Point: Identifier of an airport in the TRACON terminal area
- and
- Distance or TRACON radius: Radial distance (nmi) from the TRACON's Airport Reference Point to a terminal area circular boundary

- Bearing: Azimuth (clockwise degrees from North) to the Fix from the TRACON's Airport Reference Point
- or
- Fix Latitude/Longitude: Earth coordinates

The user specifies the following parameters that define the operating procedures for each terminal boundary fix:

- Fix Flight Operation Type: Fix's eligibility for use by Arrival (A) or Departure (D) or Over/Cruise (C) flights
- Fix Engine Type: Fix's eligibility for use be jet (J), turbojet (T) and/or piston (P) (default: jet, turbojet and piston J/T/P)
- Airport Id's: Airport identifier (3 or 4 letter) codes of airports served by the indicated fix

These data enable the user to designate each boundary fix according to eligibility for use by arrival or departure operation type, engine type and airport. The user may define collocated boundary fixes by designating a unique name and identifier for each such virtual fix by specifying a common location. ACES treats each boundary fix as a procedurally-independent entity, where air traffic crossing a boundary fix is separated from (i.e., does not intermingle with) traffic crossing another boundary fix. The user may define separate but collocated fixes for each engine type or commingled streams (e.g., segregated or combined streams of jet, turbojet and/or piston engine type). ACES applies spacing rules only to flights within each stream crossing a common (real or virtual) boundary fix.

ACES interprets the terminal boundary specifications and translates distance/radius and bearing data to latitude/longitude data and vice versa. The resulting definition of each fix describes name, location (latitude/longitude), bearing and great circle distance from the TRACON's reference point (normally a major airport's reference point), and engine type and operation type of aircraft eligible to use the fix. Each fix also is linked with specific runways and airports as described above in Section III.B.1.

B. Boundary Fix Spacing

The ACES Build 3 Fix Aircraft Spacing Requirement utility determines the time spacing required between two successive aircraft crossing a terminal airspace boundary fix (which may be a virtual fix collocated with other fixes). The spacing is based on a user-adjustable boundary fix in-trail minimum separation parameter (default: 5 nmi) and each aircraft's speed at the fix.

ACES en route flight trajectory modeling assign TRACON boundary fixes crossing altitudes by engine type (10,000, 8,000 and 6000 feet for jet, turboprop and piston respectively) regardless of terminal airspace modeling fix designations. En route trajectory modeling requires specific altitude assignments at the boundary fixes to define end points. NOTE: Trajectory modeling is not performed in terminal airspace, and specific altitude assignments are not needed for terminal modeling.

C. Terminal Airspace Transit Time

The ACES Build 3 Terminal Airspace Transit Time utility calculates a representative terminal transit time for each flight based on user-definable or default (ACES calculated) terminal airspace flight distance and (user-adjustable) speed data.

1. Terminal Area Flight Distance

The ACES Build 3 user interface supports user specification or default assignment of flight distance between each fix-airport/runway pair. The user has the option to enter the terminal airspace flight distance data for each fix-runway or fix-nodal airport link. Otherwise as a default ACES approximates short-side and long-side geometric routing relationships between boundary fixes and airports/runways based on latitude and longitude data for the boundary fix, airport reference point and (default or user-specified) final approach fix.

For nodal-modeled airports, ACES calculates great circle distance between the boundary fix and airport reference point. For runway modeling for an arrival flight, ACES calculates and sums the great circle distance between the boundary fix and final approach fix and the great circle distance between the final approach fix and the airport reference point. For departure or arrival flights in runway modeling mode, ACES adjusts the flight distance to compensate roughly for non-direct (non-great circle) routing between the boundary fix and the airport runway system (as a function of the angular difference between the runway centerline and the vector to the boundary fix).

2. Terminal Area Flight Speed

ACES Build 3 provides user-adjustable data describing representative operating characteristics by aircraft type. These data include typical zero-wind true airspeed (TAS) in the terminal airspace by aircraft type. Instantaneous speeds specified at boundary fix, final approach fix and runway threshold are used to calculate average speeds on segments between fixes during climb and descent:

3. Terminal Area Flight Time Calculation

ACES Build 3 calculates transit time for each flight using the terminal airspace flight distance and speed data.

D. Terminal Synchronized Concurrent Operations

ACES Build 3 provides a Synchronized Formation Landing utility that simulates side-by/near-by approach and landings on closely-spaced runways (typically parallel runways). The utility provides for and implements user-specified modeling parameters that build on the runway modeling capability. The user specifies or applies the following parameters to activate and define the formation landing procedure:

- Airport Id: Airport identifier (3 or 4 letter) code
- Operating condition: Name of airport operating condition
- Runway identifier: Identifier code of each runway used for the operating condition.
- Runway operations: Valid runway operations for the operating condition: arrival (A), and if applicable, departure (D).
- Runway engine types: Aircraft engine types eligible for each runway for the operating condition, default: jet (J), turbojet (T), piston (P) or in any combination.
- Synchronization Group Id: Identification code (alphanumeric) of the synchronization operation (default: 0).
- Flight Time Adjustment Tolerance (seconds): Terminal airspace fight time decrease/speed-up range (default: 0 seconds) and increase/delay range (default: 120 seconds) for fitting a flight into a formation
- Flight Stagger/Other Runway Minimum Spacing Override (seconds): Minimum longitudinal spacing between adjacent flights in a formation and between a formation flight and a predecessor flight on another synchronized runway (default: 0 seconds)
- Formation Flight Time Range (seconds): Maximum allowed time span between the first/leading and last/following flight in a formation (default: 20 seconds)

These parameters identify one (or more) Runway Synchronization Group(s) and the specific airport operating condition, runways and flight operations associated with that Group. Each group identifier references a unique synchronized procedure (i.e., each group is independent). The grouping identifies runways on which flights are synchronized (e.g., land simultaneously or nearly simultaneously regardless of standard spacing rules). Parameters define conditions by which landing flights are allowed to approach the runways in closely-spaced, side-by or near-by formation (i.e., with or without longitudinal stagger), subject to a formation time range limit (i.e., the time span between the first and last flight) that accounts for wake vortex development or other considerations (e.g., a need to build slots for crossing runway operations). The formation landing parameters override the standard spacing requirement between the subject landing flight and predecessor flights on other runways that are members of the Synchronization Group. Standard spacing requirements are applied to predecessors on the same-runway and non-member runways.

The Synchronized Formation Landing utility identifies a qualifying flight, determines the allowable landing time spans that satisfy the synchronization parameter constraints, and assigns the earliest conforming landing time.

E. Multiple Airports in Terminal Area

ACES Build 3 enables user assignment of multiple airports to a single TRACON in association with arrival and departure boundary fix specification.

ACES provides user flexibility in assigning operating procedures applicable to each boundary fix as described above in Section IV.A. The user is able to designate different virtual fix identifiers for individual fixes or collocated fixes (common latitude and longitude) with eligibility for use by specific flight operations (arrival or departure) and specific engine types (jet, turboprop, piston or combination thereof). This flexibility enables modeling a variety of local operating procedures in which boundary fixes are defined to serve specific airports and engine types. For example, the user is able to construct a set of separate virtual fixes to represent an actual fix serving an airport with different engine types segmented by altitude (without explicitly specifying altitude restrictions).

ACES Build 3 modeling supports shared use of a common boundary fix by multiple airports. Boundary fixes may or may not be segregated by specific airport (e.g., focal versus satellite airports) and engine type, with or without altitude separation.

F. Terminal Area Modeling Application

The ACES *Airport* TFM and ATC models are integrated with one other and with the *TRACON* TFM and ATC models. A brief summarization of the Build 3 terminal area roles for the Airport TFM/ATC and TRACON TFM/ATC models is as follows.

1. Airport TFM Model

Departures -- The Airport TFM model in a single or multiple airport TRACON configuration assigns projected takeoff times for nodal and runway modeled airports independently for each airport. The projected takeoff times are used to determine and issue acceptance rates to its Airport ATC Nodal Model.

Arrivals -- The Airport TFM model in a single or multiple airport TRACON configuration assigns projected landing times for nodal and runway modeled airports independently for each airport. The projected landing times are used to determine and issue arrival acceptance rates to its Airport ATC Nodal Model and TFM landing restrictions to its TRACON TFM model for arrival flights. The Airport TFM Model also applies the Synchronized Formation Landing utility if specified for a runway modeled airport.

2. Airport ATC Model

Departures -- The Airport ATC model assigns actual takeoff times for nodal and runway modeled airports and periodically reports actual takeoff queue state to the Airport TFM model.

Arrivals -- The Airport ATC model assigns actual landing times for nodal and runway modeled airports and periodically reports actual landing queue state to the Airport TFM model. The Airport ATC Model also applies the Synchronized Formation Landing utility if specified for a runway modeled airport.

3. TRACON TFM Model

Departures -- The TRACON TFM model forwards/relays to the Airport ATC model any TFM boundary crossing time restrictions on departure flights received from ARTCC TFM models. The TRACON TFM model calculates transit times for these restricted flights to translate the departure fix crossing time restrictions into takeoff time restrictions.

Arrivals -- The TRACON TFM model forwards/relays to ARTCC TFM model any TFM landing time restrictions on arrival flights received from Airport TFM model. The TRACON TFM model calculates transit times for these restricted flights to translate the landing time restrictions into arrival fix crossing time restrictions.

4. TRACON ATC Model

Departures -- The TRACON ATC model calculates terminal airspace transit times and assigns valid departure fix crossing times using the Fix Aircraft Spacing Requirement utility

Arrivals -- The TRACON ATC model calculates transit times and assigns a requested landing times for arrival flights. The TRACON ATC agent issues requested landing times to its Airport ATC model.

V. Modeling Complexity Alternatives

ACES Build 3 supports modeling of a range of procedural alternatives. ACES enables the user to manipulate input parameters to examine various runway and fix spacing separation requirements, runway configurations and aircraft assignments, acceptance rate limits, boundary fix configurations and aircraft assignments, airport-to-fix routing configurations, aircraft type mix and so forth. The Runway Model can be used for detailed modeling of airport study sites of interest while the Nodal Model can be used to describe other sites requiring less detailed modeling. We are able to apply the higher fidelity Runway Model to targeted airports and operations in order to examine and characterize salient operational issues.

In addition, ACES is capable of examining the potential gains in NAS performance due to advanced decision support tools. This capability is derived from the agent-based modeling architecture which enables simulation of specific functions associated with TFM, ATC, flight deck, AOC and infrastructure components and their interactions. In particular, ACES modeling parameters and algorithms enable assessment of the impacts of (1) improved knowledge of future airport operating conditions and (2) dynamic traffic load-sensitive airport Automated TFM planning as opposed to static Manual TFM planning. These ACES modeling features are addressed below.

A. TFM Planning Horizon and Knowledge Limit

ACES provides a user-adjustable Knowledge Limit parameter that controls the airport operating conditions data provided to the Airport TFM module at the start of a TFM assessment. Depending on the Knowledge Limit parameter setting, the Airport TFM may have at the start of an assessment: (1) accurate knowledge only of current airport operating conditions; (2) accurate knowledge of current and a limited range of upcoming airport operating conditions; or (3) accurate knowledge of airport operating conditions over the entire (6-hour) TFM planning horizon (i.e., perfect knowledge).

The Knowledge Limit parameter defines the time range over which the Airport TFM model has accurate airport conditions data. A persistence forecast is applied beyond the Knowledge Limit time, meaning the Airport TFM extrapolates the last known airport operating condition (e.g., VFR of IFR) over the remainder of the TFM assessment. A parameter value of zero minutes means the Airport TFM model knows the airport operating condition only at the current simulation time (i.e., the start of the TFM assessment) and applies this initial operating condition to all subsequent time frames in the six-hour TFM assessment. Similarly, the user may set the Knowledge Limit parameter value such that the Airport TFM model has accurate airport operating conditions data through 30 minutes into the future, and extrapolates this 30-mimute condition for the remainder of the TFM assessment. A parameter

value of 60 minutes provides the Airport TFM model with accurate airport operating conditions data through the first hour and the extrapolated persistence data thereafter. A parameter value of six hours means the Airport TFM model is provided with accurate airport operating conditions data for the entire TFM assessment.

B. Airport Automated TFM and Manual TFM

The ACES Build 3 default operation applies the Airport Automated TFM model in which projected runway takeoff and landing times are determined by exercising the Runway Aircraft Spacing utility for each successive flight. This process is exactly the same as used by the Airport ATC model in assigning actual takeoff and landing times. The Airport Automated TFM model essentially mimics the anticipated behavior of the Airport ATC model. The difference being the Airport TFM model has as input the latest updated schedule covering the (6-hour) TFM planning horizon, while the Airport ATC model has as input the actual traffic state at the current simulation time. The Airport Automated TFM model, like its ATC counterpart, is reacting to dynamic traffic loadings and applying individual aircraft and runway operating procedures to develop traffic plans and decisions.

The ACES Build 3 Airport Manual TFM modeling alternative enables the user to specify static arrival and departure acceptance rates. The Airport TFM model determines projected landing and takeoff times based on these manual rates. The manual acceptance rates represent a TFM operation in which acceptance rates are pre-defined for specific operating conditions as illustrated in Table 6. The Airport TFM model uses the projected landing times to determine TFM restrictions for arrival flights. The corresponding Airport ATC model implements aircraft separation minima using the Runway Aircraft Spacing utility regardless of the TFM manual acceptance rates.

At the start of each TFM assessment, the Airport TFM Model extracts the applicable acceptance rate corresponding to specified operating condition and arrival/departure operation type. The Manual TFM model assigns projected landing and takeoff times to a target arrival or departure flight using a Nodal Model-like calculation routine where the pair-wise aircraft spacing is defined by inverse of the Manual Arrival or Manual Departure Acceptance Rate

Table 6. Illustrative Manual TFM Airport Acceptance Rates

Operating Condition	Manual Arrival Acceptance Rate (ac/hr)	Manual Departure Acceptance Rate (ac/hr)
VFR SW 22L/R-11	52	56
IFR SW 22L/R-11	34	44
VFR NE 04/R-11	50	58
IFR NE 04/R-11	34	44

C. Complexity Analysis and Results

We use an internal development version ACES Build 3 to examine the Automated TFM and Manual TFM modes and the effect of the TFM Knowledge Limit parameter. We use data obtained in support of a previous study[3] of Newark International Airport (KEWR). These KEWR data (see Table 1 through Table 6) do not necessarily represent current operations and are used only for illustrative purposes. The analyses and results are preliminary and intended to provide an understanding of the potential applications of ACES.

We generate a hypothetical future KEWR traffic demand for input into ACES that purposely stresses the capacity of the runway configuration as shown in Figure 6. We use KEWR acceptance rates shown in Table 6 to define nominal capacity. Traffic surges exceeding nominal capacity occur between 6AM and 9PM. This busy period has a total of 1175 departure and arrival flights. The full-day has 1300 flights, which we load into ACES. No other traffic is loaded, but all KEWR trajectories to and from other airports are simulated. En route sector capacity constraints and surface traffic limitations are not applied. Hence, the KEWR runway system is the constraining factor. We specify IFR operating conditions for the 9:00AM to 12:00 Noon (local EDT) span and VFR for all other times during the day. We specify a 6-hour TFM

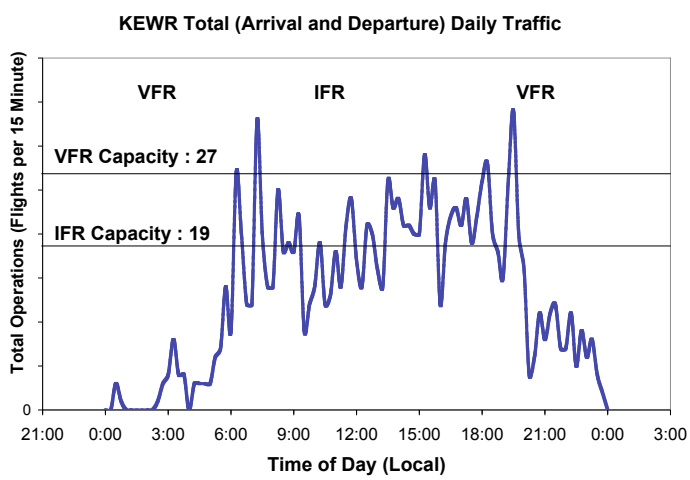

Figure 6 Illustrative Daily Traffic Demand

assessment horizon for traffic projection and planning. We employ the Runway Model to simulate KEWR operations.

TFM Knowledge Limits -- We examine three different TFM Knowledge Limit parameters: 6-hour look-ahead (i.e., perfect knowledge of future airport operating conditions over the TFM planning horizon), 1-hour look-ahead (i.e., accurate forecast is limited to the first hour), and 0-hour look-ahead (i.e., current conditions are extrapolated). We apply ACES in the Automated TFM mode for each of the three TFM Knowledge limits. The resulting KEWR total average busy period delays for departures and arrivals (i.e., actual takeoff or landing time versus scheduled time) are summarized in Table 6. These preliminary results indicate that significant reductions in delay can be supported by technology that enables TFM to develop airport operating plans using improved knowledge of operating conditions. Limited forecast accuracy provides proportionately smaller savings. Figure 7 shows corresponding average delays for each 15-minute period.

Table 6 Illustrative Average Delay (Preliminary) by TFM Airport Conditions Knowledge Limit

Mode: Automated TFM	
TFM Knowledge Limit (hours)	Busy Period Average Delay (minutes/flight)
0	20.2
1	17.6
6	9.5

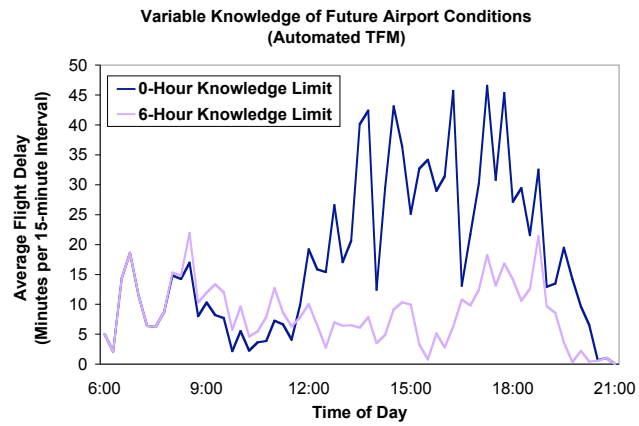

Figure 7 Illustrative 15-minute Average Delay (Preliminary) by TFM Airport Conditions Knowledge Limit

Automated and Manual TFM – We use ACES to simulate Automated TFM and Manual TFM operating modes. We apply ACES using the 6-hour TFM Knowledge Limit for both modes (i.e., both TFM modes have accurate knowledge of future operating conditions). The resulting KEWR total average busy period delays for departures and arrivals are summarized in Table 7. These preliminary results indicate that significant delay reductions can be supported by technology that enables continual dynamic adjustment of airport operating plans (versus imposition of static acceptance rates). Figure 8 shows corresponding average delays for each 15-minute period.

Table 7 Illustrative Average Delay (Preliminary) by TFM Operating Mode

TFM Operating Mode	Busy Period Average Delay (minutes/flight)
Manual	28.0
Automated	9.5

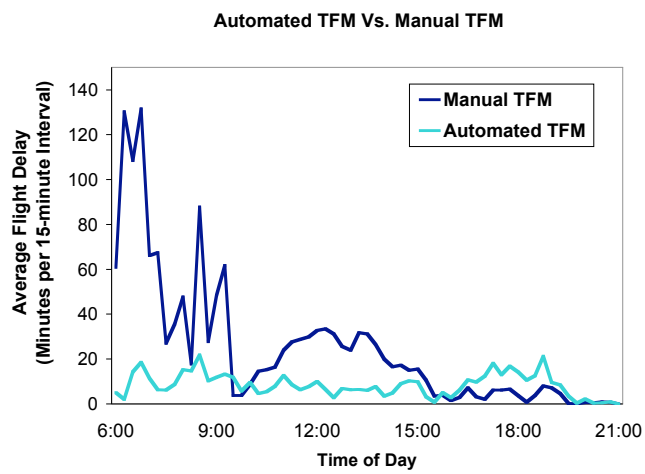

Figure 8 Illustrative 15-minute Average Delay (Preliminary) by TFM Operating Mode

VI. Conclusion

ACES Build 3 introduces capabilities to apply more complex runway and terminal airspace modeling to selected airports while retaining the less-complex nodal model at other airports. ACES also supports variable complexity modeling by enabling users to define the time span over which Traffic Flow Management agents have accurate knowledge of upcoming airport operating conditions (versus extrapolated forecasts) and to define the mode by which traffic flow restrictions are simulated (i.e., determined by runway system operating dynamics versus manually-defined static acceptance rates). These features support the modeling of decision support tools of variable levels of sophistication, enabling ACES users to assess the relative value of alternative advanced tool developments.

Acknowledgments

The ACES simulation is under development for the NASA Virtual Airspace Modeling and Simulation Project under the Air Traffic Management System Development and Integration Contract. The Build 3 development team, which is led by the Raytheon Company, includes Seagull Technology, Inc., SAIC, and Intelligent Automation, Inc.

While selected references are cited, we emphasize that this effort reflects the common knowledge and expertise accumulated over 30 years of collective work in airspace, airport, flight dynamics, traffic demand and computer modeling conducted by many, many individuals and organizations, far too many to identify one-by-one. Much of this previous work has been sponsored by FAA, NASA, DOD and various other public and private members of the aviation and computer science communities.

References

[1]Couluris, G. J., Hunter, C. G., Blake, M., Roth, K., Sweet, D., Stassart, P., Phillips, J., Huang, A., "National Airspace System Simulation Capturing Interactions of Air Traffic Management and Flight Trajectories," *AIAA Modeling and Simulation Technologies Conference*, AIAA-2003-5597, Austin, Tx, August 2003.

[2]Federal Aviation Administration, "Air Traffic Control," FAA Document 7110.65P, Washington, DC, February 2004.

[3]Couluris, G. J., Weidner, T. J., "Terminal Airspace Decision Support Tools Preliminary Benefits Analysis," Final Report, NASA Contract NAS2-98074, Subcontract R-0003, Seagull Technology, Inc., Campbell. CA, December 1999.