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Advanced Interval Management: A Benefit Analysis

Sebastian Timar and Mark Peters
Saab Sensis Corporation, Campbell, California

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Sebastian Timar and Mark Peters
Saab Sensis Corporation, Campbell, California

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

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Available from:

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Fax: 757-864-6500

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Acronyms

A&A .... Arrival and Approach
ABP .... Achieve-by Point
ACSS .... Aviation Communication & Surveillance
ADS-B .... Automatic Dependent Surveillance-Broadcast
AFMP .... Arrival Flow Management Point
AGD .... ADS-B Guidance Display
AIM .... Advanced Interval Management
APT .... Airport
ARC .... Aviation Rulemaking Committee
AOC .... Airline Operations Center
ARTCC .... Air Route Traffic Control Center
ASG .... Assigned Spacing Goal
ASPM .... Aviation System Performance Metrics
ASTAR .... Airborne Spacing for Terminal Arrival Routes
ATC .... Air Traffic Control
ATCT .... Air Traffic Control Tower
ATIS .... Automatic Terminal Information Service
ATOP .... Advanced Technology and Oceanic Procedures
AVOSS .... Aircraft VOrtex Spacing System
CAS .... Calibrated Airspeed
CAVS .... CDTI Assisted Visual Separation
CDTI .... Cockpit Display of Traffic Information
ConOps .... Concept of Operations
CPDLC .... Controller Pilot Data Link Communications
CSPO .... Closely Spaced Parallel Runway Operation
CTA .... Controlled Time of Arrival
Data Comm .... Data Communications
DI .... Defined Interval
DME .... Distance Measuring Equipment
DO .... Departure Operation
DRNP .... Dynamic Required Navigation Performance
DSA1 .... Dependent Staggered Arrivals with One Target
DSA2 .... Dependent Staggered Arrivals with Two Targets
EFB .... Electronic Flight Bag
ERFMP .... En Route Flow Management Point
FAA .... Federal Aviation Administration
FAF .... Final Approach Fix
FIM .... Flight deck-based Interval Management
FIM-S .... Flight deck-based Interval Management-Spacing
FL .... Flight Level
FMP .... Flow Management Point
FMS .... Flight Management System
GIM-S .... Ground-based Interval Management – Spacing
IDAC .... Integrated Departure/Arrival Capability
IAF .... Initial Approach Fix
IFPI .... Intended Flight Path Information
ILS .... Instrument Landing System
IM .... Interval Management

IMC .... Instrument Meteorological Conditions
IM DI .... Interval Management Defined Interval
IM-S .... Interval Management – Spacing
IM DO .... Interval Management during Departure Operations
IM FAS .... Interval Management Final Approach Spacing
IM MSA .... Interval Management with Multi-Stream Arrivals
JPDO .... Joint Planning and Development Office
LOC .... Localizer
LDA .... Localizer-type Directional Aid
LRU .... Line Replaceable Unit
MCP .... Mode Control Panel
MFD .... Multi-function Display
MIT .... Miles-In-Trail
MOPS .... Minimum Operational Performance Standards
NAS .... National Airspace System
NASA .... National Aeronautics and Space Administration
NextGen .... Next Generation Air Transportation System
NM .... Nautical Mile
NOAA .... National Oceanic and Atmospheric Administration
NTZ .... No Transgression Zone
OPD .... Optimized Profile Descent
OTS .... Organized Track Systems
PA .... Paired Approach
PDS .... Paired Dependent Speed
PFAS .... Planned Final Approach Speed
PRM .... Precision Runway Monitor
PTM .... Pair-Wise Trajectory Management
RA .... Resolution Advisory
RNAV .... Area Navigation
RNP .... Required Navigation Performance
RTA .... Required Time of Arrival
SAMM .... Surface Area Movement Management
SAPA .... Simplified Aircraft-based Paired Approach
SID .... Standard Instrument Departure
SOIA .... Simultaneous Offset Instrument Approach
STA .... Scheduled Time of Arrival
STAR .... Standard Terminal Arrival Route
TBFM .... Time-Based Flow Management
TCAS .... Traffic Collision Avoidance System
TMC .... Traffic Management Coordinator
TFMP .... Terminal Flow Management Point
TOD .... Top Of Descent
TRA .... Traffic Resolution Advisory
TRACON .... Terminal Radar Approach Control
TRP .... Target Reference Point
VHF .... Very High Frequency
VOR .... VHF Omni-directional Radio
VMC .... Visual Meteorological Conditions
VSI .... Vertical Speed Indicator
WTMD .... Wake Turbulence Mitigation for Departures

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1 Executive Summary

This document is the final report for the NASA Langley Research Center (LaRC)-sponsored task order "*Possible Benefits for Advanced Interval Management Operations*." Under this research project, Architecture Technology Corporation performed an analysis to determine the maximum potential benefit to be gained if specific Advanced Interval Management (AIM) operations were implemented in the National Airspace System (NAS). The motivation for this research is to guide NASA decision-making on which Interval Management (IM) applications offer the most potential benefit and warrant further research.

AIM operations are enabled by ADS-B (Automatic Dependent Surveillance-Broadcast) technology, which transmits high-accuracy position and velocity information derived from the aircraft's Global Positioning System (GPS) navigation system. Aircraft capable of ADS–B Out transmit this information which is received by ground systems and aircraft with ADS–B In. The ADS-B In capability of aircraft supports flight-deck IM technologies and procedures which enable air traffic control to delegate responsibility for inter-aircraft spacing to the flight crew of the aircraft. The controller issues an IM clearance to an IM capable aircraft to satisfy an Assigned Spacing Goal (ASG) with a target aircraft scheduled to arrive ahead of it to a designated Achieve By Point (ABP). The Flight-deck IM (FIM) technologies and procedures support the flight crew in satisfying the assigned spacing goal at the achieve-by point. The benefits of the flight deck IM operations include reduced inter-aircraft spacing due to greater precision in meeting the assigned spacing goal, reduced controller workload, and increased flight efficiency.

This project evaluated three flight deck IM concepts: IM for Dependent Parallel Approaches, IM for Departure Operations, and IM with Wake Mitigation. For IM for Dependent Parallel Runway Operations, the IM arrival aircraft must satisfy the wake-vortex spacing goal with the target arrival aircraft to the same runway, and diagonal "stagger" spacing goal with the other target arrival aircraft to the parallel runway. For IM for Departure Operations, the IM departure aircraft must satisfy the Miles In Trail (MIT) spacing goal with the target aircraft from the same or different origin airport to the same, or otherwise operationally coupled, departure fix or departure gate. For IM with Wake Mitigation, the IM arrival aircraft must satisfy dynamically-specified wake vortex spacing goal with the target arrival aircraft to the same or operationally coupled arrival runway, and potentially must respond to dynamic changes to the spacing goal prior to landing.

For each concept, we evaluated the maximum expected benefits, the conditions under which the operations are viable, and the limitations of, and impediments to, the concept. Literature review supported these tasks in establishing and refining, as necessary, the theory of operation.

Maximum benefits analysis for each concept used modeling and simulation to estimate the maximum airport arrival or departure capacity increase that could be realized when the concept was applied. Operations conditions analysis used operational data, particularly FAA Aviation System Performance Metrics (ASPM) data as well as traffic and route data, to estimate how many hours per year the concept could be applied at candidate airports or metroplexes in the NAS. Analysis results for the maximum benefits and operations conditions of each concept were combined to estimate the NAS-Wide benefit of each concept. For each concept, the NAS-Wide benefit was expressed as the sum of the theoretical hourly arrival or departure rates among the airports and metroplexes evaluated, and as the average number of hourly periods in a year that the concept could be applied.

Impediments and limitations analysis identified potential requirements and considerations for implementing each concept. After establishing a baseline for current-day and near-term operations and capabilities of the aircraft and air crew and air traffic control, the requirements and considerations for each concept were evaluated against this baseline to identify potential impediments to implementing the concept or limitations to realizing benefits from the concept. Impediments and limitations were estimated to be of high, medium and low severity, with respective numerical rankings of 3, 2 and 1. The severities were summed for relative ranking of the concepts.

For IM Dependent Arrival Operations, we estimated the concept could have been applied to 22 NAS airports with parallel runways to enable an additional 237 arrivals per hour during 1691 hours in 2014, and that the concept has an impediments and limitations score of 18. These values were estimated as follows. Operations analysis of ASPM data for the airports identified an average of 1691 hours in 2014 when the airports were operating in Instrument Meteorological Conditions (IMC). Maximum benefits analysis extended an established statistical method for estimating the saturation capacity of a single airport runway to dependent parallel runways to estimate a theoretical capacity of approximately 60 arrivals per hour. Enforcing this as the minimum to the ASPM-reported arrival rates of the airports in their most commonly used parallel arrival runway configuration in IMC in 2014 estimated an average of 237 additional arrivals per hour that could have been accommodated by the airports. Impediments and limitations analysis identified aircraft equipage requirements, traffic and aircraft characteristics for pairing, facility coordination and traffic control precision as having medium to high impact on concept implementation and benefit level.

For IM Departure Operations, we estimated the concept could be applied to 21 NAS metroplexes to enable an additional 176 departures per hour during 6570 hours per year, and that the concept has an impediments and limitations score of 18. These values were estimated as follows. Operations analysis of FAA traffic schedules forecast for May 13, 2020 for the airports in 8 metroplexes, and the departure fixes we estimated for those metroplexes, identified an average of 18 hours per day that the concept could be used to space metroplex departures crossing common departure fixes. We assumed this could be realized 365 days per year. For maximum benefits analysis we implemented a multi-airport, multi-departure fix scheduling algorithm based on the NASA Traffic

Management Advisor, and applied this to the traffic and fix models of the 8 metroplexes to estimate 67 additional departures per hour on average when fix spacing is reduced from 10 miles-in-trail to 7 miles-in-trail. Extrapolating the throughput results to 13 other FAA metroplexes estimated the concept could afford 176 additional departures per hour among the 21 FAA metroplexes. Impediments and limitations analysis identified airspace and traffic characteristics, multi-airport traffic coordination and scheduling, departure trajectory prediction and potential datalink requirements as having medium to high impact on concept implementation and level of benefit.

For IM Wake Mitigation, we estimated the concept could be applied to many more than the 27 airports evaluated. Among the 27 airports, we estimated the concept could have enabled 77 additional arrivals per hour during 4660 hours in 2014, and that the concept has an impediments and limitations score of 16. These values were estimated as follows. Operations analysis of ASPM data for the 27 airports identified an average of 4660 hours in 2014 when arrival runway crosswinds were 3 knots or greater. For maximum benefits analysis, we lacked an established estimate for the typical spacing reduction afforded by the concept. We assumed the average of the hourly arrival rates of each airport when in Visual Meteorological Conditions (VMC) in 2014 as the achievable arrival rate. Enforcing this as the minimum to the ASPM-reported arrival rates of the airports in VMC in 2014 estimated an average of 77 additional arrivals per hour that could have been accommodated by the airports. An alternative theoretical analysis of single-runway arrival capacity with 2 nautical mile wake vortex separation for all aircraft estimated 40 arrivals per hour per runway, however this was deemed potentially too high. Impediments and limitations analysis identified specifying safe separations, integration with time-based metering freeze horizons, and managing traffic response to dynamic spacing as having medium to high impact on concept implementation and level of benefit.

2 Introduction

This document is the final report for the NASA Langley Research Center (LaRC)-sponsored task order "*Possible Benefits for Advanced Interval Management Operations*." Under this research project, Architecture Technology Corporation (subcontractor to Saab Sensis Corporation) performed an analysis to determine the maximum potential benefit to be gained if specific Advanced Interval Management (AIM) operations were implemented in the National Airspace System (NAS). The motivation for this research is to guide NASA decision-making on which Interval Management (IM) applications offer the most potential benefit and warrant further research.

2.1 Background

The deployment of ADS-B (Automatic Dependent Surveillance-Broadcast) has enabled the development of advanced capabilities to improve the efficiency and safety of the National Airspace System (NAS). ADS-B, an extension of 1090 MHz, Mode-S transponder technology, transmits a message containing high-accuracy position and velocity information, derived from the aircraft's GPS navigation system. Aircraft equipped with ADS–B transmitters (ADS–B Out) transmit datalink messages that both ground systems and suitably equipped aircraft (ADS–B In) are able to receive. This technology enables aircraft as well as ground systems to have high-fidelity traffic information.

IM is a capability enabled by the advent of ADS–B. IM consists of a set of ground and flight deck capabilities and procedures for Air Traffic Control (ATC) and the flight crew that are used in combination to more efficiently achieve and manage inter-aircraft spacing. FIM delegates a subset of merging and spacing tasks to airborne systems, under careful monitoring by ATC. The premise of IM concepts is that in a sequence of several aircraft, a trailing/tracking aircraft (referred to as the *IM Aircraft*) can be assigned a clearance by ATC to satisfy a spacing goal at an Achieve-By Point with a Target Aircraft which precedes it in crossing the stated point [3]. The navigation equipment on-board the IM aircraft uses the state information of the leader aircraft to command trajectory control actions (e.g., speed adjustments, and possibly path adjustments) to satisfy the assigned spacing goal. Specialized ATC procedures and, possibly, equipment, are likely needed to initiate and manage the operations. NASA has been a leading authority on developing and testing IM operations to date.

In 2011, the ADS-B-In Aviation Rulemaking Committee (ARC) (chartered by the Federal Aviation Administration) published recommendations for future ADS-B-enabled airborne applications. Among their recommended list of 10 applications were several IM-related applications. NASA is looking to determine which of these ARC-recommended applications would be most beneficial to develop.

2.2 Scope

The scope for this project is to investigate three of the ARC-recommended IM concepts and to offer insight into the following: 1) the maximum expected benefits of the concept,

2) the conditions under which the operations are viable, and 3) the limitations of, and impediments to, the concept.

Regarding the selection of the particular concepts for evaluation, the ARC committee identified three IM concepts that are the focus of this research:

- FIM-S for Closely Spaced Parallel runway Operations (CSPO) [IM-CSPO]
- FIM-S Departure Operations [IM-DO]
- GIM-S with Wake Mitigation [IM with Wake Mitigation]

However, there are multiple variants of each of these concepts. To manage project scope, it was necessary to identify a single, specific version of each concept to be studied. Several concepts in each of the three IM application areas were reviewed, and then, through collaboration with NASA civil servants, the particular variation of each concept that would represent the overall concept arena for evaluation on the project was selected. The three concept arenas are abstracted to IM with Parallel Runway Arrivals, IM with Departure Operations and IM with Wake Mitigation. The specific concepts considered within each of these arenas of IM concept application are listed below.

The concepts considered for IM with Parallel Runway Arrivals included the following:

- Simplified Aircraft-Based Paired Approach (SAPA) [2][41][42]
- Paired Approaches [43]
- Interval Management for Dependent Parallel Runways [2][3][6][8][32][35]

The concepts considered for IM with Departure Operations included:

- Spacing to Departure Fix [3][35]
- Spacing to Departure Gate [3][35]

The concepts considered for IM with Wake Mitigation included:

- IM with Wake Mitigation [2]
- Wake Vortex Re-categorization Phases I, II and III [9][11][19][23]
- Wake Turbulence Mitigation for Departures (WTMD) [13][19][24]
- The Aircraft Vortex Spacing System (AVOSS) [44][45][46]

The three (3) concepts selected for evaluation were:

- IM with Dependent Parallel Runway Arrivals
- IM with Departure Operations
- IM with Wake Mitigation

3 Methodology

Each of the three concepts is studied independently through the application of the same underlying methodology. The methodology consists of two main elements, the Maximum Benefits analysis, and the Limitations analysis. Figure 3.1 depicts the project tasks and their relationships.

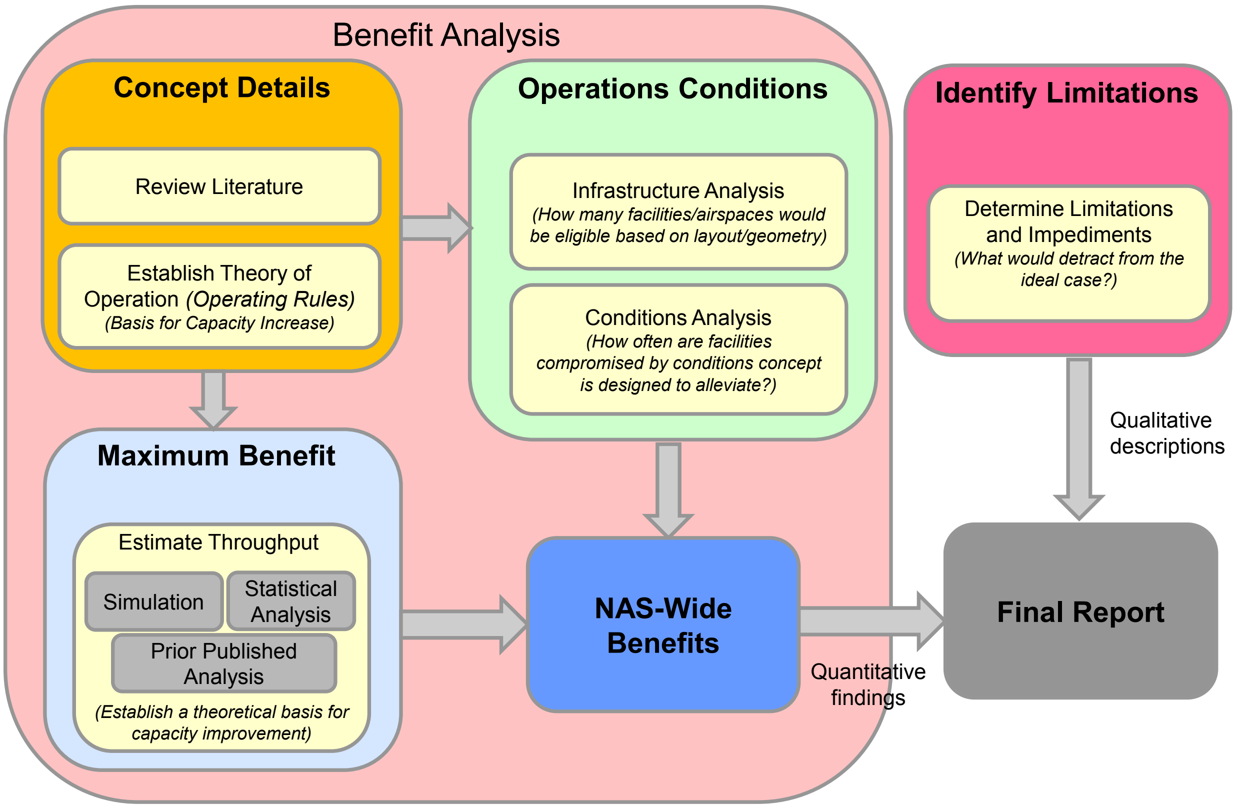


Figure 3.1. Individual Project Tasks and their Relationships.

3.1 Benefits Analysis

The Maximum Benefits analysis represents the bulk of the effort and is divided into major subtasks. This section provides a detailed description of the methodology.

3.1.1 Concept Details

The objective of the Concept Details task is to establish the Theory of Operation governing each concept and establish a basis for realizing capacity increase from the concept. The approach to this task involves a review of the available literature and consultation with NASA personnel, to establish the basic operating principles of the concept, and to understand how the concept differs from current-day operations. The conditions required to apply the concept are identified. We explicitly quantify the rules and constraints governing the concept. We also identify primary factors influencing concept implementation.

3.1.2 Maximum Benefit

The objective of the Maximum Benefit task is to estimate the impact of concept application at case study site(s) under appropriate application conditions. This is achieved through data analysis, modeling and simulation, and is based on prior published analyses. To do this, we first establish a theoretical basis for estimating the capacity improvement afforded by each interval management concept. Here we leverage the Theory of Operation of the concept, established during the Concept Details analysis, and apply it to a representative or notional scenario. We select capacity and/or throughput-impact as the figure of merit for each concept and determine the theoretical throughput via analysis, simulation or prior published research. Candidate analysis methods include ABP modeling [15]; terminal airspace arrival and departure route link-node modeling [16][17]; and trajectory modeling leveraging energy methods [18].

3.1.3 Operations Conditions

The objective of the Operations Conditions task is to characterize the primary factors influencing the application and benefit of the operational concept in the real-world environment. In essence, the analysis is designed to determine where and how often a particular concept could be employed in the NAS and achieve meaningful benefit. This analysis considers airport/airspace infrastructure, operational conditions, and typical traffic at select sites where the concept could be applied. The infrastructure analysis determines a facility's eligibility for the concept based on its layout, geometry or other characteristics. Operational conditions analysis determines how often a facility's capacity is saturated or compromised by conditions that the particular IM concept is designed to alleviate. Traffic analysis determines how often minimum spacing afforded by the concept would result in higher throughput. The purpose is to determine the frequency of conditions and primary factors influencing concept application and benefit. To analyze the operating conditions, we identify various databases useful for characterizing the operating conditions for the concept, as listed in Table 3.1.

Table 3.1. Available Data Sources for the Operations Conditions Task.

Source	Elements	Application
Aviation System Performance Metrics (ASPM)	Airport runway configurations	Occurrence of runway configuration for concept application
	Airport meteorological conditions: ceiling, visibility, wind speed and direction	Occurrence of meteorological conditions for concept application
	Airport called arrival and departure rates	Baseline airport throughput and capacity Occurrence of peak demand levels for concept application
	Airport scheduled arrival and departure traffic demand	Occurrence of peak demand levels for concept application
Aircraft Situation Display to Industry (ASDI)	Filed route of flight	Occurrence of common routes/fixes among airport departure flights
Bureau of Transportation Statistics (BTS)	Scheduled departure and arrival times	Occurrence of peak demand levels for concept application

The results of this analysis are applied in the NAS-Wide Benefits task, to estimate the true benefit of the concept from the theoretical maximum benefit and the frequency of application.

3.1.4 NAS-Wide Benefit

The objective of the NAS-Wide Benefits task is to quantitatively estimate the broader benefit of concept across multiple applicable sites (airports or metroplexes) in the NAS by combining the results from the Maximum Benefits analysis and the Operations Conditions analysis. For example, how many sites might employ the concept and what would be the corresponding throughput increase? The approach to this task was to first consider the ‘need-for’ and then viability of each concept at applicable sites. For example, how frequently do imbalances between traffic demand and site capacity occur? The estimated maximum benefit for the concept can be applied at each imbalance, to estimate a net benefit of the concept. This net benefit supports ranking of the individual concepts. We apply our fundamental analysis approaches to multiple sites, and as needed extrapolate those findings to additional sites, in order to estimate the throughput benefit of concept at numerous applicable sites across the NAS.

3.2 Impediments and Limitations

The objective of this task is to qualitatively describe the impediments and limitations of each concept that are not captured in the quantitative benefits analysis. For example, what meteorological or airport operational conditions prevent implementing the concept? What aircraft navigation capabilities and flight crew procedures are required to implement the concept? What controller tools and procedures might be required to implement the concept? Our approach is to determine high-level requirements for concept, such as airborne and ground automation, crew and controller training, and other operational requirements. For each, we qualitatively estimate its impact on applying the concept. We apply this to the NAS-wide benefits estimated for each concept to recommend a relative ranking of the concepts for future research.

3.3 Final Report

This document serves as the Final Report and documents the methodology and findings of the effort. Regarding organization of the Final Report, the Benefits Analysis, including the Concept Details, Maximum Benefit, Operations Conditions, and the NAS-wide benefits, is covered for each concept in its own respective section. Sections 4, 5 and 6 are dedicated to the Benefits Analysis. The Impediments and Limitations task is covered in Section 7. Impediments and limitations are identified for IM in general, then for each concept.

4 Interval Management for Dependent Parallel Approaches

This section details the analysis performed for Dependent Parallel Approaches. The concept details are presented first, followed by the Maximum Benefit and Operations Conditions analysis. The results are then applied to the NAS wide benefits analysis.

4.1 Concept Details

The *IM for Dependent Parallel Approaches* concept applies to airports that conduct simultaneous dependent Instrument Landing System (ILS) approaches to parallel runways in Instrument Meteorological Conditions (IMC). The criteria for conducting parallel operations to adjacent runways are listed in Table 4.1. The criteria were identified from [6][47][48]. The criteria vary by runway centerline spacing.

Table 4.1. Conditions for Independent and Dependent Approaches to Parallel Runways.

Parallel Runway Centerline Spacing, Feet	Visual or Instrument Meteorological Condition (VMC or IMC)	Arrival Operations
> 9000	VMC or IMC	Independent operations all the time
4300 - 9000	VMC	Independent operations, pilot responsible for separation
	IMC	Independent operations require 4.8-second radar, ATC monitoring position, 2000-feet No Transgression Zone (NTZ) Many airports meet these conditions
	IMC	Dependent operations require 2-nautical mile stagger and wake vortex separations on final approach, 3-nautical mile or 1000-feet vertical before established
3400 - 4300	VMC	Independent operations, pilot is responsible for separation
	IMC	Independent operations with Precision Runway Monitor (PRM)
	IMC	Dependent operations require 1.5-nautical mile stagger and wake vortex separations on final approach, 3-nautical mile or 1000-feet vertical separations before established
3000 - 3400	VMC	Independent operations, pilot is responsible for separation
	IMC	Independent operations with 1-second PRM with display, ILS localizers are offset by greater than or equal to 2.5-degrees
	IMC	Dependent operations require 1.5-nautical mile stagger and wake vortex separations on final approach; 3-nautical mile or 1000 feet vertical separations before established
2500 - 3000	VMC	Independent operations, pilot responsible for separation
	IMC	Independent operations not permitted
	IMC	Dependent operations require 1.5-nautical mile stagger and wake vortex separations on final approach; 3-nautical mile or 1000-feet vertical separations before established
700 - 2500	VMC	Independent operations, pilot responsible for separation
	IMC	Independent operations not permitted
	IMC	Dependent operations require 1.5-nautical mile stagger and wake vortex separations on final approach; 3-nautical mile or 1000 feet vertical separations before established
< 700	VMC	Single-runway only
	IMC	Single-runway only

Our evaluation focuses on concept application to parallel runways with centerlines spaced 2500-feet to 9000-feet, thus falling outside the category of closely-spaced. In baseline (non-IM) operations, an airport may or may not be capable of dependent runway operations in IMC depending on whether it meets established criteria.

Airports not capable of conducting independent parallel runway operations may conduct dependent parallel runway operations with the appropriate approval. If they have not been approved to conduct dependent parallel runway operations, they must operate in a single-runway configuration, significantly reducing airport arrival throughput. For those airports approved to conduct dependent parallel runway arrival operations, controllers must manage the trailing aircraft to meet stagger and wake vortex spacing requirements. Additional spacing buffers may be applied, as needed, to account for the level of imprecision in managing the aircraft to satisfy the stagger and wake-vortex spacing minima. This can reduce the airport arrival throughput during dependent arrival operations.

With IM capabilities, the controller delegates spacing responsibility to the flight crew of the IM Aircraft, and the flight crew uses on-board equipment to meet the assigned spacing goals. The spacing goals are defined with respect to the two Target Aircraft ahead in the arrival stream that are to arrive at the same runway and to the runway parallel to the IM Aircraft, while the controller monitors the operations. Spacing buffers, intended to account for positional uncertainty, can be reduced due to the increased spacing precision afforded by the IM equipment. This can increase the airport arrival throughput by either enabling dependent runway operations where only single-runway operations could previously be performed, or by increasing the airport arrival throughput by reducing inter-flight spacing. Table 4.2 summarizes the theory of operation for dependent approaches to parallel runways with centerlines spaced 2500 – 9000 feet.

Table 4.2. Theory of Operation for Dependent Approaches to Parallel Runways 2500 – 9000 Feet.

Conditions for Application	• Instrument Meteorological Conditions (IMC) with Instrument Landing System (ILS) Category I ceiling and runway visibility range conditions
Baseline Operations	• Single-runway operations
Concept Rules & Constraints	• 3-nautical mile lateral separation until established on final approach • On final approach, stagger separation of 2-nautical miles with parallel-runway aircraft, wake-vortex separation with same-runway aircraft • Follower meets larger of stagger or wake-vortex separation requirements • Spacing buffer to account for controller workload and spacing precision
Concept Factors & Dependencies	• Application of minimum spacing requires closely-scheduled arrivals • Inter-flight spacing realized depends on the initial approach speeds, final approach speeds and weight classes of the aircraft involved, and the spacing between the centerlines of the parallel runways
Concept Requirements	• Ground-based traffic planning and management tools to support pairing flights for dependent operations

	• Aircraft- or ground-based tools for aircraft speed guidance to support satisfying inter-flight spacing minima throughout operations

Figure 4.1 provides a schematic of inter-flight spacing requirements for dependent approaches to parallel runways.

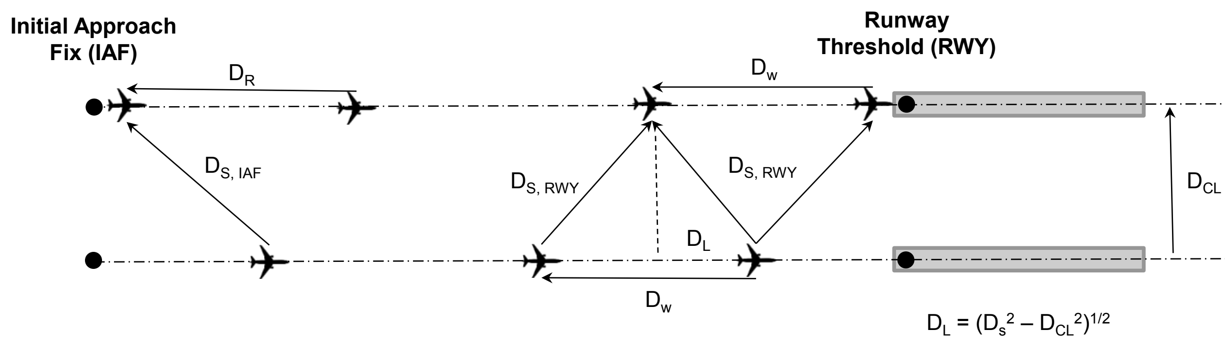


Figure 4.1. Inter-Flight Spacing Requirements for Dependent Parallel Approaches.

As indicated in Figure 4.1 at the Initial Approach Fix (IAF), the IM Aircraft (trailing) satisfies 3-nautical mile radar separation with the Target Aircraft to the parallel runway ($D_{S,IAF}$) and 3-nautical mile radar separation with the Target Aircraft to same runway (D_R). A spacing buffer (D_B) may be added to each of these minimum spacing values to account for spacing imprecision. At the runway threshold, the IM Aircraft satisfies stagger spacing with Target Aircraft to the parallel runway ($D_{S,RWY}$) and wake vortex spacing with the Target Aircraft to the same runway (D_W). The exact longitudinal spacing (D_L) to satisfy the stagger spacing depends on the centerline spacing of the parallel runways. A spacing buffer to accommodate imprecision may also be added. The current-day separation standards to protect against wake vortex at airports which have not yet implemented RECAT are shown in Table 4.3 [9].

Table 4.3 Current FAA Wake Separation Standards for non-RECAT Airports [9].

		Follower (Nautical Mile)				
		Super	Heavy	B757	Large	Small
Leader	Super	2.5	6	7	7	8
	Heavy	2.5	4	5	5	6
	B757	2.5	4	4	4	5
	Large	2.5	2.5	2.5	2.5	4
	Small	2.5	2.5	2.5	2.5	2.5

Figure 4.2 depicts the wake vortex separation minima and the diagonal stagger separation between the IM Aircraft and the Target Aircraft to the parallel runway as a function of the centerline spacing of the parallel runway system.

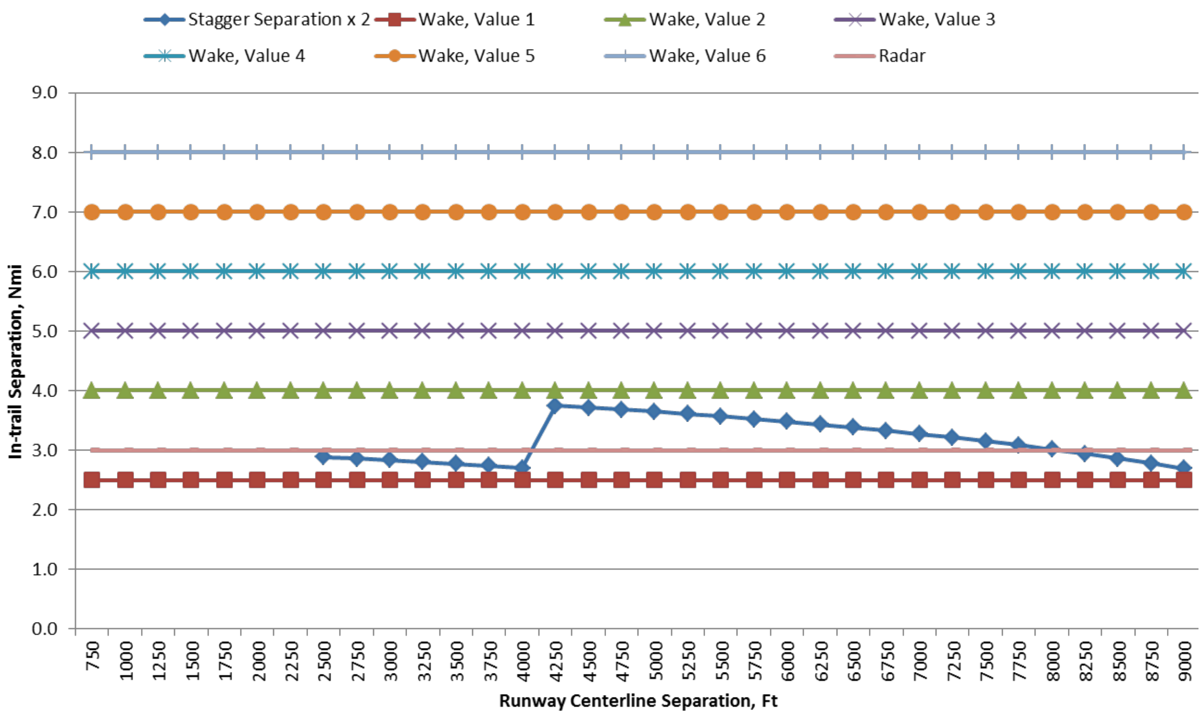


Figure 4.2. Wake Vortex and Stagger In-Trail Separation Requirements.

The data show the interference of the stagger separation with the smaller 2.0-nautical mile and 3.0-nautical mile separation minima governing Super, Heavy, B757, Large and Small weight class aircraft following Large and Small weight class aircraft. In these cases, the stagger separation may be the dominant spacing constraint over the wake vortex separation. The inclusion of spacing buffers shifts the spacing profiles upwards. Airports with parallel runways to which dependent arrival operations may be implemented are listed in [22].

4.1.1 Relevant Literature

The concept details and theory of operation are summarized from an extensive literature search. The noteworthy references are summarized in this section.

- FAA Order JO7110.308 [5] documents the requirements and procedures for arrivals to conduct dependent ILS approaches to Closely Spaced Parallel Runways (CSPRs); that is, parallel runways with centerlines spaced to 2500-feet or closer. Operations require differences in the glide slope heights which are achieved with runway threshold stagger or by approach procedure design, and are specified for individual runway pairs. Aircraft are to satisfy 3-nautical mile lateral or 1,000-feet vertical separation until established on the localizer and cleared for final approach. While on final approach, the trailing aircraft must be on the higher vertical approach, and must satisfy 1.5-nautical mile diagonal spacing with the leader aircraft to the parallel runway. The leader aircraft must be a small or large weight class aircraft. The operations may be conducted down to ILS Category I ceiling and runway visibility range conditions.

- Barmore, *et al.* [6] document a concept of operations and requirements for dependent operations to parallel runways leveraging FIM. This includes a summary of the concept; analysis of minimum inter-flight spacing requirements and constraints of the concept; a description of the Paired Dependent Speed (PDS) aircraft navigation capability for the following aircraft to meet the minimum spacing requirements with the lead aircraft; procedures for initiating and conducting the operations, including identification and consideration of the failure modes for the operation; information requirements to conduct the operations, including candidate requirements for ADS-B messaging; and an example scenario. The reference also includes a summary of the fundamental principles of dependent approaches to parallel runways.

- Smith [7] evaluates the performance of the Airborne Spacing for Terminal Arrival Routes (ASTAR) 10 algorithm [7][10] extended to support dependent approaches to parallel runways. ASTAR is an aircraft navigation system which computes and recommends to the flight crew speed settings to meet and/or maintain an assigned spacing goal with a target aircraft. ASTAR 10 extends this capability to support meeting a stagger spacing goal with a target aircraft on a parallel runway. The document also includes a summary of the fundamental principles of dependent arrival operations to parallel runways.

- Baxley *et al.* [8] document the methodology for and findings from conducting human-in-the-loop experiments of a concept of operations for using FIM to conduct dependent, staggered approaches to parallel runways. This includes detailed descriptions of the flight deck equipment, approach procedures, clearances, and flight deck operations for the concept; and it includes detailed analysis of the operations evaluated in the experiment. The concept evaluated includes Controller–Pilot Data Link Communications (CPDLC) to communicate FIM clearances to aircraft. The document also includes a summary of the fundamental principles of dependent arrival operations to parallel runways.

- Doyle *et al.* [10] provide comprehensive documentation of airports in the US with parallel runway systems used for arrivals and departures. Information includes the availability and type of equipage and operations to perform independent operations to the runways, local specifications for minimum ceiling and visibility minima that warrant IMC, and other information relevant to parallel runway arrival operations. Our analysis relied on the airports and runway systems listed in this reference, realizing that certain airports such as Seattle-Tacoma International Airport (SEA) had been omitted due to the age of the document. Nevertheless, it provided an extensive and relevant list of airports to initiate the analysis.

- The *FAA WakeNet Workshop Highlights* [11] lists the number of pairs of parallel runways and the distance between those runways for airports across the US.

- Raytheon [12] lists airports and their closely-spaced parallel runways to which a NASA-developed Terminal Area Capacity Enhancing Concept for paired arrivals could be applied.

- FAA Order JO7110.316 [13] lists the particular airport parallel runway pairs to which dependent parallel runway operations could be applied.

4.2 Maximum Benefits Analysis

To estimate the maximum arrival throughput achievable with the IM for Dependent Parallel Approaches concept, we apply a methodology originally suggested by Credeur [15]. In his analysis, Credeur was interested in the effects of wake vortex separation standards on throughput to a single runway, and the capacity benefit that could be realized if those standards were reduced. Credeur used a simple scenario with pairs of arrival aircraft aligned on the final approach course to demonstrate his methodology. Each aircraft pair generated a unique separation requirement, which was expressed in time that allowed the calculation of an overall runway capacity. Credeur then computed the expected value of the capacity for a single runway, under saturated traffic conditions, assuming a particular mix of traffic (by weight class). The spacing rules accounted for the wake-vortex separation required by the leading / trailing aircraft (as a function of weight class) and the characteristic final approach speeds by aircraft weight class. A spacing buffer to account for delivery uncertainty was also added.

To extend this method for parallel runway operations, we add the parallel runway and a third arrival aircraft on the parallel runway, named the *parallel aircraft*. The minimum stagger spacing requirements are then applied due to the presence of the parallel aircraft, in addition to the in-trail requirements associated with the original leading/trailing aircraft pair. Then, as with the original Credeur analysis, we consider a range of possible traffic mixes (now for three aircraft) and parallel runway centerline spacing conditions to estimate the breadth of possible, maximum arrival throughput outcomes. We apply our analysis to evaluate the arrival throughput of specific concept designs for dependent parallel runway operations and parallel runway centerline spacing conditions evaluated by The MITRE Corporation for the RTCA Special Committee 186, Automatic Dependent Surveillance-Broadcast (ADS-B). We obtain comparable results.

4.2.1 Analysis Methodology

This section describes the detailed methodology for estimating the maximum arrival throughput for the parallel runway system. We first present the single runway approach of Credeur [15], and then describe the extension to the scenario of two runways in parallel.

4.2.1.1 Arrival Capacity for Single Runway Operations

In general, when $g(x, y)$ is a function of two random variables *x* and *y,* then the expectation of $g(x, y)$ is expressed in Equation 4.1:

$$E\{g(x,y)\} = \sum_k \sum_n g(x_k, y_n) p(x_k, y_n) \tag{4.1}$$

Where $p(x_k, y_n)$ is the joint probability function of *x* and *y*. For our case, let *i* and *j* be the random variables where *i* = lead aircraft of a pair on final approach, *j* = trailing aircraft of a pair on final approach and $g(i, j) = t_{ij}$ = the time interval between aircraft *i* and *j* when aircraft *i* is at the end of the final approach segment of length *L*.

Inter-arrival Separation on Final Approach

Consider the case as shown in the Figure 4.3 where the trailing aircraft is faster and is overtaking the slower aircraft.

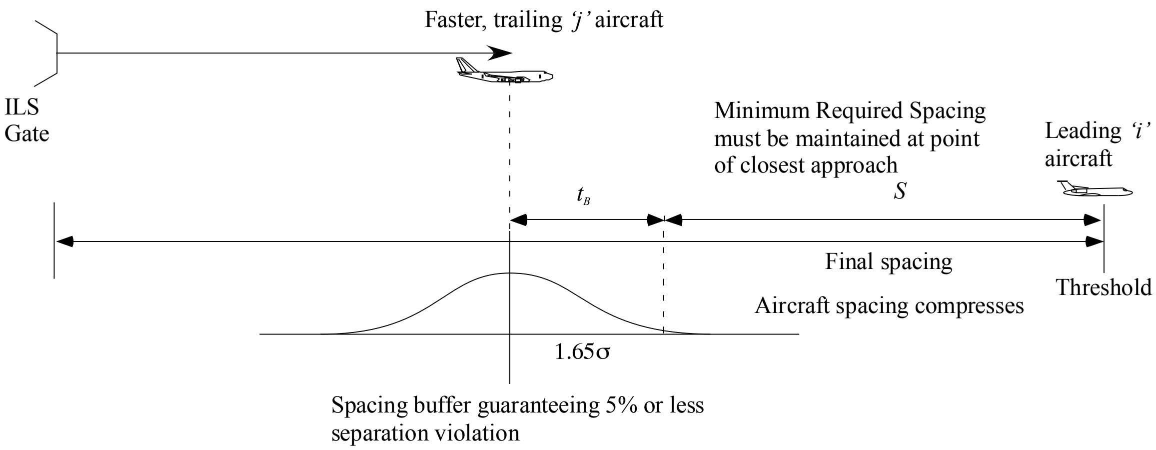


Figure 4.3. In-Trail Separation Components for Approach, Faster Trailing Aircraft.

For the situation when $V_j \geq V_i$ the minimum required separation S_{ij} for that aircraft pair occurs when aircraft *i* is at the threshold and is expressed in Equation 4.2:

$$t_{ij}(V_j \geq V_i) = \frac{S_{ij}}{V_j} \tag{4.2}$$

Consider the opposite situation as shown in the Figure 4.4, where the leading aircraft is the faster of the two.

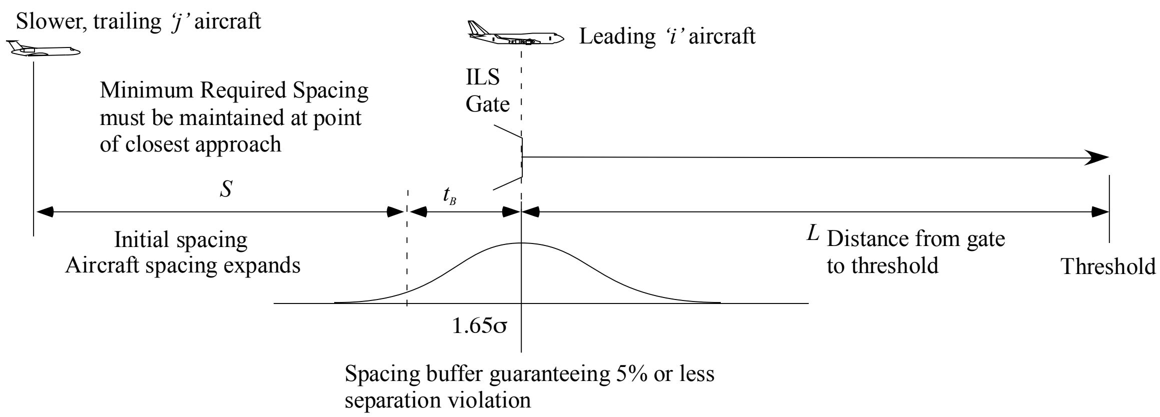


Figure 4.4. In-Trail Separation Components for Approach, Slower Trailing Aircraft.

For the situation when $V_j < V_i$, the minimum required separation S_{ij} for that aircraft pair occurs when aircraft *i* is at the beginning of the final approach segment and the separation opens until aircraft *i* reaches the threshold, expressed in Equation 4.3:

$$t_{ij}(V_j < V_i) = \frac{S_{ij}}{V_j} + L\left(\frac{1}{V_j} - \frac{1}{V_i}\right) \tag{4.3}$$

Inter-arrival Separation Buffer

We include a separation buffer to account for uncertainty in meeting target inter-flight spacing. We model the spacing uncertainty as a Gaussian distribution with a standard deviation of σ. We specify the spacing buffer time t_B to keep the probability of separation violation less than some specified value. To maintain the probability of a separation violation P_j to be less than 5%, we need a buffer time t_B of 1.65σ. We account for this buffer in the inter-arrival time spacing for the cases of a faster and a slower trailing aircraft, expressed in the Equations 4.4 and 4.5.

$$t_{ij}(V_j \geq V_i) = \frac{S_{ij}}{V_j} + t_B \tag{4.4}$$

$$t_{ij}(V_j < V_i) = \frac{S_{ij}}{V_j} + L\left(\frac{1}{V_j} - \frac{1}{V_i}\right) + t_B \tag{4.5}$$

Average Arrival Rate

From Equation 4.1, the average or expected value of the inter-arrival spacing $\overline{t_{ij}} = E(t_{ij})$ is expressed in Equation 4.6,

$$\overline{t_{ij}} = \sum_j \sum_i t_{ij} p_{ij} \tag{4.6}$$

where p_{ij} is the probability that an aircraft pair will consist of aircraft i followed by aircraft j. For independent arrivals and first come first serve control, the joint probability of aircraft i followed by aircraft j may be expressed as the product of the individual probabilities,

$$p_{ij} = p_i p_j \tag{4.7}$$

where p_i, p_j are the probabilities of those weight classes of aircraft in the traffic mix. In turn, Equation 4.6 can be simply rewritten as

$$\overline{t_{ij}} = \sum_j \sum_i t_{ij} p_i p_j \tag{4.8}$$

Finally, the average arrival throughput is the inverse of the average inter-arrival time, expressed in Equation 4.9,

$$\lambda = \frac{1}{\overline{t_{ij}}} \tag{4.9}$$

4.2.1.2 Arrival Capacity for Dependent Parallel Runway Operations

We extend the methodology for estimating the arrival capacity of a single runway to the case of two parallel runways which cannot operate independently. Thus, a minimum diagonal stagger separation with the leading aircraft to the parallel runway must be included.

Inter-arrival Separation on Final Approach with Spacing Buffer

The flow rate of the two runways is considered as a single, coupled two-runway system. The upper bound on the performance of this system is represented as the trivial case of two independently operating runways. Here, the flow rate is double the single runway arrival rate described in the previous section. Considering the case of dependent parallel runway operations, Figure 4.5, depicts the parallel runway geometry for dependent arrivals where the stagger separation D_s with the aircraft to the parallel runway is the greater in-trail spacing constraint than the wake-vortex spacing D_w:

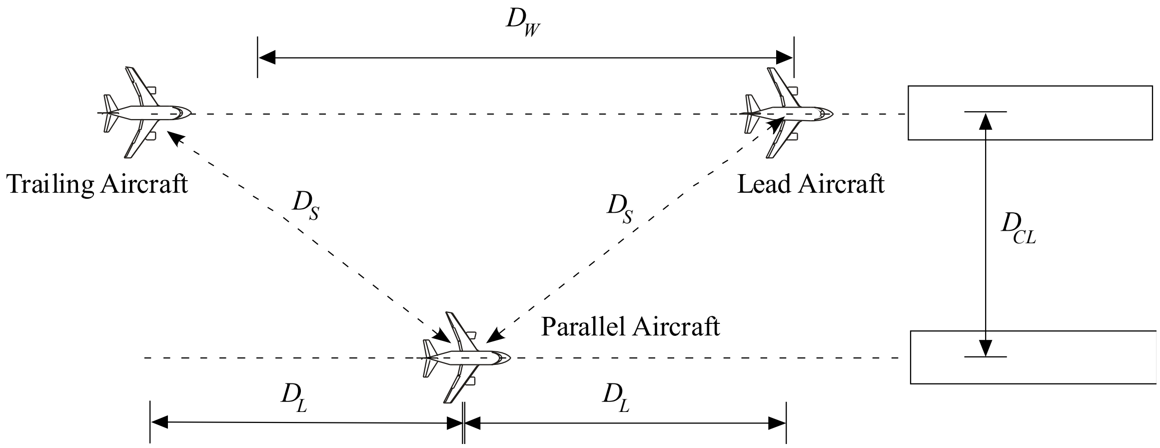


Figure 4.5. Parallel-Runway Stagger Separation Exceeds Same-Runway Wake-Vortex Separation.

Figure 4.5 shows the two constraints on the trailing aircraft. First, it must maintain normal in-trail, wake-vortex separation D_w from the lead aircraft to the same runway. Secondly it must maintain a stagger separation, *Ds*, from the lead aircraft to the parallel runway. This stagger distance is represented by D_L as expressed in Equation 4.10.

$$D_L = \sqrt{D_S^2 - D_{CL}^2} \tag{4.10}$$

Depending on the spacing between the centerlines of the parallel runways, D_{CL}, either the stagger constraint or the in-trail constraint is dominant in dependent runway operations. In Figure 4.5, the runways are sufficiently close, so the stagger constraint with the lead aircraft to the parallel runway is the dominant spacing constraint. In Figure 4.6, the runways are sufficiently apart, so that the wake vortex separation with the lead aircraft to the same runway is the dominant constraint. The exact distances depend on the types of aircraft involved and the spacing of the runways.

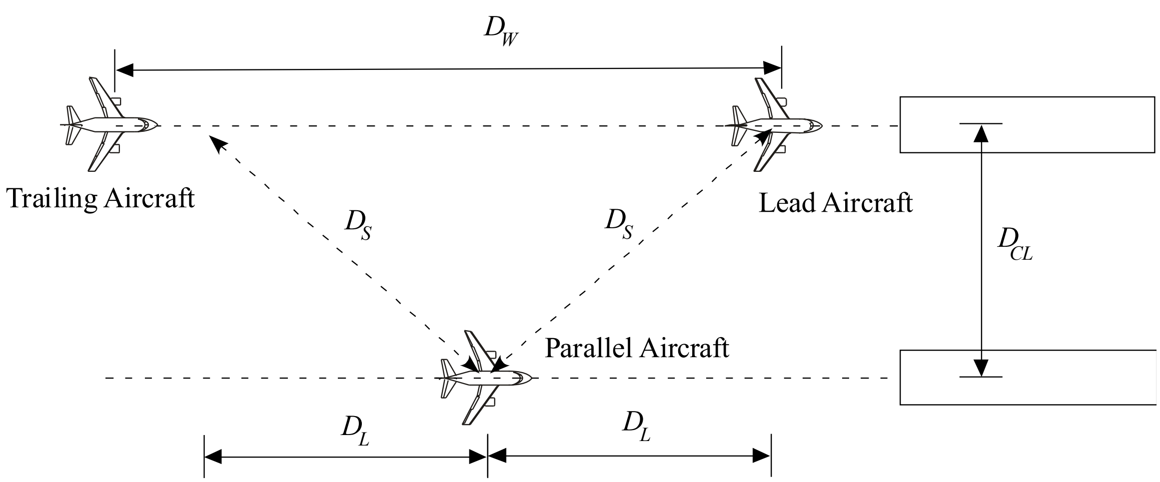


Figure 4.6. Same-Runway Wake-Vortex Separation Exceeds Parallel-Runway Stagger Separation.

The wake vortex spacing requirement, D_w, is a function of the aircraft types involved and the order of the aircraft on the final approach course. Assuming n aircraft-types, there are n^2 potential spacing scenarios. These can be represented in a table as in Equation 4.11.

$$M_{D_W} = \begin{bmatrix} D_{W_{11}} & D_{W_{12}} & \cdots & D_{W_{1n}} \\ D_{W_{21}} & D_{W_{22}} & \cdots & D_{W_{2n}} \\ \vdots & \vdots & \ddots & \vdots \\ D_{W_{n1}} & D_{W_{n2}} & \cdots & D_{W_{nn}} \end{bmatrix} \tag{4.11}$$

The stagger distance is fixed with respect to aircraft types, therefore it is just a function of the spacing between the centerlines of the parallel runways. To determine arrival throughput, separation interval times must be determined from the separation distances. The in-trail separation time is managed as with the single runway. The correct expression depends on which aircraft is faster. The fundamental expressions for single-runway spacing accounting for a faster or slower trailing aircraft are shown, respectively, in Equations 4.12.

$$t_{W_{ij}} = \begin{cases} \dfrac{D_{W_{ij}}}{V_j} + t_B, (V_j \geq V_i) \\ \dfrac{D_{W_{ij}}}{V_j} + L\left(\dfrac{1}{V_j} - \dfrac{1}{V_i}\right) + t_B, (V_j < V_i) \end{cases} \tag{4.12}$$

In the case of two parallel runways, the wake-vortex spacing between the i, j pair to the same runway must still be satisfied. However, the additional stagger spacing requirements with the other aircraft to the parallel runway, and the associated permutations, must be included. The aircraft to the parallel runway, aircraft k, must satisfy stagger separation with the lead aircraft i. The trailing aircraft j must satisfy stagger separation with the parallel runway aircraft k. The time separations for aircraft to meet stagger separation requirements for the cases of the parallel runway aircraft k being slower or faster than follower aircraft j, and the parallel runway aircraft k being faster or slower than lead aircraft i, are expressed in Equation 4.13.

$$t_{L_{ijk}} = \begin{cases} \dfrac{D_L}{V_j} + t_B, (V_j \geq V_k) \\ \dfrac{D_L}{V_j} + L\left(\dfrac{1}{V_j} - \dfrac{1}{V_k}\right) + t_B, (V_j < V_k) \end{cases} + \begin{cases} \dfrac{D_L}{V_k} + t_B, (V_k \geq V_i) \\ \dfrac{D_L}{V_k} + L\left(\dfrac{1}{V_k} - \dfrac{1}{V_i}\right) + t_B, (V_k < V_i) \end{cases} \tag{4.13}$$

The final time spacing is the greater of the wake-vortex time spacing and parallel runway stagger time spacing, as shown in Equation 4.14.

$$t_{ijk} = \begin{cases} t_{w_{ij}}, (t_{w_{ij}} > t_{L_{ijk}}) \\ t_{L_{ijk}}, (t_{w_{ij}} < t_{L_{ijk}}) \end{cases} \tag{4.14}$$

Average Arrival Rate

From Equation 4.1, the average inter-arrival spacing $\bar{t}_{ij} = E(t_{ij})$ is written in Equation 4.15.

$$\bar{t}_{ijk} = \sum_k \sum_j \sum_i t_{ijk} p_{ijk} \tag{4.15}$$

where p_{ijk} is the probability that an aircraft trio will consist of aircraft i followed by aircraft j with aircraft k on the parallel runway. For independent arrivals and first come first serve control, the joint probability of aircraft i followed by aircraft j, now with parallel runway aircraft k, may be expressed as the product of the individual probabilities in Equation 4.16, where p_i, p_j and p_k are the probabilities of that aircraft-type in the traffic mix.

$$p_{ijk} = p_i p_j p_k \tag{4.16}$$

Consider a vector of aircraft-type probabilities in the overall traffic mix, expressed in Equation 4.17,

$$P_{ac} = \begin{bmatrix} p_1 & p_2 & \cdots & p_n \end{bmatrix} \tag{4.17}$$

The matrix of probabilities for any two aircraft being in a spacing pair is expressed in Equation 4.18.

$$M_{P_{ij}} = P_{ac}^T P_{ac} = \begin{bmatrix} p_1 \\ p_2 \\ \vdots \\ p_n \end{bmatrix} \begin{bmatrix} p_1 & p_2 & \cdots & p_n \end{bmatrix} = \begin{bmatrix} p_1 p_1 & p_1 p_2 & \cdots & p_1 p_n \\ p_2 p_1 & p_2 p_2 & \cdots & p_2 p_n \\ \vdots & \vdots & \ddots & \vdots \\ p_n p_1 & p_n p_2 & \cdots & p_n p_n \end{bmatrix} \tag{4.18}$$

To capture the parallel aircraft k, the term $M_{P_{ij}}$ must be scalar multiplied by the original probability matrix, creating a $\left(n^2 \times n\right)$ matrix of probabilities, represented in Equation 4.19:

$$M_{P_{ijk}} = \begin{bmatrix} p_1 M_{P_{ij}} \\ p_2 M_{P_{ij}} \\ \vdots \\ p_n M_{P_{ij}} \end{bmatrix} \tag{4.19}$$

The average flow rate λ is expressed in Equation 4.20. The "2" in the numerator represents the fact that for each interval, two aircraft arrive, the trailing aircraft and the parallel aircraft.

$$\lambda = \frac{2}{\bar{t}_{ijk}} \tag{4.20}$$

4.2.2 Analysis Findings

We applied the analysis methodology to conduct a parametric analysis of the theoretical arrival throughput of the dependent parallel runway operations for a range of weight classes and runway centerline spacings, and to conduct analysis of specific alternative concept instantiations and airport implementations identified by members of the RTCA SC-186, ADS-B Concepts committee. The conditions and findings for each analysis are detailed below.

4.2.2.1 Parametric Analysis

For a parametric analysis of the throughput impact of the IM for Dependent Parallel Approaches concept, we construct a simple scenario with a traffic mix consisting exclusively of Large and Heavy weight class aircraft. The traffic mix has a probability matrix as shown in Equation 4.21, where the traffic mix is varied as a function of the probability of large jets.

$$P_{ac} = \left[p_{large} \quad p_{heavy} \right], p_{heavy} = 1 - p_{large} \tag{4.21}$$

We consider standard separations as defined by FAA, and we consider hypothetical reduced separation standards of 3 and 2 nautical miles. The different cases of wake turbulence separation standards are shown in Table 4.4.

Table 4.4. Three Scenarios of Separations (Standard, 3 Nautical Mile, 2 Nautical Mile) for Leading-Trailing Large-Heavy Weight Class Aircraft.

Leading-Trailing Aircraft Separations, Nautical Miles			
Standard		Trailing Aircraft	
		Large	Heavy
Leading Aircraft	Large	3	3
	Heavy	5	4
3 Nautical Mile		Trailing Aircraft	
		Large	Heavy
Leading Aircraft	Large	3	3

	Heavy	3	3
2 Nautical Mile		Trailing Aircraft	
		Large	Heavy
Leading Aircraft	Large	2	2
	Heavy	2	2

The final approach speeds of the aircraft are assumed to be 127 knots for the large aircraft and 137 knots for the heavy aircraft, as assumed in Credeur [15]. Figure 4.7 shows the saturation arrival rate for a single runway for the cases of standard FAA wake-vortex separation and a hypothetical reduced 3- and 2-nautical mile separation without regard for weight class.

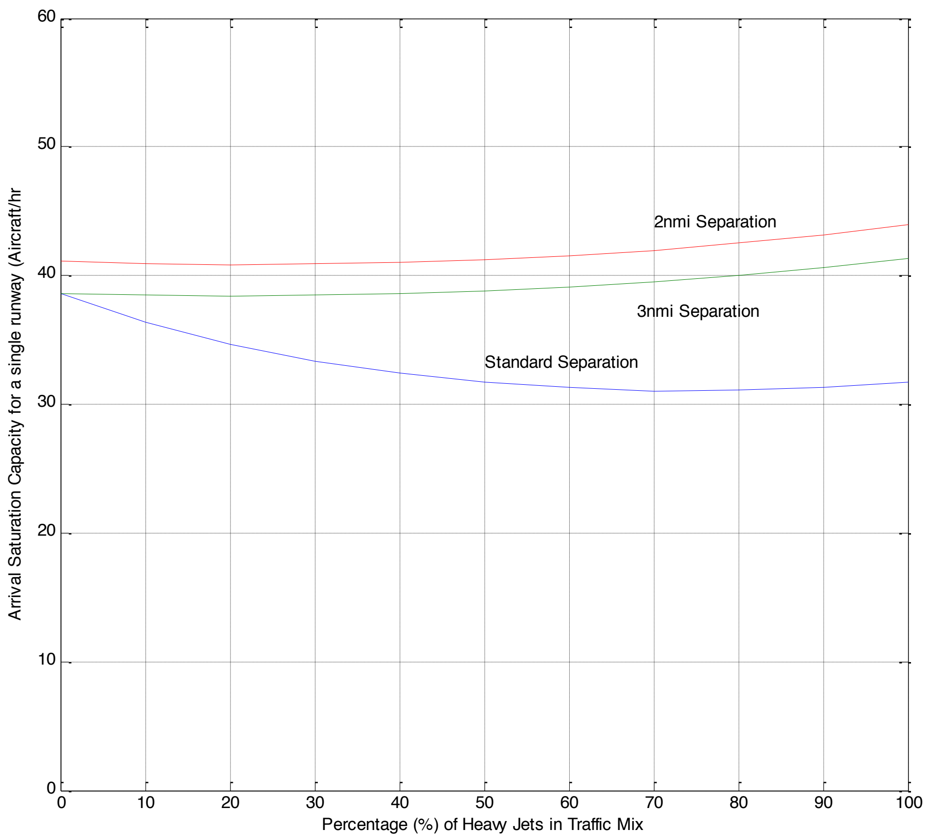


Figure 4.7. Saturation Capacity of a Single Arrival Runway for Three Separation Scenarios and a Range of Large-Heavy Weight Class Aircraft.

The results show the single runway arrival throughput is approximately 30 to 40 arrivals per hour with standard separation criteria. This represents the throughput performance of an independent runway; doubling the throughput value to obtain 60 to 80 arrivals per hour represents the best possible performance of two independent runways. Reducing the separation standards to 3- and 2-nautical miles reduces the variation in single-runway throughput to approximately 40 arrivals per hour.

Figure 4.8 shows the saturation arrival rate for dependent parallel runways with different spacing between the parallel runway centerlines using standard separation criteria and stagger separation between parallel runway aircraft of 1.5-nautical miles. Runway centerline spacing varies from 500 to 7000 feet in 500 feet increments.

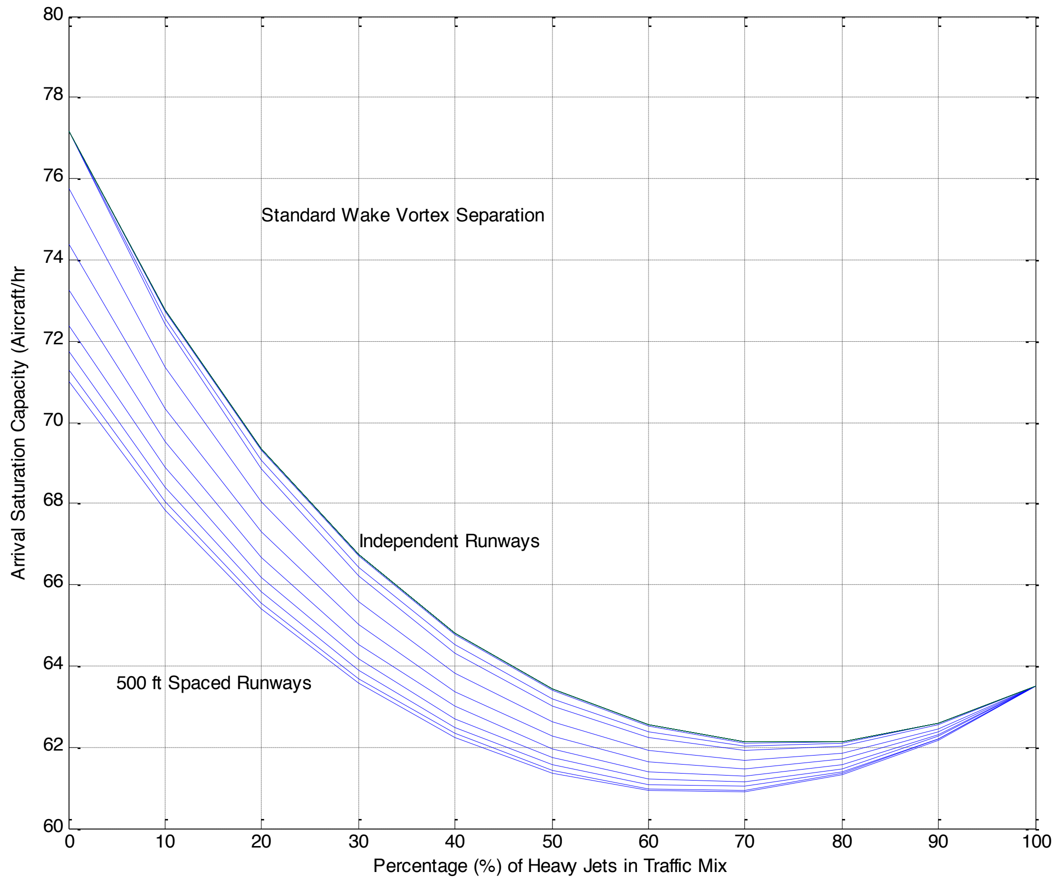


Figure 4.8. Saturation Capacity of Dependent Arrival Runways for 500-feet Incremental Runway Centerline Spacing and Range of Large-Heavy Weight Class Aircraft.

The results show the arrival throughput of the dependent parallel runways varies from 61 arrivals per hour to 77 arrivals per hour throughout the range of weight class and runway centerline spacing conditions, and is relatively close to the throughput realized with independent parallel runways. As a conservative estimate, we assume a throughput of 60 arrivals per hour for dependent parallel runway operations.

4.2.2.2 Analysis of RTCA SC-186, Automatic Dependent Surveillance-Broadcast (ADS-B) Committee Conditions

We extend our benefits analysis to analyze three different concepts falling within the arena of IM for Dependent Parallel Approaches that are being evaluated by the RTCA SC-186, ADS-B Concepts committee. The three concepts are Single Runway, Dependent Staggered Arrivals with One Target (DSA1), and Dependent Staggered Arrivals with Two Targets (DSA 2) [32] which were evaluated by The MITRE Corporation. The concepts are summarized in Table 4.5.

Table 4.5. Advanced Interval Management Concepts for Single and Dependent Parallel Arrival Runways.

A-IM Operation	Description	Spacing Impact
A-IM Single Runway	Follower uses IM to satisfy wake-vortex spacing with same-runway target	IM wake-vortex spacing buffer, baseline stagger spacing buffer
A-IM DSA1	Follower uses IM to satisfy stagger spacing with parallel runway target	Baseline wake-vortex spacing buffer, IM stagger spacing buffer
A-IM DSA2	Follower uses IM to satisfy wake-vortex spacing with same-runway target Follower uses IM to satisfy stagger spacing with parallel runway target Parallel runways >2500 feet	IM wake-vortex spacing buffer, IM stagger spacing buffer

We compute the expected value of inter-flight spacing, and the resulting airport arrival throughput, under the following conditions. We evaluate a range of possible large and heavy aircraft weight classes to the same- and parallel-runways. We assume the following:

- Current-day wake-vortex spacing minima (see Table 4.6)
- 1.5-nautical mile minimum stagger spacing with parallel-runway aircraft
- The exact longitudinal spacing depends on the spacing between the runway centerlines
- Final approach speeds of 140 knots for all aircraft.

Table 4.6. Wake-Vortex Separation Criteria.

Aircraft Weight Class	Lead Aircraft	
Trailing Aircraft	**Large**	**Heavy**
Large	3 nautical miles	5 nautical miles
Heavy	3 nautical miles	4 nautical miles

The spacing buffers for IM aircraft are assumed to be 8.4-seconds, corresponding to a 5 percent controller intervention rate and a Gaussian distributed spacing precision with a standard deviation of 5.1-seconds. The standard deviation value is implied by the spacing precision of +/- 10-seconds 95 percent of the time as stipulated in Penhallegon *et.al.* [32], assuming a two-tailed probability of a Gaussian distribution. The spacing precision is stipulated by FAA performance requirements for IM aircraft. The spacing buffers for the baseline condition are 25.7-seconds, corresponding to 1-nmi spacing distance at 140 knots [32].

We conduct two sets of evaluations: one for airports with CSPR, and another for airports with parallel runways spaced greater than 2500 feet between their centerlines. The specific CSPR runway spacing conditions we evaluated are listed in Table 4.7 [32].

Table 4.7. Closely-Spaced Parallel Arrival Runway Conditions Evaluated.

Airport Arrival Runways	Centerlines Spacing (Feet)
Newark (EWR): 04L, 04R	950
Cleveland (CLE): 24L, 24R	1240
Boston (BOS): 04L, 04R	1500

For our analyses of the CSPR conditions, we compare the arrival throughput values we obtained with the following values for each concept condition as documented in [32]: No IM (Baseline), approximately 40 arrivals per hour; IM Single Runway, approximately 40 arrivals per hour; and IM DSA1, approximately 50 arrivals per hour.

Figure 4.9 shows our arrival throughput results for the 950 feet runway centerline spacing case for each of the IM concept conditions: No Interval Management (IM), IM Single Runway, IM DSA2, and IM DSA1.

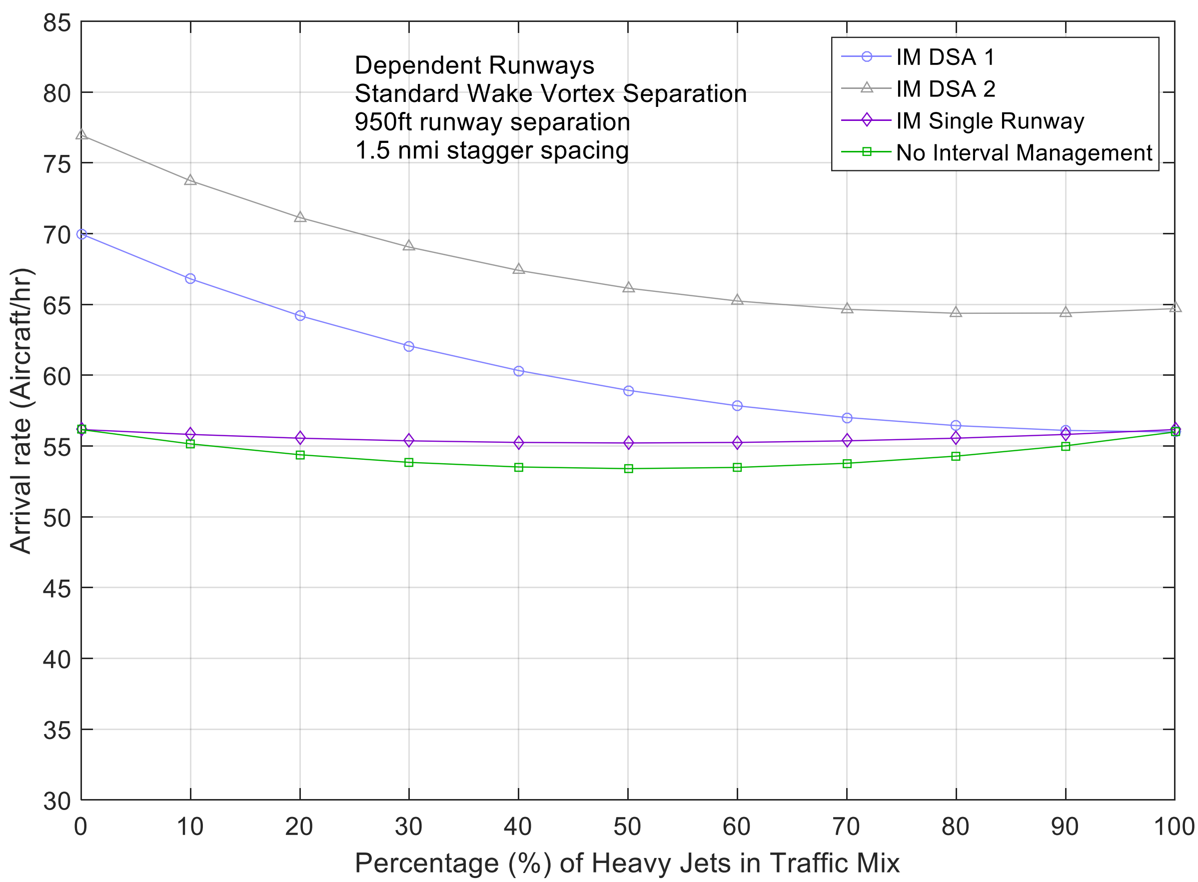


Figure 4.9. Saturation Capacity of Alternative Advanced Interval Management Concepts for 950-feet Runway Centerline Spacing and Range of Large-Heavy Weight Class Aircraft.

The results for the 950 feet spacing case indicate the following arrival throughput values for each concept condition: For No IM (Baseline), approximately 55 arrivals per hour; for

IM Single Runway, approximately 55 arrivals per hour; for IM DSA1, approximately 55 to 70 arrivals per hour. The results for the 1240 feet and 1500 feet spacing cases indicated essentially the same arrival throughput values, with slight but negligible differences in the peak throughput values.

The specific runway spacing cases we evaluated for the 2500 feet and greater runway centerline spacing conditions are listed in Table 4.8 as taken from Penhallegon *et.al* [32].

Table 4.8. Parallel Arrival Runway Conditions Evaluated [32].

Airport Arrival Runways	Centerlines Spacing (Feet)
Kennedy (JFK): 04L, 04R Kennedy (JFK): 22L, 22R	3000
Minneapolis (MSP): 30L, 30R, 35	3400
Fort Lauderdale (FLL): 10L, 10R	4000

For our analyses of these runway centerline spacing conditions, we compare the arrival throughput values we obtained with the following values for each concept condition as documented in [32]: No IM (Baseline), approximately 40 arrivals per hour; IM Single Runway, approximately 40 arrivals per hour; IM DSA1, approximately 50 arrivals per hour; and IM DSA2, approximately 68 arrivals per hour.

Our findings for the 3000 feet runway centerline spacing case for each of the IM concept conditions, No IM, IM Single Runway, IM DSA1, and IM DSA2, provided very similar arrival throughput results. For brevity, we present the Figure 4.10 showing our arrival throughput results for the 3000 feet runway centerline spacing case.

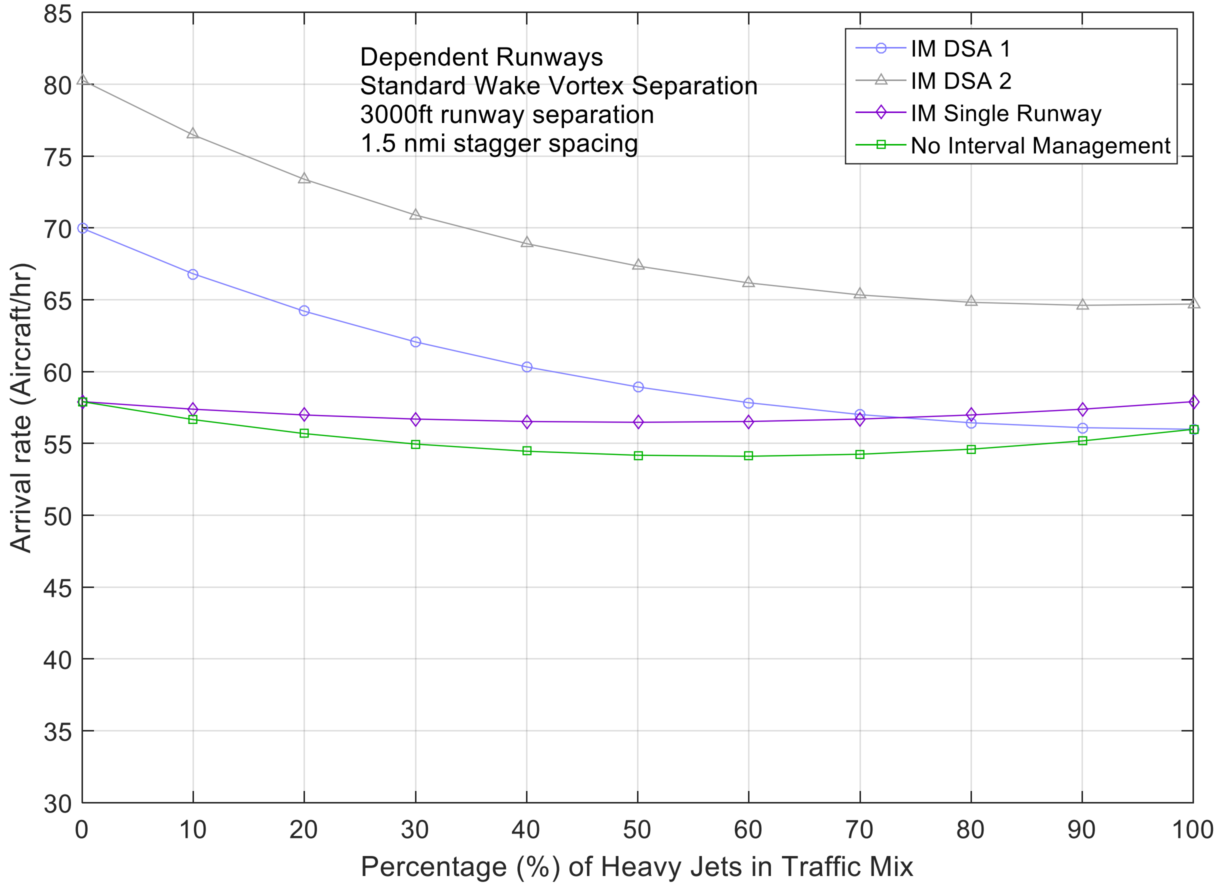


Figure 4.10. Saturation Capacity of Alternative Advanced Interval Management Concepts for 3000-feet Runway Centerline Spacing and Range of Large-Heavy Weight Class Aircraft**.**

The results for the 3000 feet spacing case above indicate the following arrival throughput values for each concept condition: For No IM (Baseline), approximately 52 arrivals per hour; for IM Single Runway, approximately 56 arrivals per hour; for IM DSA1, approximately 55 to 70 arrivals per hour; and for IM DSA2, approximately 65 to 80 arrivals per hour. The results for the 3400 feet and 4000 feet spacing cases indicated essentially the same arrival throughput values, with slight but negligible differences in the peak throughput values.

As with the MITRE study, our findings show that, with zero departures, little difference was seen between IM Single Runway and No IM for most conditions. Our study also showed very similar results for arrival runway centerline spacing conditions greater than 2500 feet. For arrival runway spacing centerline conditions of less than 2500 feet, our results calculate significantly more (approximately 5 – 20) absolute arrivals per hour for the No IM, IM Single Runway, and DSA1 cases than the MITRE study with zero departures. However, the relative difference between the DSA1 and IM Single Runway and No IM throughputs is generally consistent with the MITRE study with lower percentages of heavy jets in the traffic mix. It is likely that the absolute differences are a result of varying fleet mixes and specific facility and configuration conditions.

4.3 Operations Conditions Analysis

The objective of the Operations Conditions task for the IM for Dependent Parallel Approaches is to assess the frequency of application of dependent arrival operations to individual airports with parallel runways. This includes estimating the frequency of imbalances between airport arrival demand and capacity during IMC and identifying when parallel runway capacity is less than what is theoretically possible.

The approach to the Operations Conditions task is to analyze the meteorological conditions, traffic peaks and arrival capacity of airports with parallel runways as recorded in hourly FAA ASPM data for 2014. We analyze airport meteorological conditions (ASPM data field MC) to estimate how often the airport experienced IMC. We analyze airport scheduled arrival traffic (ASPM data field ARR_DEMAND) and airport arrival capacity (ASPM data field ARR_RATE) to estimate how frequently scheduled airport arrival demand exceeded airport capacity during time periods of IMC. We analyze airport arrival capacity (ASPM data field ARR_RATE) during periods of arrival demand-capacity imbalance in IMC to characterize the airport acceptance rate during the periods. We analyze airport runway configuration (ASPM data field RUNWAY) to determine the parallel arrival runways used during those periods of arrival demand-capacity imbalance in IMC. We identify the parallel runways most used during those periods, and their characteristic called arrival capacity. In turn, we use these results to identify airports which are candidates for dependent parallel runway operations in IMC; that is, which airports demonstrate arrival capacities of their parallel runways that are less than theoretically possible, and could in turn benefit from the IM for Dependent Parallel Approaches concept.

We analyzed airports with parallel runways with centerlines separated by 2500 feet or more among those detailed in [22]. The airports include Atlanta (ATL), Nashville (BNA), Baltimore/Washington (BWI), Charlotte (CLT), Cincinnati/Northern Kentucky (CVG), Dallas Love Field (DAL), Denver (DEN), Dallas/Fort Worth (DFW), Detroit Metropolitan Wayne County (DTW), Fort Lauderdale/Hollywood (FLL), Honolulu (HNL), Washington Dulles (IAD), Houston (HOU), Indianapolis (IND), John F Kennedy (JFK), Los Angeles (LAX), Kansas City (MCI), Orlando (MCO), Memphis (MEM), Miami (MIA), Minneapolis-St Paul (MSP), Chicago O'Hare (ORD), Portland (PDX), Phoenix (PHX), Pittsburg (PIT), Raleigh-Durham (RDU), Salt Lake City (SLC) and Tampa (TPA). We note that, due to the age of the document, some airports which had installed additional parallel runways since publication of the document, such as Seattle-Tacoma International Airport (SEA), were not included in the analysis.

4.3.1 Frequency of Excess Airport Arrival Demand in IMC

Figure 4.11 depicts for each airport the percentage of 1-hour periods of IMC throughout 2014 when the airport exhibited excess arrival demand; that is, when the number of scheduled arrivals exceeded the called arrival capacity at the airport. The results are presented as a percentage of all the 1-hour periods of IMC throughout 2014, and as a percentage of all the 1-hour periods (IMC or VMC) throughout 2014 (i.e., 8760 1-hour periods).

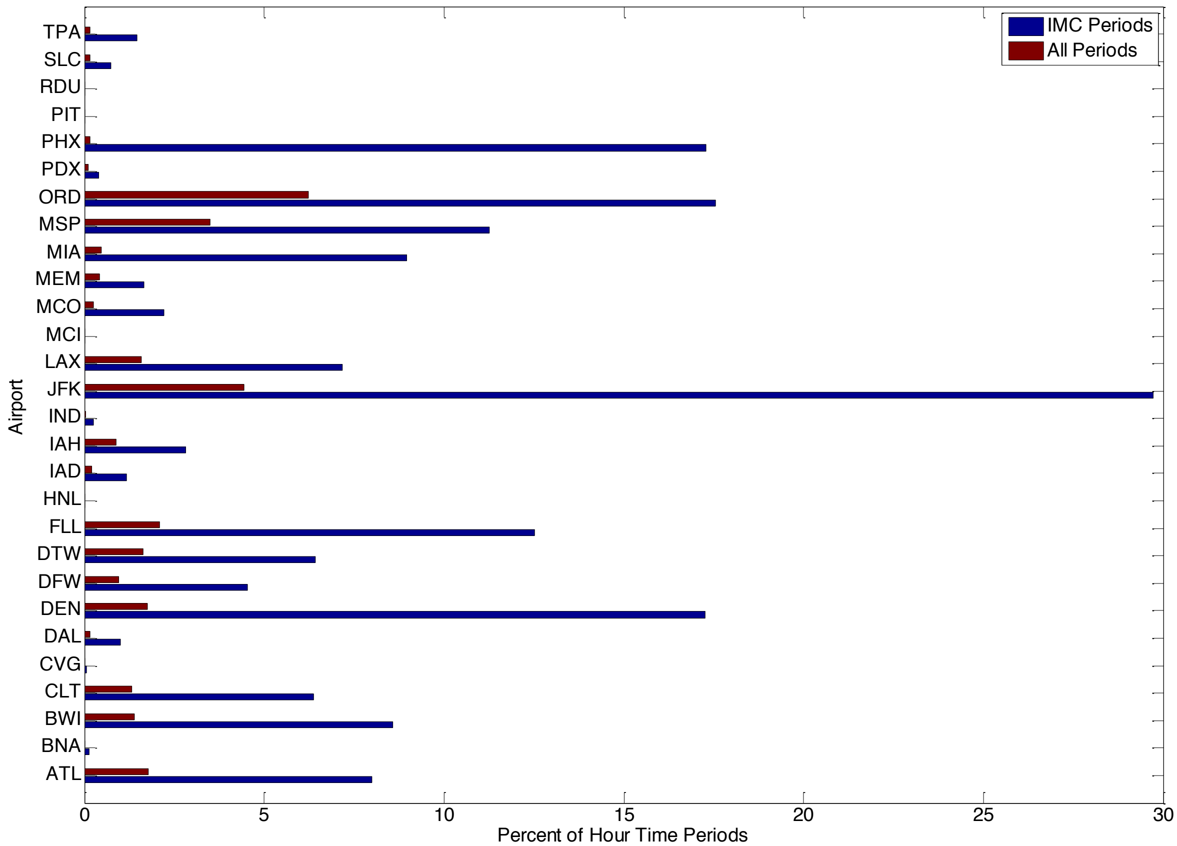


Figure 4.11. Percentage of 1-hour Periods (IMC and All) at Airports in 2014when the Number of Scheduled Arrivals Exceeded the Called Arrival Rate.

The results indicate that the number of 1-hour periods of excess arrival demand in IMC varied greatly among the airports. PHX, ORD, MSP, MIA, JFK, FLL, DEN, CLT, BWI and ATL exhibit higher numbers of occurrences, with 1-hour periods of excess arrival demand occurring in 10 to 30 percent of the times that the airport was operating in IMC during 2014. CVG, HNL, MCI, PIT and RDU do not exhibit periods of excess arrival demand. Excess arrival demand occurred in approximately 5 percent or less of all the 1-hour periods the airports were operating in 2014, with ORD, MSP and JFK demonstrating the highest occurrence rates.

4.3.2 Magnitude of Excess Airport Arrival Demand in IMC

Figure 4.12 depicts for each airport the number of scheduled arrivals beyond the called arrival capacity for 1-hour periods of excess arrival demand IMC throughout 2014. The results are presented as a box and whisker plot showing the characteristics of the distribution of the number of excess arrivals for each airport as done in Dixon [26]. The lower and upper whiskers represent the minimum and maximum values of the distribution, the lower and upper ends of the box represent the lower and upper quartiles of the distribution, the line dividing the box represents the median of the distribution, and the cross inside the box represents the mean of the distribution.

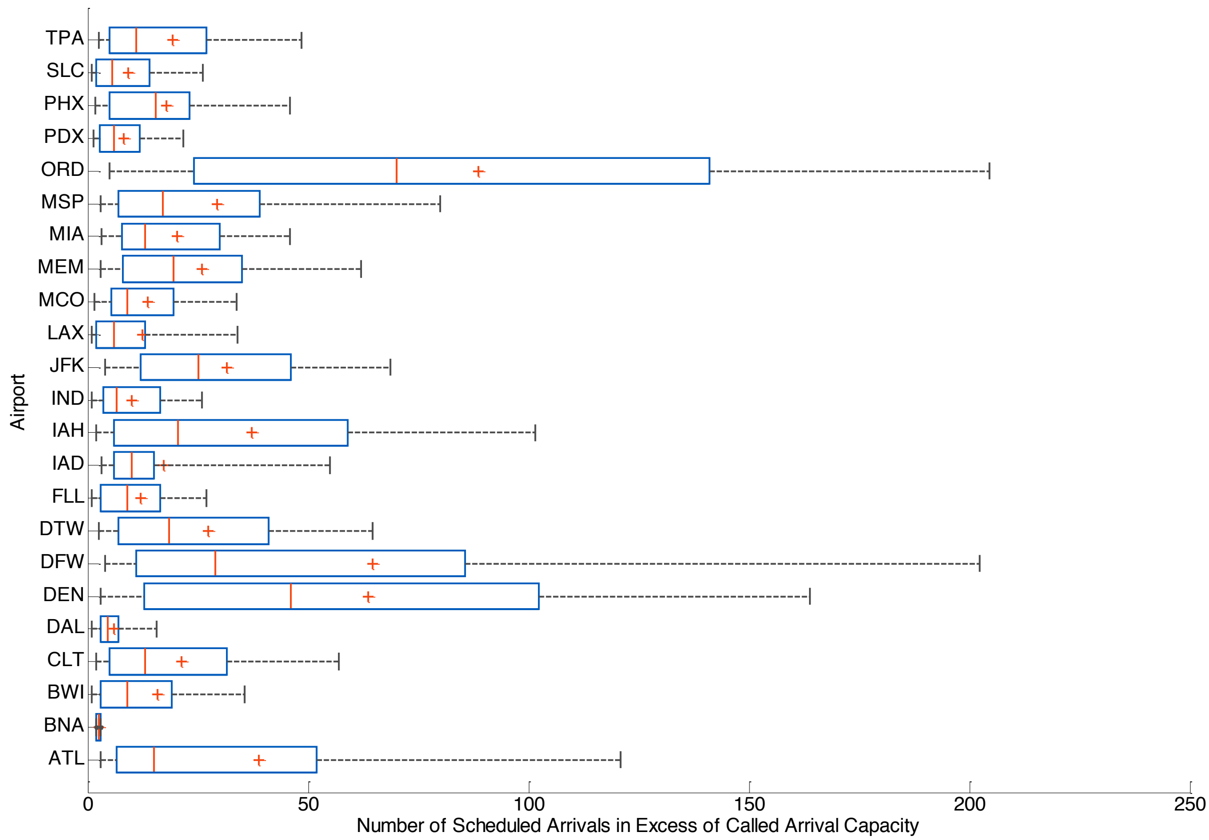


Figure 4.12. Distribution of the Number of Scheduled Arrivals in Excess of the Called Arrival Capacity in 1-hour Periods at Airports in 2014 when the Number of Scheduled Arrivals Exceeded the Called Arrival Rate.

The results indicate that the number of excess arrivals in a given 1-hour period of excess demand in IMC varied greatly throughout 2014. This is especially true for ORD, DFW, DEN and ATL which range from several excess arrivals to over 100 to 200 excess arrivals. We note that the latter results likely correspond to the airport being completely shut down due to weather. A deeper understanding of the scheduled demand data may be warranted. Nevertheless, for the majority of the airports, the median values are fewer than 20 arrivals, with only ORD and DEN standing out having median excess arrivals of approximately 50 or greater. For some airports, the quantity of excess arrivals can be quite large.

4.3.3 Capacities of Parallel Arrival Runways during Periods of Excess Arrival Demand in IMC

We first analyze each airport to determine its most frequently used parallel arrival runway configuration among the 1-hour periods of excess arrival demand in IMC throughout 2014. In turn, we analyze the called arrival capacities when that configuration was used during 1-hour periods of excess arrival demand in IMC. The results are presented in Figure 4.13 as a box and whisker plot of the called arrival capacities for the parallel runway configuration of each airport.

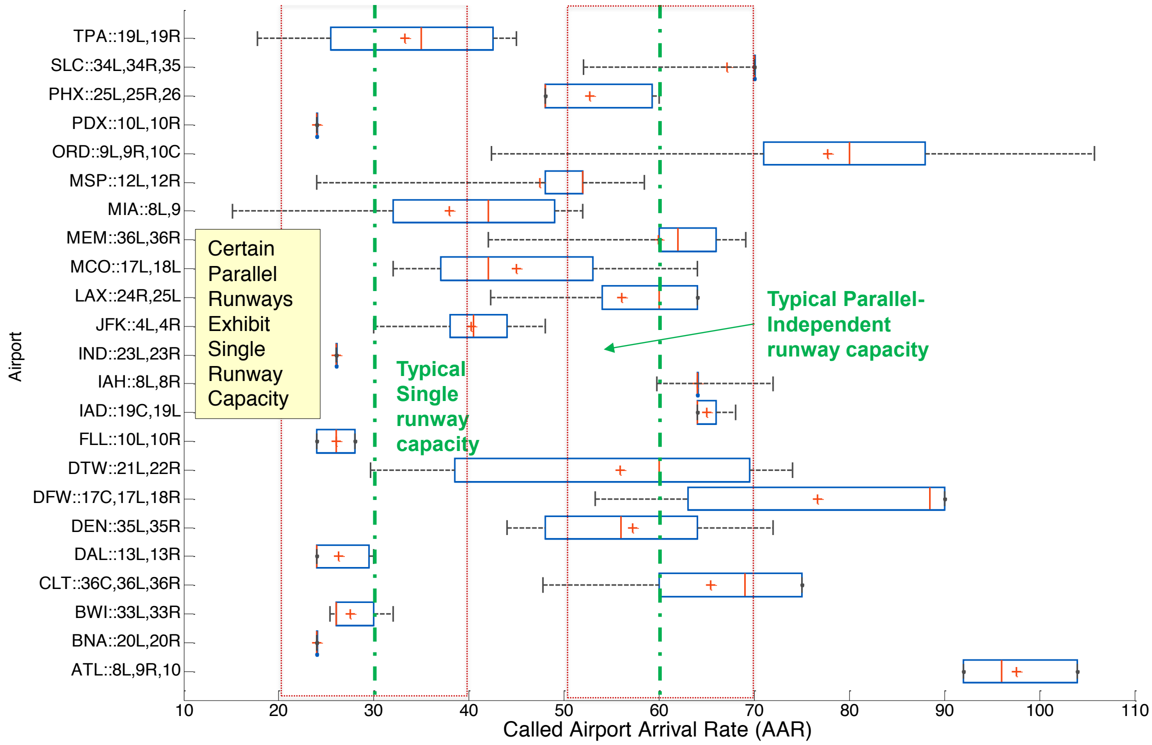


Figure 4.13. Distribution of Called Arrival Capacity for Most-Used Parallel Arrival Runways in 1-hour Periods at Airports in 2014 When Scheduled Arrivals Exceeded Called Arrival Rate.

The results indicate that the called arrival rates for some airports during 1-hour periods of excess arrival demand in IMC during 2014 correspond to single-runway capacities of approximately 30 arrivals per hour, despite the recorded use of parallel runways for arrivals. Distributions of the called arrival capacities for PDX, IND, FLL, DAL, BWI and BNA are consistently fewer than 30 arrivals per hour, and the distributions for MIA, MCO, JFK, MSP and DTW are in the neighborhood of this value. We note that some of the airports may have arrival runways which are shared with departures, thereby impacting their throughput. In addition, we also note that BWI runway 33R is only 5000 feet long, therefore would not be suitable for landing large and heavy aircraft.

4.4 NAS-Wide Benefit Analysis

The objective of the NAS-wide Benefits task for the IM for Arrivals to Dependent Parallel Runways is to estimate the net benefit of the concept for a set of representative airports across the NAS. The approach taken is to first qualitatively evaluate the airports to select candidates that meet minimum criteria, such as runway lengths, for application of the concept, and to identify other factors that might influence the benefit of the concept. Then, we conduct quantitative analysis to estimate the capacity of each airport under the baseline conditions and application of the concept, and the frequency of concept application.

4.4.1 Candidate Airports for Concept Application

Table 4.9 presents the information considered to identify airports as candidates for concept application and benefits assessment. For the particular parallel arrival runway pair of each airport, evaluation considered the runway lengths to support arrival landings, the existence of instrument approach procedures to support dependent approaches, and the sharing of an arrival runway for departures that could impact throughput benefit. Approaches include ILS, Localizer (LOC) and Localizer-type Directional Aid (LDA) Very High Frequency (VHF) Omni-Directional Radio (VOR) Distance Measuring Equipment (DME) approaches, and Area Navigation (RNAV) approaches.

Table 4.9. Airport Factors Impacting Implementation of Dependent Parallel Approaches.

Apt Arrival Runways	Runway Lengths, Feet	Instrument Approach	Shared Departure Runways
ATL::8L,9R,10	9000, 9000, 9000	ILS, ILS, ILS	8L
BNA::20L,20R	8000, 7703	ILS/DME, ILS/DME	20L,20R
~~BWI::33L,33R~~	~~9500, 5000~~	~~ILS, ILS~~	~~33R~~
CLT::36C,36L,36R	10000, 9000, 8676	ILS/DME, ILS/DME, ILS/DME	36C,36R
DAL::13L,13R	7752, 8800	ILS/DME, ILS/DME	13L,13R
DEN::35L,35R	12000, 12000	ILS, ILS	Not applicable
DFW::17C,17L,18R	13401, 8500, 13400	ILS, ILS, ILS	17C
DTW::21L,22R	8501, 10000	ILS, ILS	NA
FLL::10L,10R	9000, 8000	ILS/DME, ILS/DME	10L,10R
IAD::19C,19L	11500, 11500	ILS, ILS	19L
IAH::8L,8R	9000, 9402	ILS, ILS	Not applicable
IND::23L,23R	10000, 11200	ILS/DME, ILS/DME	23L,23R
JFK::4L,4R	12079, 8400	ILS/DME, ILS/DME	4L
LAX::24R,25L	8296, 11095	ILS, ILS	24R,25L
MCO::17L,18L	9001, 12005	ILS, VOR/DME or RNAV	17L,18L
MEM::36L,36R	9320, 9000	ILS, ILS	36L
MIA::8L,9	8600, 13016	LOC/DME, ILS	8L,9
MSP::12L,12R	8200, 10000	ILS, ILS	12L,12R
ORD::9L,9R,10C	7500, 7967, 10801	ILS, ILS, ILS	10C,9R
PDX::10L,10R	9825, 11000	ILS/DME, ILS/DME	10L,10R
PHX::25L,25R,26	7800, 10300, 11489	ILS/DME, ILS/DME, ILS/DME	25R,26
SLC::34L,34R,35	12000, 12000, 9597	ILS, ILS, LDA/DME or RNAV	34R,35
TPA::19L,19R	8300, 11000	LOC/DME, ILS/DME	19L,19R

The results indicate BWI is the only airport with insufficient runway length to support dependent parallel arrivals. Almost all airports have ILS approach procedures to each runway to support dependent parallel arrivals. Exceptions are MCO 18L, MIA 8L and SLC 35 which have GPS RNAV approach procedures. Most airports exhibit shared-use runways which would impact frequency of applying the concept and the resultant benefit.

4.4.2 Airport Arrival Capacity Benefit

To estimate the arrival capacity benefit of each airport, we compare the baseline arrival capacity to the theoretical arrival capacity for each airport.

To estimate the baseline arrival capacity of each airport, we identify from the FAA ASPM data the most frequently used parallel arrival runway pair during 1-hour periods of IMC when scheduled airport arrivals exceeded the called airport capacity (excess arrival demand). We then identify from FAA ASPM data all the 1-hour periods when that parallel arrival runway pair was used in IMC, regardless of the demand-capacity condition. We compute the average of the called arrival rates among those 1-hour periods of IMC when the parallel arrival runway pair was in use.

To estimate the theoretical arrival capacity of each airport, we identify from FAA ASPM data each 1-hour period where the airport was operating in IMC and the parallel arrival runway pair of interest was in use. For each 1-hour time period, we enforce the minimum theoretical arrival rate of 30 arrivals per hour per runway, as estimated from our Maximum Benefits analysis, if the called arrival rate was less than that. We then estimate the theoretical arrival capacity as the average of the revised arrival rates for the 1-hour periods. Figure 4.14 depicts the average of the called arrival rates and the average of the theoretical arrival rates for each airport during 1-hour periods of IMC when the airport is in its primary parallel arrival runway configuration.

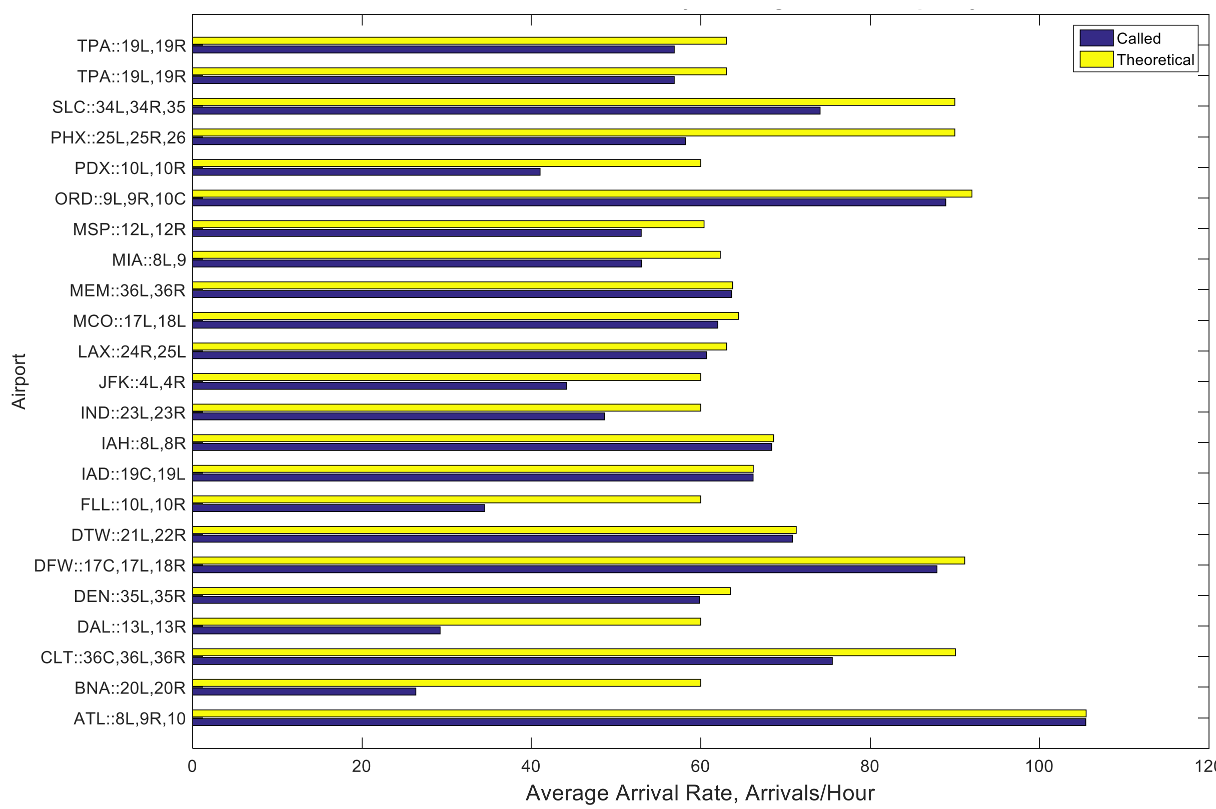


Figure 4.14. Average Arrival Rates for Parallel Arrival Runways of Airports for Historical Called Arrival Rates and Theoretical Arrival Rates Using Dependent Parallel Approaches.

The results indicate that the majority of the airports demonstrate some level of arrival capacity increase with application of the dependent parallel arrival runways concept to the most-used parallel arrival runways. In particular, TPA SLC, PHX, PDX, MSP, MIA, JFK, IND, FLL, DAL, CLT and BNA demonstrate noticeable arrival capacity increases.

4.4.3 NAS-Wide Arrival Capacity Benefit

To estimate a NAS-wide arrival benefit of the concept, we estimate the arrival capacity impact of the concept and the frequency of concept application across the airports evaluated.

We estimate the arrival capacity impact as the difference between the theoretical and baseline capacities for each airport for the most-used parallel arrival runways. We sum the capacity changes of the airports to estimate a NAS-wide arrival capacity increase. We estimate the frequency with which arrival capacity increases could be realized based on the number of 1-hour periods that each airport was operating in IMC during 2014 (from FAA ASPM data).

Table 4.10 presents, for each airport in its primary parallel arrival runway configuration, the average of the called rates in IMC, the average of the theoretical arrival rates in IMC, and the difference between the two. The per-airport changes are summed to estimate the total NAS-wide arrival capacity impact of the dependent arrival operations concept. Table 4.10 also presents the number of 1-hour periods each airport was operating in IMC in 2014. The per-airport values are averaged to estimate the number of hours that the NAS-wide arrival capacity impact of the dependent arrival operations concept could be realized.

Table 4.10. Comparison of the Average Airport Arrival Rates in IMC for Baseline Historical and Theoretical Dependent Parallel Approach Conditions and the Number of Time Periods in IMC.

Airport::Runways	Average Airport Arrival Rate in IMC (Arrivals/Hour)			Number of Hourly Periods in 2014 Where Airport Was In IMC
	Baseline, Historical	Theoretical, Dependent Arrival Operations	Change	
ATL::8L,9R,10	105	105	0	1953
BNA::20L,20R	26	60	34	1560
CLT::36C,36L,36R	76	90	15	1804
DAL::13L,13R	29	60	31	1404
DEN::35L,35R	60	63	4	886
DFW::17C,17L,18R	88	91	3	1834
DTW::21L,22R	71	71	0	2239
FLL::10L,10R	35	60	25	1469
IAD::19C,19L	66	66	0	1603
IAH::8L,8R	68	69	0	2760
IND::23L,23R	49	60	11	1598
JFK::4L,4R	44	60	16	1305
LAX::24R,25L	61	63	2	1927
MCO::17L,18L	62	64	2	1043
MEM::36L,36R	64	64	0	2289
MIA::8L,9	53	62	9	457
MSP::12L,12R	53	60	7	2720
ORD::9L,9R,10	89	92	3	3107
PDX::10L,10R	41	60	19	2313
PHX::25L,25R,26	58	90	32	81
SLC::34L,34R,35	74	90	16	1885
TPA::19L,19R	57	63	6	961
			Sum = 237	**Average = 1691**

The results indicate that, on average, the NAS could accommodate 237 additional arrivals per hour among these airports, and that, on average, this capacity could be realized for 1691 hourly periods throughout the year. Caveats to these values include, but are not limited to the shared use of arrival runways with departures was not accounted for; and, periods where the called arrival rate of the airport was zero due to, presumably, the airport being shut down due to weather or other causes, were not filtered from the analysis. In addition, analysis has only considered a single parallel arrival runway configuration for each airport, and the concept is assumed applicable to all time periods of IMC.

5 Interval Management for Departure Operations- Initial Climb Out

This section details the analysis performed for departure operations. The concept details are presented first, followed by the Maximum Benefit and Operations Conditions analysis. The results are then applied to the NAS wide benefits analysis.

5.1 Concept Details

The *IM for Departure Operations -Initial Climb Out* concept applies to departures from the same metroplex (not necessarily the same airport), which transit a common departure fix or gate, or different fixes or gates which are otherwise coupled. Figure 5.1 summarizes of the theory of operation for IM with Departure Operations.

Table 5.1. Theory of Operation for Departure Operations, Initial Climb Out.

Conditions for Application	• Same- or different-airport departures which are assigned to the same departure fix or gate. This may include: 1) same-route, same-airport departures; 2) different-route, same-airport departures; or 3) different-route, different-airport departures
Baseline Operations	• Minimum in-trail spacing requirements at the departure fix or gate satisfy minimum radar separation and Miles-In-Trail restrictions specified to facilitate merging departures • Additional in-trail spacing buffers may be specified as per variances characteristic of current-day controller-managed spacing • Excessive spacing or missed departure slots as per the limitations of controller-managed spacing
Concept Rules & Constraints	• Departures in-trail satisfy radar separation or Miles-In-Trail restrictions, with reduced spacing buffers due to increased spacing precision • Departures in-trail meet assigned slots or meet them more precisely. No missed slots, no excessive spacing
Concept Factors & Dependencies	• Closely-scheduled departures from same or different airports such that benefits of reduced spacing may be realized
Concept Requirements	• Controller tools and procedures for identifying departures destined for same departure fix or gate, determining their crossing sequence, and assigning target aircraft and spacing goals to them • Aircraft and flight crew capabilities to satisfy spacing goals with designated target aircraft

The departure fix (*or gate*) typically establishes the boundary of control jurisdiction between the Terminal Radar Approach Control (TRACON) and the Air Route Traffic Control Center (ARTCC). The departure fix/gate typically serves as a point for metering the departure flow from the TRACON to the ARTCC. A spacing value of 7 Miles-In-Trail (MIT) between successive departures is a typical value for metering departures. To this value, ARTCC controllers may specify an additional 3 MIT spacing buffer to account for uncertainty.

In current-day operations, the local controller of an airport will use ad-hoc spacing rules between successive departures to meet the required in-trail spacing at the departure fix. Local controllers will also use ad-hoc spacing rules at the runway to provide gaps for merging with departures from other airports, such that the resulting traffic flow can satisfy the specified in-trail spacing at the departure fix/gate. TRACON controllers use vector and speed control techniques to merge departures and meet the MIT spacing at the departure fix. Imprecision in these coarse techniques for spacing departures results in excessive inter-flight spacing or even missed slots at the departure fix or runway, as well as inefficient aircraft trajectories and excessive controller workload.

In the IM for Departure Operations concept, the ABP is the departure fix/gate. The IM Aircraft is assigned a spacing goal to satisfy with Target Aircraft at the departure fix or gate. The IM Aircraft and Target Aircraft may be from the same airport or from different airports. The flight crew of the IM Aircraft leverages specialized navigation equipment on board the aircraft to satisfy the assigned spacing goal, while the TRACON controller monitors the operations. This enables the IM Aircraft to more precisely meet the specified in-trail spacing with the Target Aircraft crossing the fix or gate to avoid excessive spacing or grounds stops.

A schematic of inter-flight spacing requirements for departures merging at departure fixes is depicted in Figure 5.1:

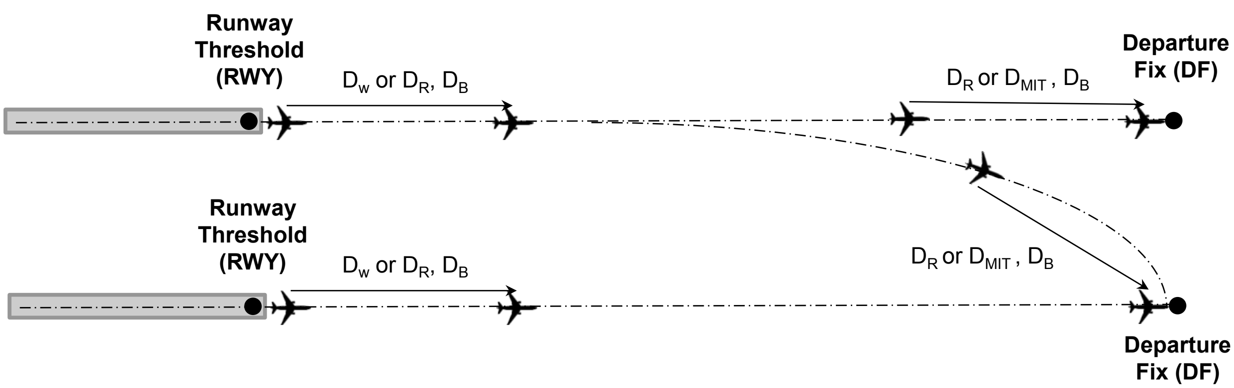


Figure 5.1. Inter-flight Spacing Requirements for Departure Operations, Initial Climb Out.

As depicted in Figure 5.1, at the runway, the IM Aircraft satisfies wake-vortex separation (D_W) and 3-nautical mile radar separation (D_R) with its runway system predecessor at the origin airport. A spacing buffer (D_B) may be added to each of these minimum spacing values to account for imprecision in satisfying these spacing requirements and to satisfy an acceptable controller intervention rate. At the departure fix or gate, the IM Aircraft satisfies the required MIT spacing (D_{MIT}) with the Target Aircraft when the Target Aircraft crosses the fix or gate, as well as 3-nautical mile radar separation (D_R) with the Target Aircraft. A spacing buffer (D_B) may be added to each of these minimum spacing values as well.

5.1.1 Relevant Literature

The concept details and theory of operation are developed from an extensive literature search. The noteworthy references are summarized in this section.

- RTCA SC-186 documents sketch the overall operations of and the possible clearance data for IM DO Initial Climb Out operations. The Target Aircraft may be from the same or different runway of the same airport as the spacing follower aircraft, or from a runway of a different airport as the spacing follower aircraft. Three possible geometries include a completely coincident route, merging route, or non-coincident route. In the non-coincident route, the two aircraft may be assigned to, say, different departure fixes of the same departure gate. [3]

- Penhallegon, *et al.* [14] evaluate the feasibility of applying IM to support merging departure aircraft at a departure fix or into an en route stream. The study cites the current-day throughput and flight efficiency limitations of controllers coordinating departure takeoffs and vectoring aircraft to merge aircraft into en route streams and to merge at departure fixes in order to satisfy MIT restrictions between aircraft at the merge point. Limitations of controller management of departures may result in excess spacing between successive departures to a common fix or merging in the overhead stream, or missed slots at the departure fixes which can result in a ground stop at an airport to recover. The study conducts Human-In-The-Loop simulations to evaluate the flight deck operations, human performance and flight deck display considerations to support IM for departure merging. The study evaluates Atlanta International Airport (ATL) departures from the north and south runway complexes to departure fix DAWGS. The study finds that IM for departure merge operations, considering the workload, heads-down time and other factors for the flight crew to conduct the procedures, is acceptable. Departure trajectory variability, and its impact on trajectory prediction for departure scheduling and speed guidance for the follower to satisfy the spacing interval, can influence the feasibility of the operations [14].

5.2 Maximum Benefit Analysis

To estimate the maximum departure throughput achievable with the IM for Departure Operations concept, we develop a simple metroplex-wide departure flight scheduling algorithm to schedule departure flight airport takeoffs and departure fix crossings. In turn, we assign excess inter-flight spacing or missed slots among a prescribed percentage of the departure flight pairs to model the baseline traffic condition, selecting pairs at random. We model minimum inter-flight spacing or no missed slots among all the departures to model the IM for Departure Operations concept. We apply the scheduling algorithm to eight metroplexes and associated airports to evaluate the metroplex throughput impact of the IM for Departure Operations concept.

5.2.1 Analysis Methodology

We develop and implement a simplified multi-airport, multi-departure fix scheduling algorithm to schedule the departure fix crossings and runway takeoffs for departures from all airports in the modeled metroplex. The algorithm is based on the NASA Traffic Management Advisor (TMA) Order of Consideration algorithm for successive scheduling of departures [33]. The algorithm preserves the sequence of departures implied in the departure traffic schedule; it enforces required minimum separation between successive departures at the airport runway and at the departure fix; and it prevents overtakes between departures from the same airport and crossing the same fix. Any delay required to satisfy minimum spacing with the flight's predecessor at the departure fix is back-propagated to its airport departure (runway takeoff) time.

For a given set of departures from multiple airports in a metroplex, the algorithm performs the following steps:

1) As a pre-processing step, estimate the departure fix for each departure flight, and the transit time from the airport to the departure fix for each flight, based on modeling of the metroplex;
2) Select from each airport the next runway takeoff flight to be scheduled to get initial candidates for scheduling;
3) If any of the selected runway takeoffs cross the same departure fix, select the earliest of the flights crossing that fix to get final candidates;
4) Select the candidate with the earliest fix crossing time as the flight for scheduling;
5) Schedule the fix crossing time of that flight to satisfy minimum separation with the previous flight scheduled to cross that fix;
6) Back-propagate any resulting delay to the flight's runway takeoff time;
7) Schedule the flight's runway takeoff time.

The inter-flight spacing values used in the scheduling algorithm are manipulated for a prescribed percentage of flights, as per the scenario, to evaluate the impact of improved inter-flight spacing precision and elimination of missed slots potentially afforded by the IM Departure Operations concept.

5.2.1.1 Eliminating Excess Inter-Flight Spacing at Departure Fixes

To model the baseline spacing precision, a prescribed percentage of flights are randomly selected from all the metroplex departures under evaluation, and they are assigned larger than required spacing values with their predecessors crossing the departure fix. As per the algorithm, the resulting excess flight delay is back-propagated to the scheduled takeoff time of each of the selected departure flights. This, in turn, delays any successive flights in the sequence of departure takeoffs from the same or other metroplex airports. This is demonstrated for two airports supplying departures to a common departure fix in Figure 5.2.

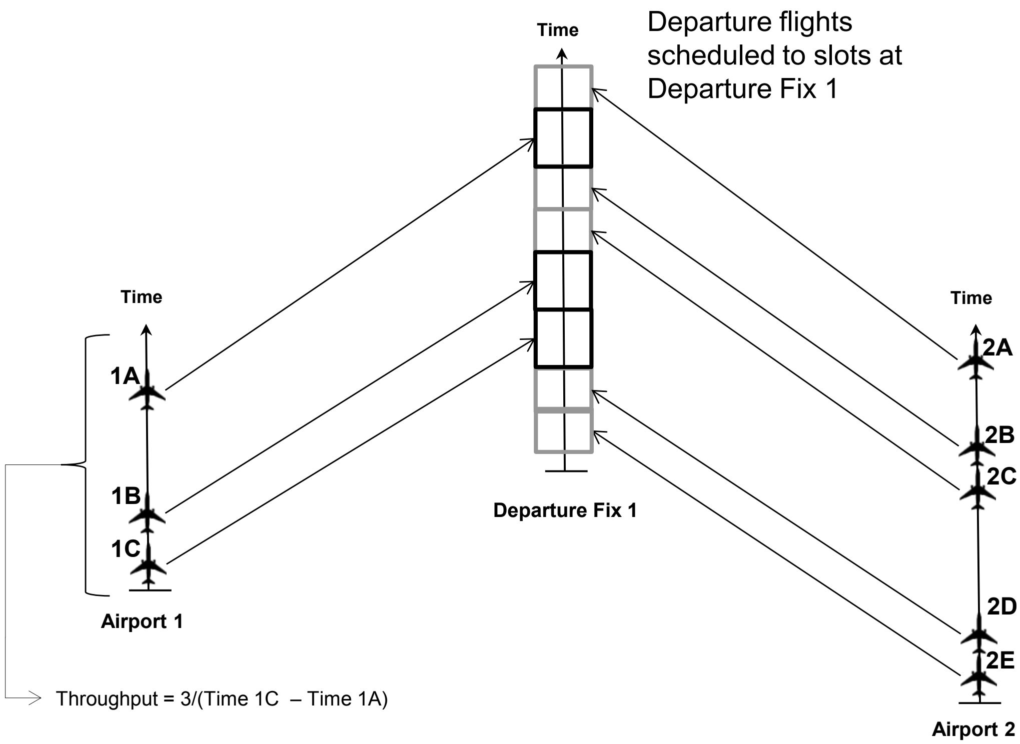


Figure 5.2. Sequencing and Scheduling of Multi-airport Departures to Common Departure Fix with Excess Spacing for Departures From Airport 1.

In Figure 5.2, each successive departure flight from Airport 1 or Airport 2 is scheduled to cross Departure Fix 1 to satisfy required minimum spacing with the previous flight crossing the fix. If Aircraft 1A from Airport 1, for example, is assigned to cross Departure Fix 1 with excess spacing behind Aircraft 2A from Airport 2, all subsequent departures from Airports 1 and 2 scheduled to cross Departure Fix 1 are delayed that much more. Excess spacing applied to Aircraft 1B and Aircraft 1C from Airport 1 delays subsequent departures from Airport 2, thereby impacting airport, departure fix, and ultimately metroplex-wide throughput.

5.2.1.2 Eliminating Missed Departure Fix Time Slots

To model the baseline missed departure slots, a prescribed percentage of flights are randomly selected from all the metroplex departures under evaluation, and they are assigned twice the required inter-flight spacing value with their predecessors crossing the departure fix to model the effect of missing a departure slot. As per the algorithm, the resulting excess flight delay is back-propagated to the scheduled takeoff time of each of the selected departure flights. This, in turn, delays any successive flights in the sequence of departure takeoffs from the same or other metroplex airports. This is demonstrated for two airports and a single departure fix in Figure 5.3.

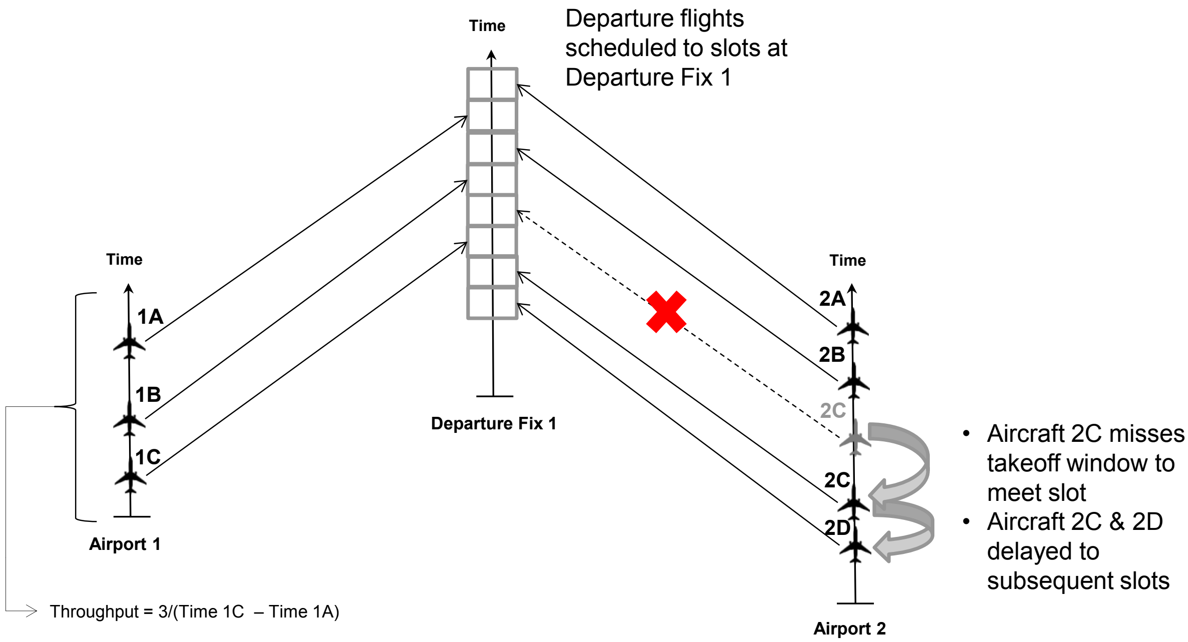


Figure 5.3. Sequencing and Scheduling of Multi-airport Departures to Common Departure Fix with Missed Departure Slot for Aircraft 2C From Airport 2.

In Figure 5.3, each successive departure flight from Airport 1 or Airport 2 is scheduled to cross Departure Fix 1 to satisfy required minimum spacing with the previous flight crossing the fix. If Aircraft 2C from Airport 2, for example, misses its takeoff time to meet its designated time slot at the departure fix, then it is delayed to the next available slot at the departure fix, which comes after Aircraft 1C from Airport 1. This, in turn, delays subsequent departure Aircraft 2D from Airport 2, thereby impacting airport, departure fix, and ultimately metroplex-wide throughput.

5.2.2 Analysis Findings

We applied the analysis approach to departures in the **Atlanta, Charlotte, North Texas, Southern California, New York, Chicago, Phoenix** and **Northern California** metroplexes. More information regarding the models and traffic scenarios for those metroplexes used in this analysis is provided under the Operations Conditions task.

In all cases, we used typical airport departure rates obtained from [34] as the basis for time separation of departures at the airport, and we used 7 nautical miles at 250 knots as the basis for the time separation of departures at the departure fix.

For the excessive spacing benefit mechanism, we evaluated numerous baseline conditions: 10 nautical miles distance spacing among 1% -100% of departures in varying increments. For the concept condition, we assumed excess spacing among *none* (0.0%) of departures. For the missed slots benefit mechanism, we evaluated two different baseline conditions: missed slots among 10% and 25% of departures. For the concept condition, we assumed missed slots among *none* (0.0%) of the departures.

5.2.2.1 Eliminating Excess Inter-Flight Spacing at Departure Fixes

Figure 5.4 depicts the time-averaged throughput for each metroplex evaluated under the numerous baseline conditions and the concept condition. Metroplex throughput is computed as the total number of departures divided by the difference between the time of the last metroplex departure flight and the first metroplex departure flight. Due to this aggregate assessment of the throughput over the 24-hour extent of the traffic schedule analyzed, throughput values are less than what might be observed at any instant during, say, peak departure traffic level conditions or individual airport capacities.

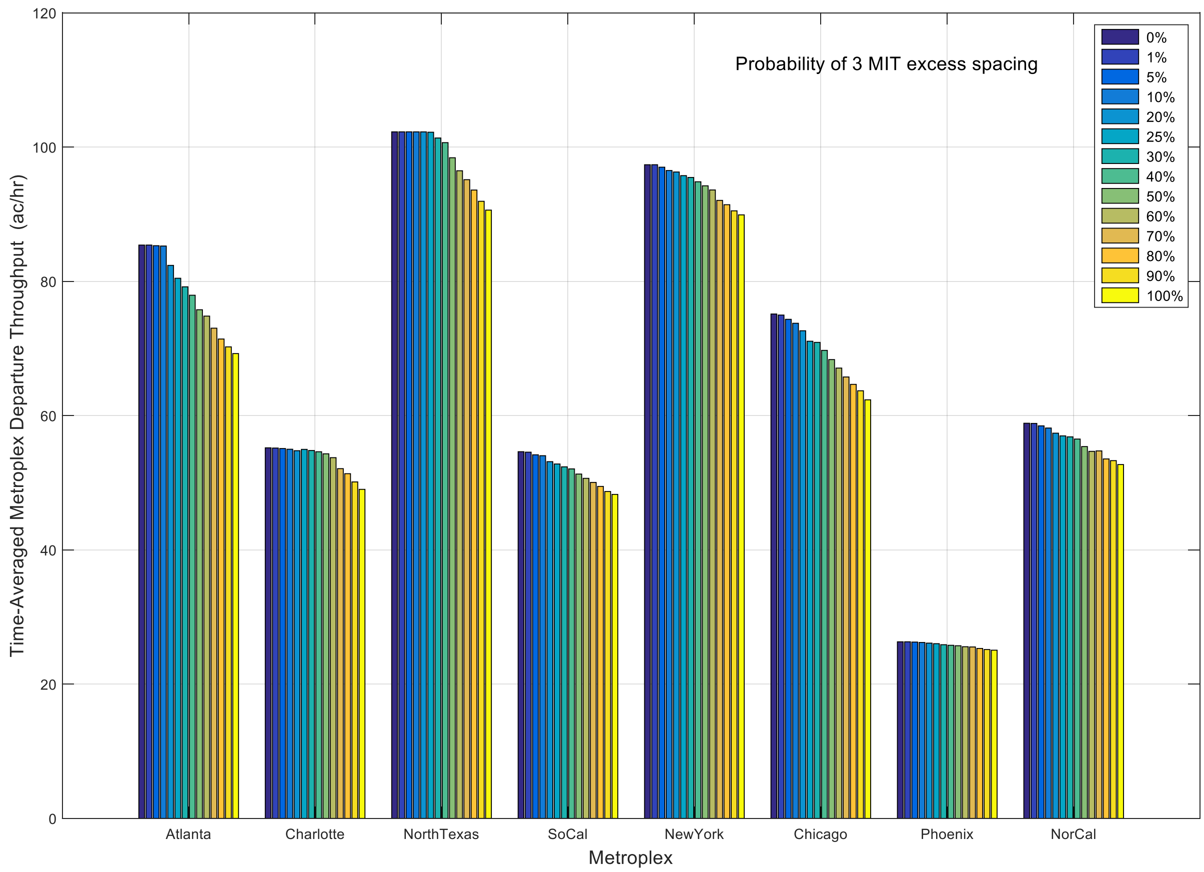


Figure 5.4. Average Departure Throughput of Different Metroplexes with Excess Spacing Among Increasing Percentages of Departures.

The results indicate that eliminating excess spacing of 3 nautical miles beyond the baseline 7 nautical miles among 50 percent or more of departures can increase average hourly departure throughput of metroplexes significantly.

5.2.2.2 Eliminating Missed Departure Fix Time Slots

Figure 5.5 depicts the time-averaged metroplex throughput for each of the metroplexes evaluated under the numerous baseline conditions and the concept condition. Metroplex throughput is computed as the total number of departures divided by the difference between the time of the last metroplex departure flight and the first metroplex departure flight.

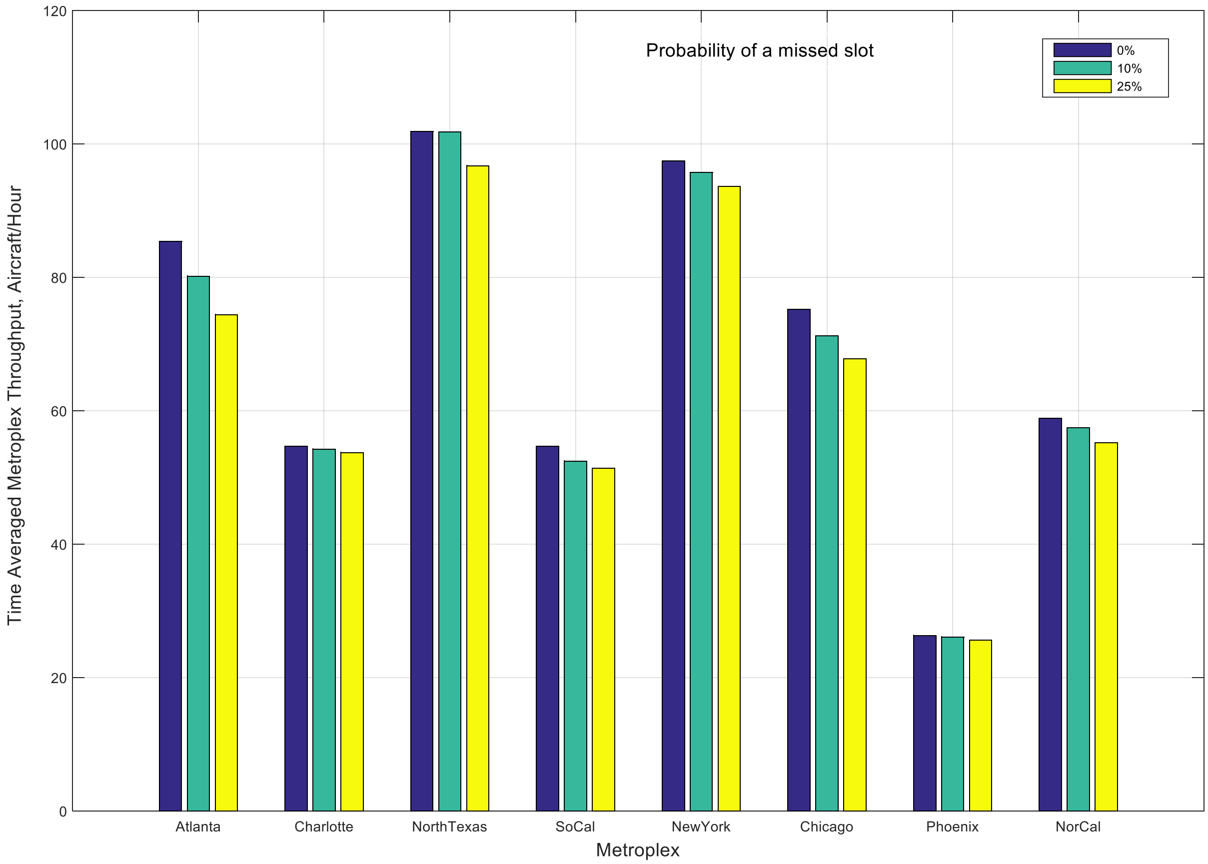


Figure 5.5. Average Departure Throughput of Different Metroplexes with Missed Slots for Increasing Percentages of Departures.

The results indicate that eliminating missed departure fix slots among 10 and 25 percent of metroplex -wide departures can significantly increase departure throughput of the majority of the metroplexes, in particular Atlanta, New York, Chicago and Northern California.

5.3 Operations Conditions Analysis

The objective of the Operations Conditions task is to estimate the frequency of merging departures from the same metroplex to common departure fixes. The design and benefit of the operational concept may differ for each scenario. The approach is to model the metroplex infrastructure and departure traffic, then apply the models for analyzing metroplex departure traffic. Metroplex modeling includes, for a subset of the FAA-defined metroplexes, modeling the key metroplex airports and estimating the departure fixes for each metroplex. Departure traffic modeling includes obtaining day of scheduled departures for each airport modeled in each metroplex, estimating a departure fix for each departure flight based on the bearing of its destination airport relative to its origin airport, and estimating a fix crossing time for each departure flight from its estimated terminal airspace transit time. Departure merging analysis comprises searching the sequence of departures crossing each departure fix to identify pairs of in-trail departures which have spacing less than the minimum required separation. In turn, each pair is identified as a same-airport pair or different-airport pair to determine the frequency of separation violations among same- and different-airport departures crossing a common fix.

5.3.1 Metroplex Modeling

The FAA defines a metroplex to comprise multiple airports in a metropolitan area which have complex air traffic flows [27]. Characteristic of metroplexes is that flights from different airports may share common airspace resources, such as transiting common departure fixes within common altitude regions. The FAA defines 21 metroplexes within the US, and lists the individual airports comprising each metroplex [27]. Among these metroplexes, we modeled the Atlanta, Charlotte, Chicago, New York, North Texas, Northern California, Phoenix, and Southern California metroplexes. We leveraged the FAA Optimization of Airspace and Procedures in the Metroplex (OAPM) Study Reports to identify satellite airports for each metroplex [28]. Departure fixes were defined based on review of literature or evaluation of the Standard Instrument Departure (SID) procedures for each airport in the metroplex [29][30]. In the evaluation of the SIDs, the departure fixes were selected as the last point in the SID, and/or as a waypoint common among the SIDs of multiple air-ports. For example, for the Charlotte metroplex, each departure fix was selected as the last waypoint in the RNAV SID for CLT. These departure fixes also had the same name as the SID. Table 5.2 summarizes the airports and departure fixes modeled for each metroplex.

Table 5.2. Airports and Departure Fixes Modeled for Each Metroplex Analyzed.

Metroplex	Airports	Departure Fixes
Atlanta	ATL, PDK, FTY, RYY	BRAVS, CADIT, COKEM, DAWGS, DOOLY, GEETK, JCKTS, JOGOR, MUNSN, NOVSS, NUGGT, PNUTT, RMBLN, SUMMT, THRSR, UGAAA
Charlotte	CLT, JQF	NALEY, MERIL, LILLS, ANDYS, ZAVER
Phoenix	PHX, IWA	IZZEY, JSSUA, IZZZO, GBN, KATMN, YOTES, SJN, TFD, GCN
Southern California	LAX, VNY, BUR, SMO, LGB, SNA, ONT, HHR	GMN, PMD, DAG, TNP, TRM, IPL, JLI, MZB, SXC
Chicago	ORD, GYY, MKE, MDW, PWK, DPA, UGN	PLL, MZV, BAE, PETTY, ELX, GIJ, RBS, GUIDO, EON
North Texas	DFW, DAL, ADS, GKY, FTW, AFW, DTO, TKI	FERRA, SLOTT, CEOLA, PODDE, NELYN, JASPA, ARDIA, DARTZ, CLARE, SOLDO, TRISS, NOBLY, AKUNA, GRABE, BLECO, LOWGN
Northern California	SFO, OAK, SJC, SMF	GRTFL, DEDHD, ORRCA, MOGEE, TIPRE, SYRAH, NTELL, RGOOD, LOSHN, EBAYE, CISKO, ALLBE, BAART, ALANN, YYUNG
New York	JFK, EWR, LGA, TEB	ARD, BAYYS, BDR, BETTE, BIGGY, COATE, DIXIE, ELIOT, GAYEL, GREKI, HAAYS, HAPIE, IGN, LANNA, MERIT, NEION, NEWEL, PARKE, RBV, SAX,SBJ, SHIPP, WAVEY, WHITE, ZIMMZ

Figure 5.6 depicts the models of the departure fixes for the Atlanta metroplex (ATL). Each modeled fix is represented by an asterisk, with its five-letter name in capital letters. For instance, the four easterly departure fixes of Atlanta are DAWGS, UGAAA, DOOLY and MUNSN.

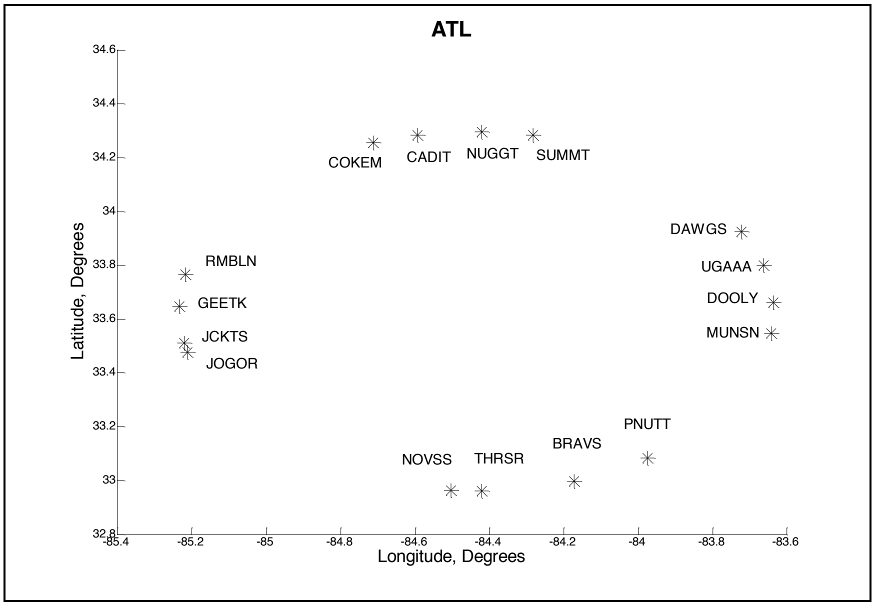


Figure 5.6. Departure Fixes Modeled for Atlanta Metroplex; Example of Many Fixes.

Figure 5.6 indicates that the Atlanta metroplex has numerous departure fixes, comprising departure gates, to the north, south, east and west. Each gate has four departure fixes. Figure 5.7 depicts the models of the departure fixes for the Charlotte metroplex (CLT).

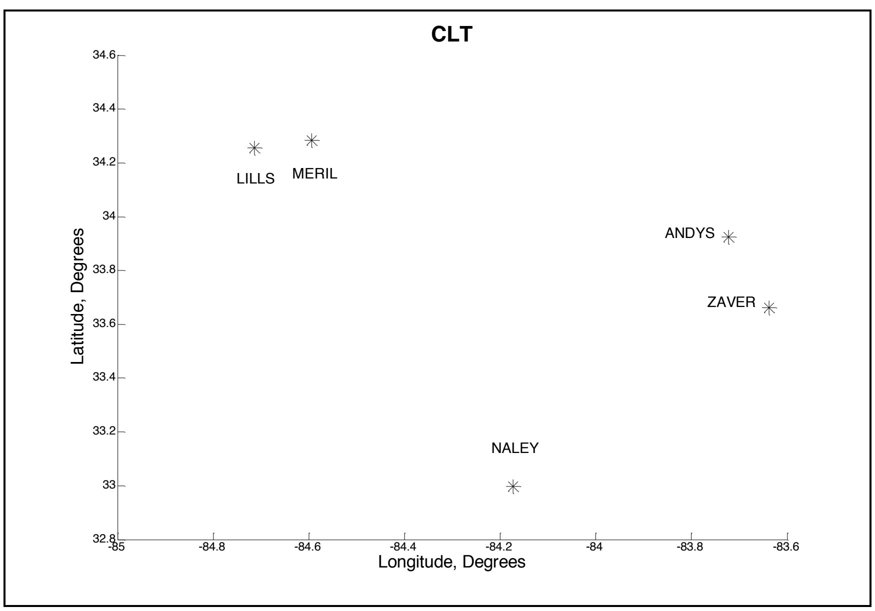


Figure 5.7. Departure Fixes Modeled for Charlotte Metroplex; Example of Few Fixes.

Figure 5.7 indicates that the Charlotte metroplex has fewer departure fixes than Atlanta, to the northwest, south and east. In turn, departure merging may occur more frequently with a selection of fewer fixes.

5.3.2 Departure Traffic Modeling

The departure traffic schedules for each modeled metroplex airport were obtained from FAA Air Traffic Organization–Planning (ATO-P). The demand sets were originally obtained for use on the Analysis of Choke Points in the NAS Project (NASA Research Announcement (NRA) Contract # NNA13AB95C, LMI Prime Contractor). Special permission was granted by the FAA ATO-P for use on this project, in coordination with the technical monitor of the project. Specifically, the airport traffic schedules used are those created for the 2020 forecast year which were derived from May 13, 2012 traffic schedule data.

Each departure flight at each modeled airport is assigned to the departure fix closest in bearing to its destination airport, relative to the origin airport. The bearings of the departure fix and of the flight's destination airport, relative to the origin airport, were computed using a method described and demonstrated in [31]. This method uses a reference latitude and longitude for the origin airport, and the latitude and longitude for the fix or a reference latitude and longitude for the destination airport, to compute the bearing of the fix or destination airport relative to the origin airport. The coordinate system assumes true north as the zero reference and clockwise as positive for bearing. A bearing is computed for each fix a priori. Then the bearing of each flight's destination airport is computed, and the departure fix closest in bearing to that of the flight's destination airport is assigned to the flight.

The transit time for each departure flight from its takeoff runway to its assigned departure fix is computed from the distance between the airport and the departure fix and an assumed transit speed. The distance between the airport and the departure fix computed as the product of the fundamental geometric distance and a distance scaling factor. The fundamental geometric distance is based on a straight-line ground track from the reference point for the airport to the fix, and a geometric vertical flight profile to reach 10,000 feet Above Ground Level (AGL) at the particular fix. The distance scaling factor is a user-configurable parameter, the value of which is specified by comparing the cumulative distance of the flight legs of the longest route in a SID to the measured straight-line distance from the airport reference point to the end point of the SID. A scaling factor of 1.2 is used based on the CLT MERIL7 SID, for which the cumulative distance is 91.2 nautical miles and the straight-line distance is 78.1 nautical miles. For each combination of origin airport and departure fix, the transit distance is computed as the product of the geometric distance for the given airport-fix pair and the distance scaling factor of 1.2. The transit speed between the airport and the departure fix is assumed to be 200 knots, an intermediate value between the takeoff speed and the speed limit of 250 knots at or below 10,000 feet in terminal airspace. Each departure flight is assumed to take off at its airline scheduled gate departure time provided in the traffic schedule.

Figure 5.8 depicts the resulting distribution of departure traffic among the departure fixes and traffic modeled for the Atlanta metroplex.

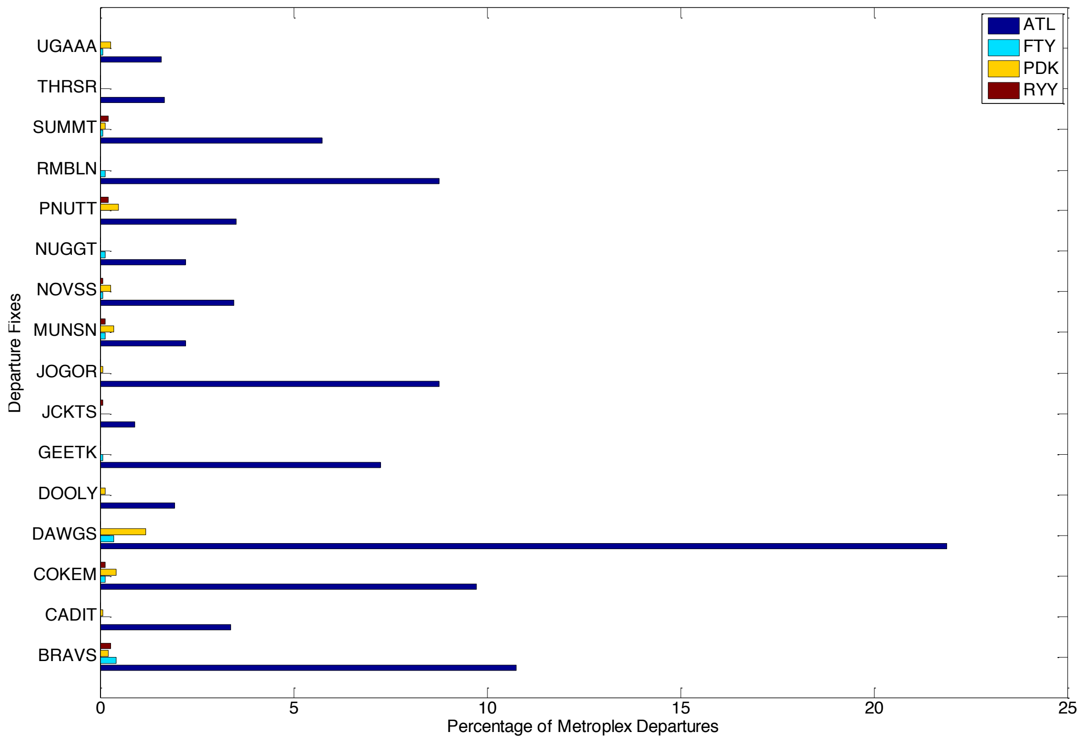


Figure 5.8. Distribution of Departure Traffic of Airports among Departure Fixes in Atlanta Metroplex; Example of Same-Airport Merging and Spacing.

Figure 5.8 indicates that the majority of the traffic crossing the departure fixes is from Atlanta Airport (ATL), while the satellite airports FTY, PDK and RYY contribute very little traffic. Departure fix DAWGS has the most departure traffic of the departure fixes in the Atlanta metroplex, while SUMMT, RMBLN, JOGOR, GEETK, COKEM and BRAVS have half the departure traffic of DAWGS.

Figure 5.9 depicts the resulting distribution of departure traffic among the departure fixes modeled for the New York metroplex.

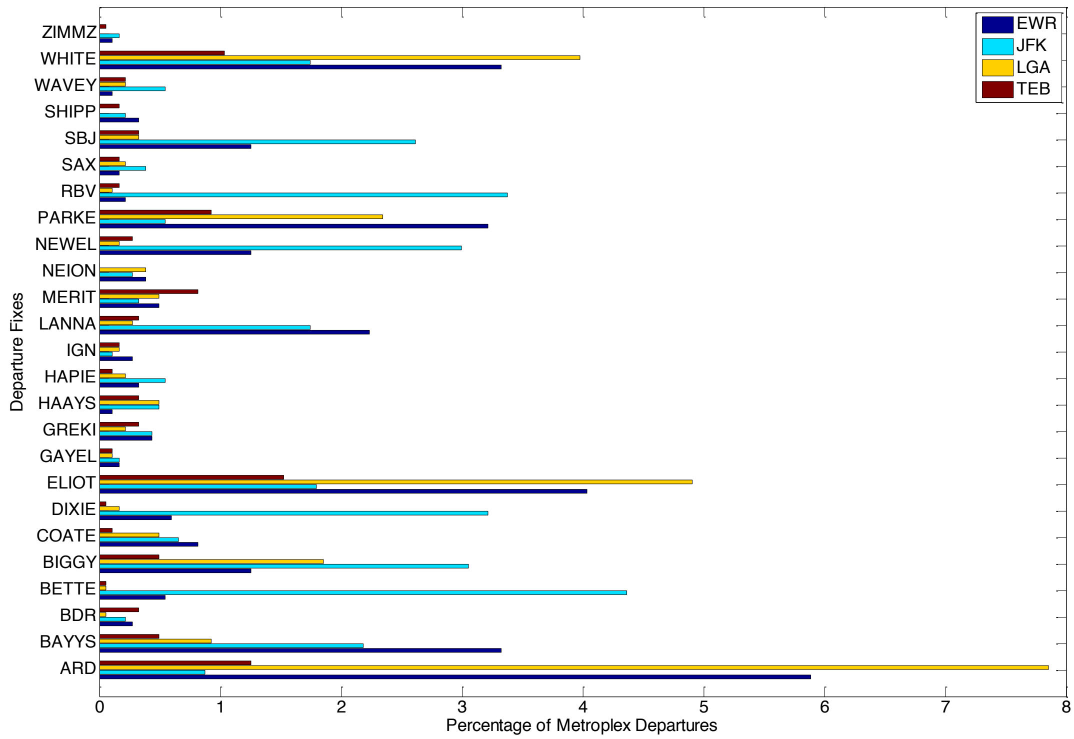


Figure 5.9. Distribution of Departure Traffic of Airports among Departure Fixes in New York Metroplex; Example of Different-Airport Merging and Spacing.

Figure 5.9 indicates that all four modeled airports, JFK, EWR, LGA and TEB, contribute traffic to many of the departure fixes. Departure fix ARD has the most departure traffic of the departure fixes in the New York metroplex, followed by ELIOT, WHITE and PARKE.

5.3.3 Departure Merging Analysis

For the IM for Departure Operations concept, coordinating IM operations for two aircraft from the same airport may have different operational requirements (and potentially less complexity) than for two aircraft from different airports in a metroplex. For instance, scheduling and coordinating the takeoff of two departures from two different airports in a metroplex, or even two different runway complexes at the same airport, to precisely meet inter-flight spacing requirements at the departure fix requires coordination between different air traffic control towers, whereas from the same airport with a single runway complex such coordination can be conducted by a single local controller. For the modeled departure traffic of each metroplex, the sequence of departures crossing each departure fix is analyzed to identify pairs of in-trail departures which are from the same airport and from different airports. Figure 5.10 depicts, for each metroplex, the percentage of departure pairs from the same airport which are crossing the fix, and the complementary percentage of departures from different airports which are crossing the same fix.

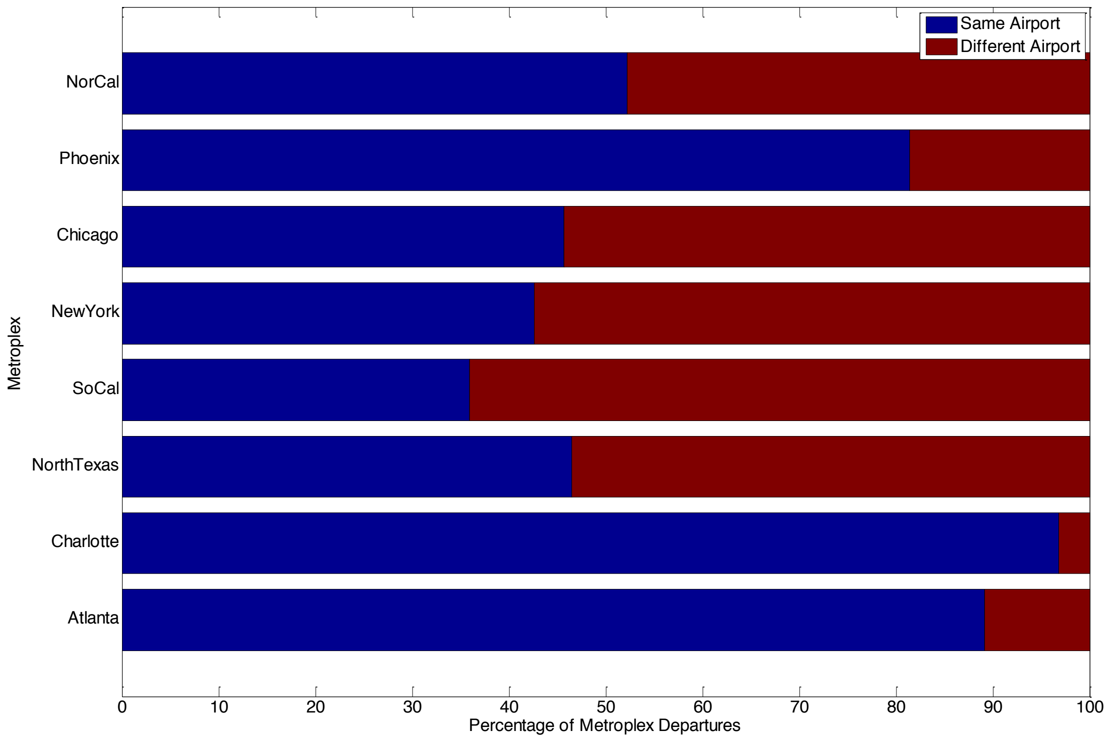


Figure 5.10. Distribution of Same- and Different-Airport Departures Crossing Common Departure Fixes for each Metroplex.

The results indicate that the metroplexes vary in the degree of merging of same-airport and different-airport departure flights at the departure fixes. Metroplexes with a majority of same-airport departures merging at departure fixes include Atlanta, Charlotte and Phoenix. Metroplexes with a majority of different-airport departures merging include North Texas, Southern California, New York, Chicago and Northern California. This is due to the quantity of departure fixes and their physical locations; and the traffic levels of and distribution of destination airports among the airports in the metroplex.

To determine how frequently the IM for Departure Operations would be applied under each merging paradigm, traffic is analyzed to determine how frequently pairs of in-trail departures had spacing less than the minimum required separation of 7-nautical miles, thus requiring active separation. In turn, each pair is identified as a same-airport pair or different-airport pair to determine the frequency of separation violations among the departures crossing a common fix. Figure 5.11 shows the results.

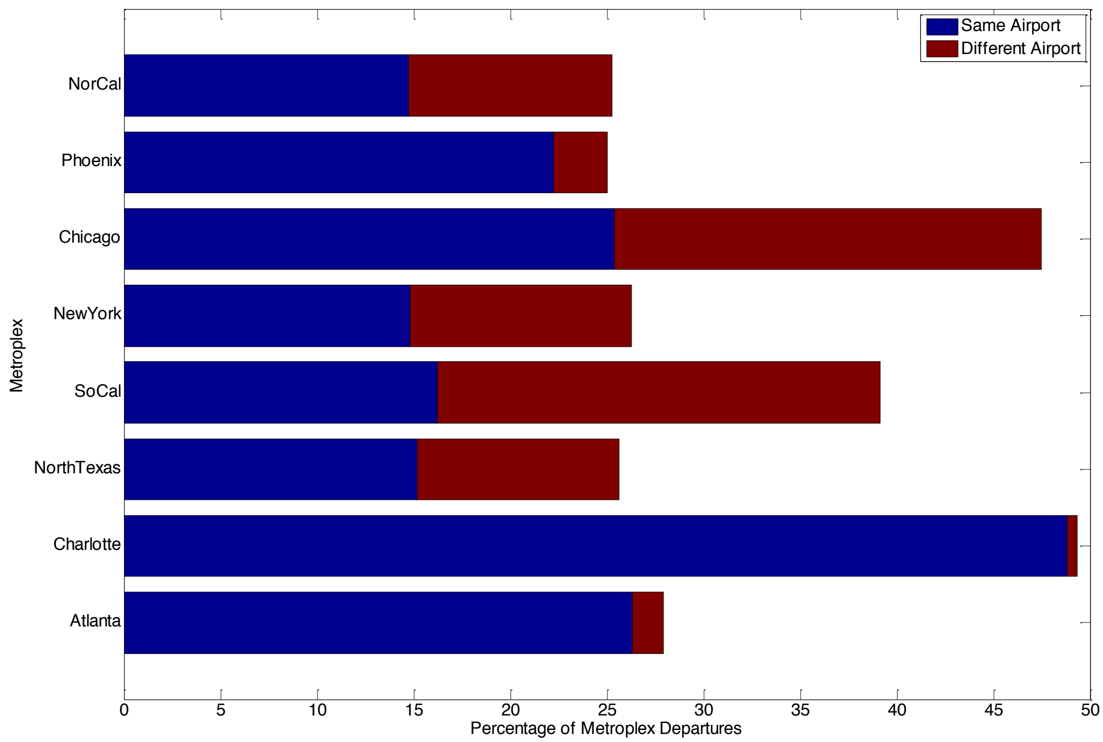


Figure 5.11. Occurrence of Minimum In-trail Separation Violations Among Same- and Different-Airport Departures Crossing Common Departure Fixes for each Metroplex.

The results indicate that the frequency of active separation of departures crossing common fixes varies by metroplex. For instance, 40 to 50 percent of departures in the Charlotte, Southern California and Chicago metroplexes require active separation, while 25 percent of the departures in the Northern California, Phoenix, New York, North Texas and Atlanta metroplexes do. This is influenced by the quantity of departure fixes and the destination airports among departures from each airport. The fraction of same- versus different-airport departures requiring active spacing is consistent with the distribution of same and different airports crossing the fixes.

5.4 NAS-Wide Benefit Analysis

To estimate the NAS-wide benefits for the IM for Departure Operations concept, we estimate the benefit of concept for a set of representative metroplexes across the NAS, and then extrapolate those results to a broader set of metroplexes across the NAS. In turn, we estimate the frequency of concept application to determine a total NAS capacity benefit.

5.4.1 NAS-Wide Departure Capacity Benefit, Eliminating Excess Spacing

To estimate the departure capacity benefit of eliminating excess spacing between departures crossing common departure fixes at each metroplex, we computed the differences in the time-averaged departure rates for each metroplex between 0 and 100 percent of the departures having 3 nautical miles excess spacing over 7 nautical miles baseline spacing and summed aggregate throughput results among 8 metroplexes. We then extrapolated our results to the remaining 13 metroplexes by computing the average departure rate increase among 8 metroplexes, then assuming this departure rate increase for each of the 13 other metroplexes. Finally, we sum the departure capacity increases of the 21 metroplexes to estimate a NAS-wide departure benefit of the concept.

We estimate the frequency with which the departure capacity increase could be realized for each metroplex as the number of 1-hour periods in the 24-hour day in which, among the departure fixes for the metroplex, one or more pairs of departures were found to have in-trail separations less than the 7 nautical mile threshold be as per the baseline schedule and transit time assumptions. We average number of time periods among the airports to estimate the number of hour periods the total departure capacity increase could be realized across the NAS. Table 5.3 below presents the results of this analysis.

Table 5.3. Comparison of Average Metroplex Departure Rates under Baseline, 100 Percent and Concept, 0 Percent Excess In-trail Spacing Conditions.

Average Departure Rate (Departures/Hour)				Number of Hours Per Day Minimum Separation Applied
Metroplex	Probability of 3 MIT Separation Over Baseline 7 MIT Separation			
	Concept, 0 Percent	Baseline, 100 Percent	Change	
Atlanta	85	69	16	16
Charlotte	55	49	6	17
North Texas	102	91	11	17
SoCal	55	48	7	20
New York	97	90	7	20
Chicago	75	62	13	18
Phoenix	26	25	1	20
NorCal	59	53	6	20
Total, 8 FAA Metroplex Sites = 67				
Average, 8 FAA Metroplex Sites = 8				
Estimated Total, 21 FAA Metroplex Sites = 176				Average = 18

The results indicate that, on average, the NAS could accommodate 67 additional departures per hour among the 8 FAA metroplexes analyzed, and 176 additional departures per hour among the 21 FAA Metroplexes considered. On average, this capacity increase could be realized for 18 hourly periods throughout the day.

5.4.2 NAS-wide Departure Capacity Benefit, Eliminating Missed Slots

To estimate the departure capacity benefit of reducing the number of missed departure slots at departure fixes at each metroplex, we computed the differences in the time-averaged departure rates for each metroplex between 0 and 20 percent of slots missed among departures and summed aggregate throughput results among 8 metroplexes. We then extrapolated our results to the remaining 13 metroplexes in the manner previously described to estimate a NAS-wide departure benefit of the concept. Finally, we sum the departure capacity increases of the 21 metroplexes to estimate a NAS-wide departure benefit of the concept. We apply the same frequency data estimated for the excess in-trail spacing benefit mechanism to the missed slots benefit mechanism. Table 5.4 presents the results of this analysis.

Table 5.4. Comparison of Average Metroplex Departure Rates under Baseline, 20 Percent and Concept, 0 Percent Missed Slot Conditions.

Metroplex Departure Rate (Departures/Hour)				Number of Hourly Periods in Day Where Minimum Separation Applied
	Probability of a Missed Slot			
Metroplex	Concept, 0 Percent	Baseline, 20 Percent	Change	
Atlanta	85	74	11	16
Charlotte	55	54	1	17
North Texas	102	98	4	17
SoCal	55	51	4	20
New York	97	93	4	20
Chicago	75	69	7	18
Phoenix	26	26	1	20
NorCal	59	55	4	20
Total, 8 FAA Metroplex Sites = 35				
Average, 8 FAA Metroplex Sites = 4				
Estimated Total, 21 FAA Metroplex sites = 93				**Average = 18**

The results indicate that, on average, the NAS could accommodate 35 additional departures per hour among the 8 FAA metroplexes analyzed, and 93 additional departures per hour among the 21 FAA Metroplexes considered. On average, this capacity increase could be realized for 18 hourly periods throughout the day.

The key caveats to this are that the frequency of merging may be overestimated, because in some metroplexes the departures from satellite airports may be procedurally separated in altitude or laterally from one another and from the primary airport departures. Also, the departure capacity benefit realized in each 1-hour period may be far less than estimated, depending on the number of pairs of departures that must be actively separated and the minimum in-trail separation criterion. In addition, the departure fix models need to be verified by subject matter experts, and actual assignment of departures to individual fixes may vary from what is modeled, such as if departures are manually assigned or shifted to different fixes by air traffic control.

6 Interval Management for Wake Mitigation

This section details the analysis performed for Interval Management analysis performed for Wake Mitigation. The concept details are presented first, followed by the Maximum Benefit and Operations Conditions analysis. The results are then applied to the NAS wide benefits analysis.

6.1 Concept Details

The '*IM for Wake Mitigation*' concept applies to arrivals destined for same runway or runway-system which are subject to wake-vortex separation requirements. The concept calls for wake-vortex separation minima to be specified in real time. Automation determines the wake vortex separation minima using fast-time models of wake transport and circulation decay in conjunction with meteorological data, such as wind speed, wind direction, temperature and Eddy Dissipation Rate (EDR), as well as aircraft data including estimated aircraft state and airframe information. Time-based metering automation schedules arrival landings takeoffs using the dynamically computed wake vortex separations. Each IM Aircraft is assigned a spacing goal with its runway system predecessor (the Target Aircraft) based on this dynamically computed wake vortex separation requirement. In baseline (non-IM) conditions, controllers may manage the trailing aircraft to meet the assigned spacing goal with the lead aircraft. Spacing control shortcomings of manual control may introduce excessive response time to implement spacing goal reductions, limiting the airport throughput that is achievable. With IM operations, the flight crew uses on-board equipment to meet assigned spacing goal, and to respond to reductions in the assigned spacing goal, while the controller monitors the operations. The improved spacing control of IM reduces the response time to spacing goal reductions, potentially enhancing achievable airport arrival throughput. Table 6.1 summarizes the theory of operation for IM for Wake Mitigation.

Table 6.1. Theory of Operation for Wake Mitigation**.**

Conditions for Application	• Arrivals to a common runway or runway system where wake-vortex separation minima apply
Baseline Operations	• Static wake-vortex separation criteria • Spacing buffers as per precision of manual control of spacing intervals by controllers • Slower aircraft response to reductions wake vortex spacing
Concept Rules & Constraints	• Dynamic wake-vortex separation criteria • Spacing buffers as per precision of automation control of spacing intervals by aircraft navigation equipment • Faster aircraft response to reductions in wake vortex spacing
Concept Factors & Dependencies	• Closely-scheduled arrivals • Atmospheric and aircraft conditions permitting separation reductions (e.g., crosswinds)
Concept Requirements	• Real-time wake prediction tool and supporting data: weather forecast, atmospheric turbulence and stratification • Operational concept for using dynamic wake vortex spacing, tool requirements for operational feasibility

A schematic of inter-flight spacing requirements for IM with Wake Mitigation is depicted in Figure 6.1.

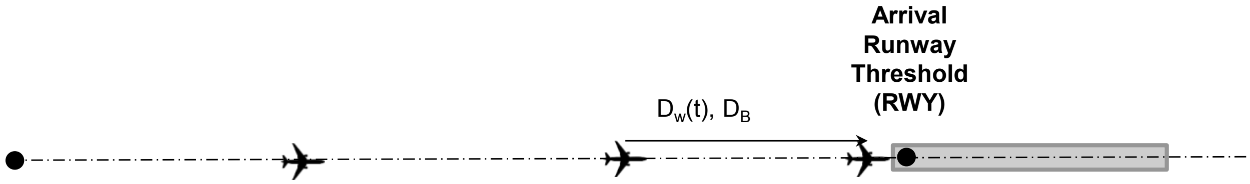


Figure 6.1. Inter-flight Spacing Requirements for Wake Mitigation.

Figure 6.1 depicts the IM aircraft satisfying the dynamic wake vortex spacing ($D_w(t)$) with the Target Aircraft to the same runway. A spacing buffer (D_B) may be added to account for spacing imprecision under manual control or automation control.

6.1.1 Relevant Literature

The concept for IM for Wake Mitigation is documented in a single reference. In addition, there has been extensive research into a related concept.

- Barmore, *et al.,*[2] provide a summary of the current operations and FAA NextGen operational improvements motivating the Wake Mitigation concept, and a description of core components and operations of the Wake Mitigation Concept. The FAA has undertaken efforts to decrease the traditional runway leader-follower separation standards to protect against aircraft wake vortex through its three-phase Wake Vortex Re-categorization (RECAT) efforts [19] [23]. Traditional wake separation is based on five categories of maximum certified takeoff weight: Small, Large, Heavy, B757 and Super. RECAT I introduces wake separation based on six categories of aircraft takeoff weight and wingspan combinations. Implementation of RECAT I at Louisville International Airport (SDF) has demonstrated consistent increases in average airport departure throughput by several aircraft per hour and reductions in average taxi time by approximately 1-minute [23]. RECAT II will extend this refinement. RECAT III proposes dynamic pair-wise separation. Reference [2] outlines a concept for dynamic pair-wise separation of aircraft leveraging fast-time models to predict wake transport and circulation decay. The fast-time models use weather forecast data and aircraft information (in particular, aircraft roll response to wake circulation strength) to estimate appropriate separation between pairs of arrivals at an airport runway or runway system. Traffic scheduling automation applies the dynamic wake separations to scheduled arrivals, and controllers manage arrivals to satisfy the dynamic wake separation minima [2].

- Ahmad et al. [20] used flight test data to validate two different fast-time models of wake transport and decay. Vortex-induced rolling moment coefficients estimated from the fast-time models agreed well with observations from flight test data [20].

- Hinton, *et al.* [21] provide an extensive description of the Aircraft Vortex Spacing System (AVOSS) for providing dynamic aircraft wake vortex spacing to improve airport capacity.

- Doyle, McGee [22] documents quantitative validation and throughput evaluation of AVOSS at Dallas Ft.-Worth International Airport (DFW).

- FAA documents describe a recent step towards operational implementation of dynamic wake separation is Wake Turbulence Mitigation for Departures (WTMD). This concept applies to Heavy and B757 weight class aircraft departing from CSPR in VMC. When crosswinds to the runways are 3 knots or greater and within 60 to 90 degrees to the bearing of the CSPR, controllers may authorize the runways to operate independently [24] [25].

6.2 Maximum Benefit Analysis

Ambient atmospheric conditions such as turbulence and stratification can enhance the wake vortex decay rate and the crosswinds can cause the wake of the previous aircraft landing to the runway to advect away from the runway (see Figure 6.2). The result is that less in-trail spacing distance is required to safely avoid the runway predecessor's wake.

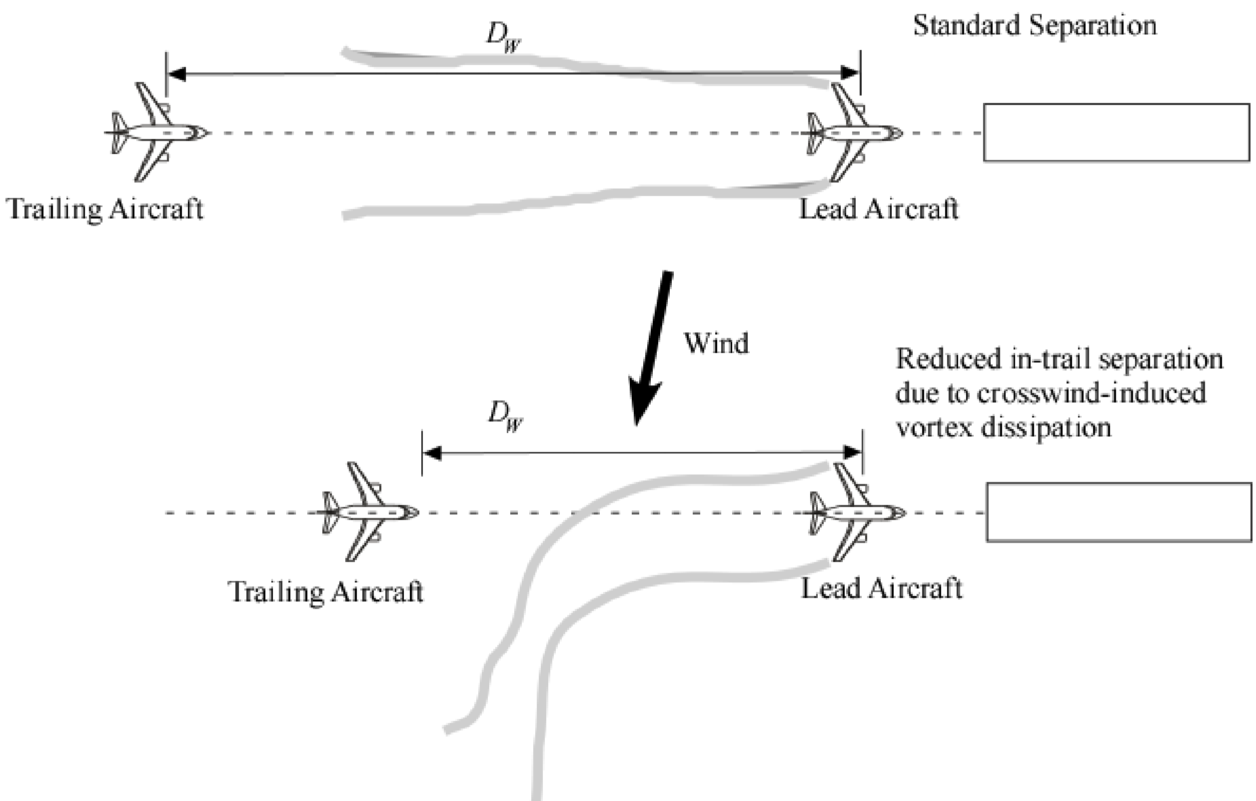


Figure 6.2. In-trail Separation between Arrivals in Standard Conditions (Top) and Crosswind Conditions (Bottom). Crosswinds Mitigate Wake Vortex Risk to Permit Reduced Spacing.

The premise of the IM component to the IM for Wake Mitigation concept is that aircraft operating with IM can more quickly respond to dynamic reductions in the minimum in-trail separation provided by the concept. In turn, the throughput benefit of dynamic reductions in the in the minimum in-trail spacing are realized to a greater extent. Figure 6.3 presents an example to illustrate the fundamental idea behind this benefit mechanism.

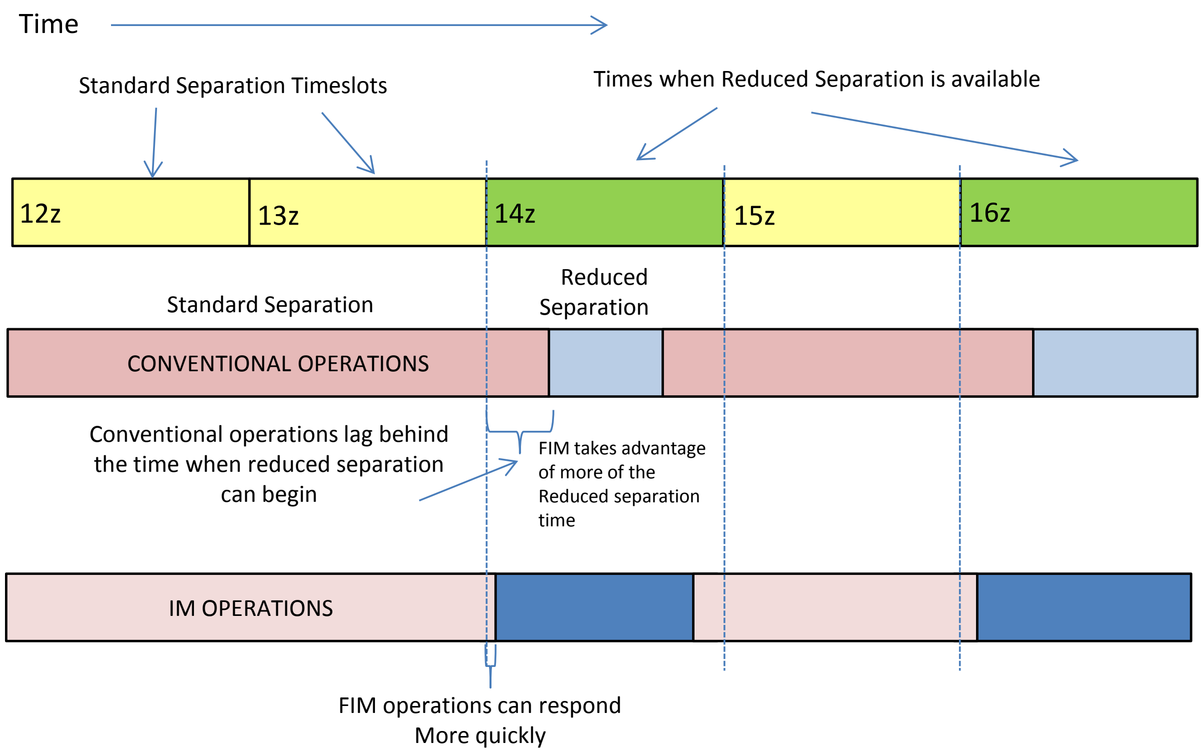


Figure 6.3. Portions of 1-hour Time Periods for Realizing Separation Reductions Under Conventional and Interval Management (IM) Operations.

In Figure 6.3 separation timeslots are assumed to occur 1-hour time periods, as per the update frequency of meteorological data. In this example, time periods of reduced separation occur at 1-hour time periods 14z and 16z. In conventional operations, manual control of air traffic may render response times of, say, 15-minutes to adapt to the reduced separation in 14z, and 15-minutes to adapt to standard separation resuming in 15z. In turn, the reduced separation minima are applied for 30-minutes, thereby limiting the throughput benefits realized (the light blue region). In IM operations, specialized aircraft navigation equipment and flight crew procedures may render much faster response times to changes in the separation minima. An IM aircraft may require, say, 3-minutes to adapt to the reduced separation in 14z, and 5 minutes to adapt to the standard separation resuming in 15z. Thus, IM enables a longer time of approximately 52-minutes to apply, and realize the throughput benefits of, the reduced separation minima (the dark blue region).

6.2.1 *Analysis Methodology*

To analyze the throughput benefit of faster response time to reduced wake-vortex spacing, we assume baseline conditions to be an even traffic mix of large and heavy aircraft. From our analysis of single-runway operations in the IM for Dependent Parallel Approaches, this yields a single runway arrival rate of 32 aircraft per hour under standard wake-vortex separation. For the concept condition, we assume 2-nautical mile spacing is achievable under crosswind conditions, which yields 42 aircraft per hour for the same traffic mix. We assume that the atmospheric conditions support an even split between standard and reduced separation minima. We assume the baseline condition affords a 10-minute lag, and that IM condition affords a 2 minute lag, in adjusting to reduced separation minima.

Regarding the distribution of the atmospheric conditions, we consider that if the weather conditions change often, more time is lost trying to adjust operations to different separation standards. A higher frequency distribution results in more time lost to adjust to the reduced standard because the time lag to respond stays constant but the available time of reduced separation is less. This is captured in Figure 6.4.

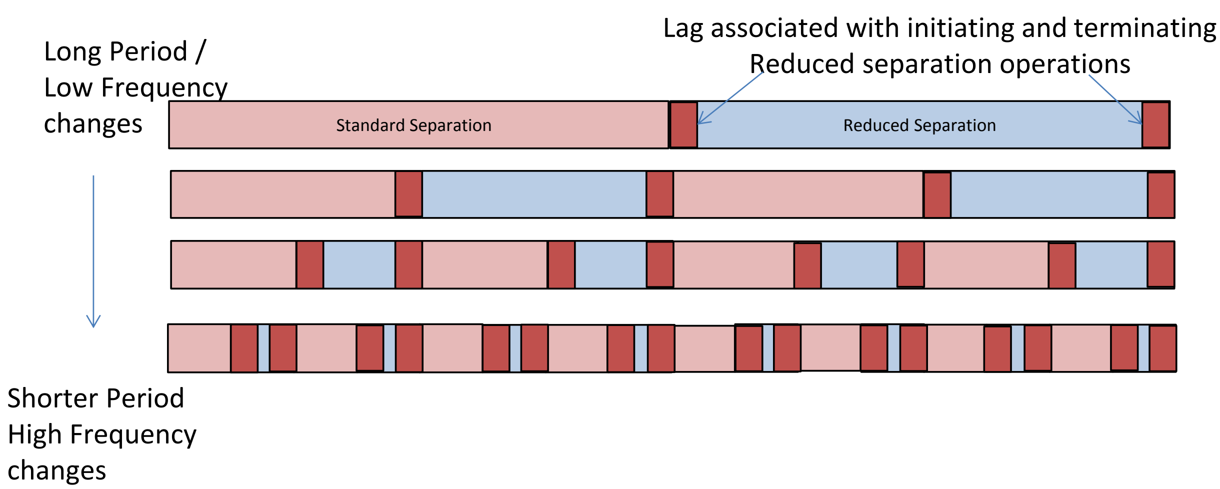


Figure 6.4. Comparison of Alternative Time Periods for Implementing Reduced Separation, and Interaction with Time Required to Adjust to Changes in Separation Standards.

Figure 6.4 indicates that as the frequency of reduced separation periods increases, but their duration decreases, the resulting time periods available for realizing the benefits of reduced separation decreases, diminishing overall benefit of the concept.

6.2.2 *Analysis Findings*

Figure 6.5 depicts the single runway arrival throughput impact of increasing the time periods under which separation minima are reduced. The throughput realized under the shorter response time afforded by IM (2-minute response time) is compared with that afforded under baseline conditions (10-minute response time).

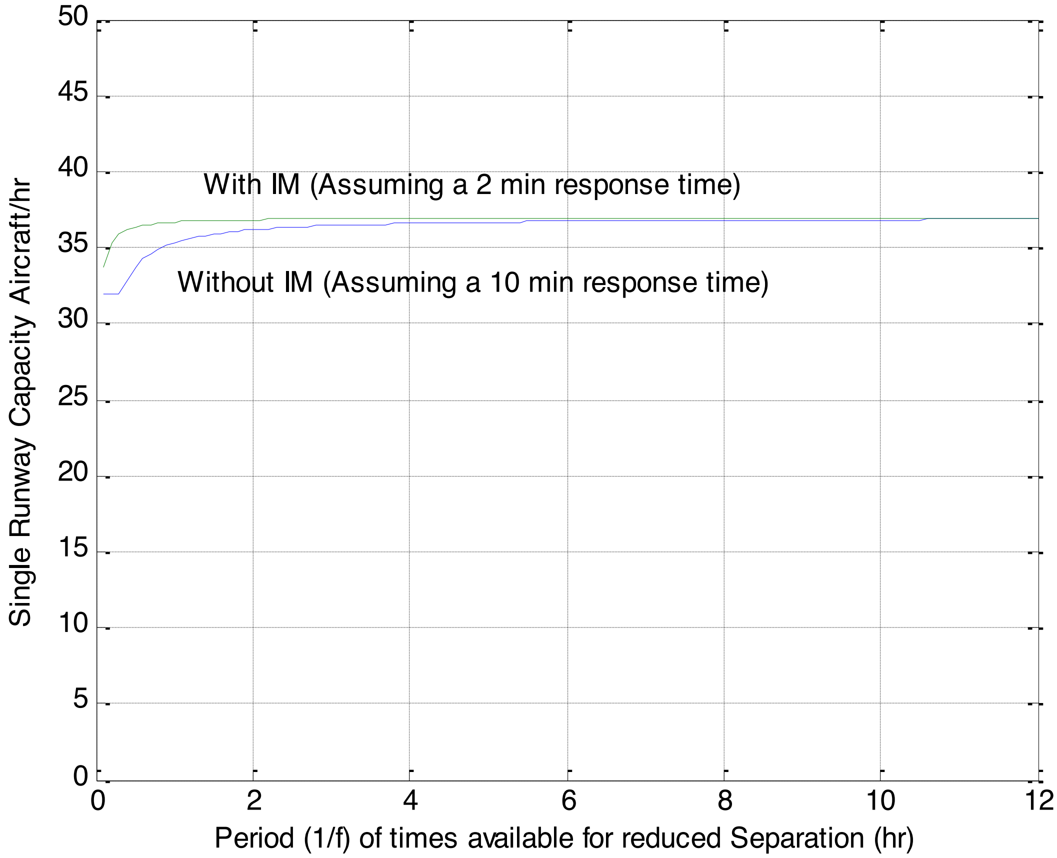


Figure 6.5. Single Runway Saturation Capacity under Increasing Durations of Reduced Separation Time Period, for Interval Management and Non-Interval Management Response Times.

The results indicate that when periods of reduced separation are on the order of 1 to 2 hours, the faster response time afforded by IM might result in an increased arrival throughput of 1 to 4 aircraft per hour. For this scenario, the ideal is around 37 aircraft per hour, corresponding to 100 percent usage of the reduced separation minima. As the continuous time period of reduced separation increases, the benefit of IM over standard operations diminishes.

6.3 Operations Conditions Analysis

The objective of the Operations Conditions task for the IM for Wake Mitigation concept is to estimate the frequency of applying minimum spacing afforded by the dynamic wake vortex prediction and mitigation system. The approach is to analyze hourly FAA ASPM data for 2014 for the same set of airports as those analyzed for the IM for Dependent Parallel Approaches concept to determine frequency of application of the concept.

The approach to the Operations Conditions task is to analyze the local wind conditions, traffic peaks and arrival capacity of airports as recorded in hourly FAA ASPM data for 2014. We analyze airport wind speed (ASPM data field WND_SPED), wind direction (ASPM data field WND_ANGL) and bearing of the arrival runways (ASPM data field RUNWAY) for each 1-hour period to estimate how often the crosswind for arrival runways is above threshold of 3 knots [24]. We analyze airport scheduled arrival traffic (ASPM data field ARR_DEMAND) and airport arrival capacity (ASPM data field ARR_RATE) to estimate how frequently scheduled airport arrival demand exceeded airport capacity. In turn, we use these results to identify airports which could benefit from the IM for Wake Mitigation concept.

6.3.1 Analysis of Crosswinds

Analysis of crosswinds estimates the speed of the crosswind to the active arrival runway at an airport. The analysis accounts for wind heading, arrival runway heading and the magnetic variation between magnetic and true heading. These elements are depicted in Figure 6.6. The magnetic variation is accounted for because the source of the local wind speed and wind direction data provided in ASPM is likely METAR, which always posts wind speed in true heading, while the runway numbering indicating the heading of the runway is given in magnetic heading used in navigation.

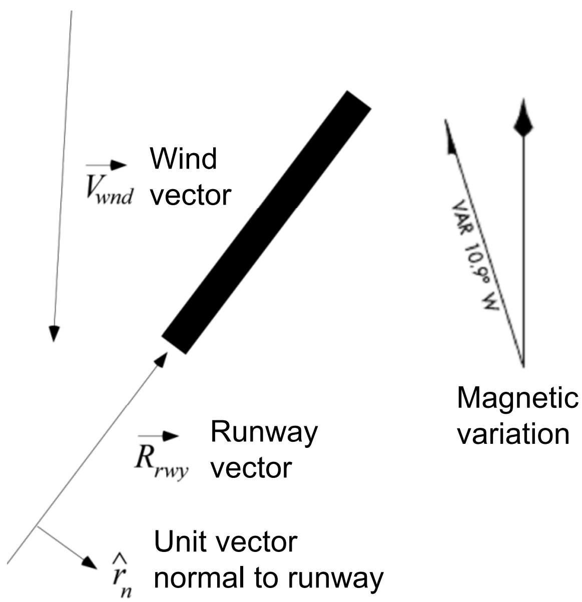


Figure 6.6. Orientations of Airport Runway and Winds, and Unit Normal to Runway in Direction of Runway Crosswind, Accounting for Magnetic Variation between True and Magnetic Headings.

Equation 6.1 details the methodology for computing the crosswind (V_{xwind}) to each airport arrival runway for each 1-hour period from the wind speed and direction (V_{wnd}), the arrival runway heading ($RunwayNumber$) and the magnetic variation (VAR).

$$\begin{aligned}
\psi_{rwy_{true}} &= \frac{\pi\left(10\left(RunwayNumber\right)-VAR\right)}{180} \\
\vec{R}_{rwy} &= L\cos\psi_{rwy_{true}}\hat{e}_n + L\sin\psi_{rwy_{true}}\hat{e}_e \\
\hat{r}_n &= -\sin\psi_{rwy_{true}}\hat{e}_n + \cos\psi_{rwy_{true}}\hat{e}_e \\
V_{xwind} &= \left|\vec{V}_{wnd}\cdot\hat{r}_n\right|
\end{aligned} \tag{6.1}$$

1) The runway number is parsed from the runway configuration string for the 1-hour period in the ASPM data, and multiplied by '*10*' to obtain the magnetic heading of the runway.
2) The true heading of each arrival runway, $\Psi_{rwytrue}$, is computed by adjusting for the magnetic variation for each airport.
3) The unit normal perpendicular to the runway is determined from the true heading of the runway.
4) The runway crosswind is the magnitude of the component of the wind velocity in the direction of the unit normal perpendicular to the runway.

Figure 6.7 depicts the results of applying this methodology to estimate the percentage of the 1-hour periods throughput 2014 that the crosswinds to the arrival runways in use were 3 knots or greater at each of the airports evaluated.

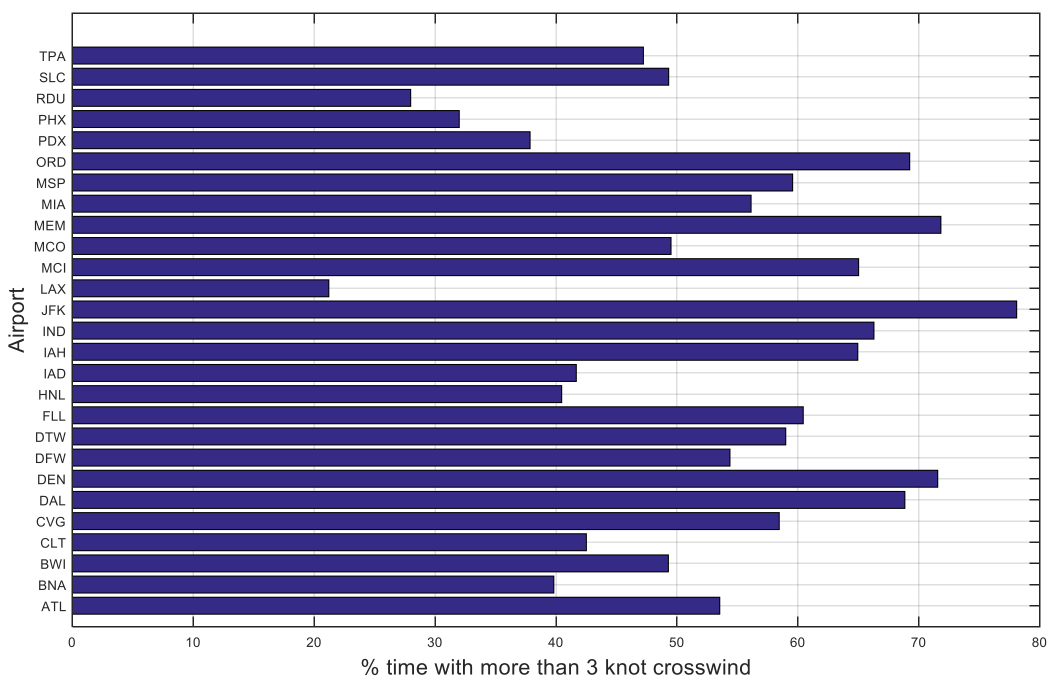


Figure 6.7. Percentage of 1-hour Periods in 2014 that Crosswinds to Active Arrival Runways at Airports Met or Exceeded 3-knot Minimum.

The results indicate that arrival runway crosswinds of 3 knots or greater occur for more than 50 percent of the 1 hour periods in 2014 at the majority of the airports. Thus, the IM with Wake Mitigation concept could be applied fairly frequently.

6.3.2 Analysis of Excess Arrivals During Crosswinds

We analyze how frequently the number of scheduled arrivals exceeds the called arrival capacity in each 1 hour period when the 3 knot crosswind conditions occur at an airport. This provides an estimate of how frequently the spacing reductions, and resulting capacity benefit, afforded by the concept could be realized. The results are presented in Figure 6.8.

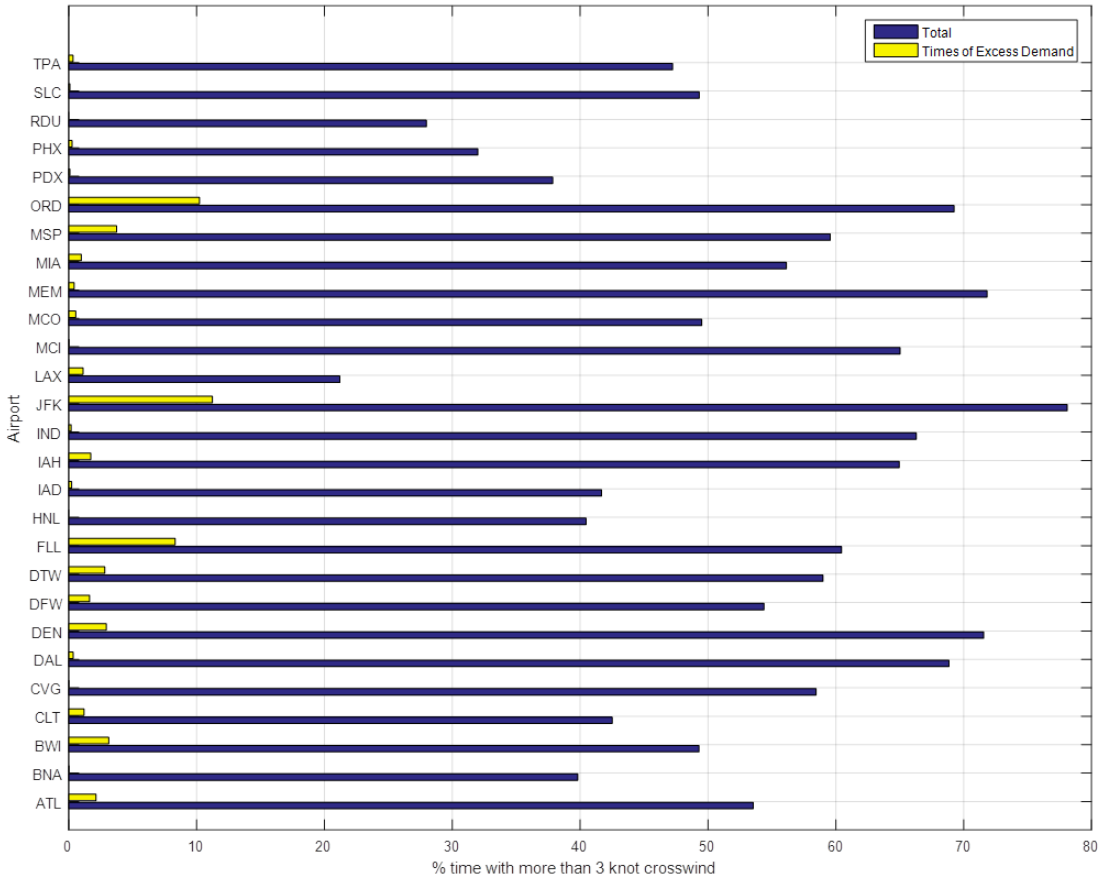


Figure 6.8. Percentage of 1-hour Periods in 2014 that Scheduled Arrival Traffic Exceeded Called Arrival Capacity and Arrival Runway Crosswinds Satisfied the 3-knot Minimum at each Airport.

The results indicate that the number of 1-hour periods in 2014 where the number of scheduled arrivals exceeded the called airport arrival rate and the arrival runway crosswinds met or exceeded 3 knots occurred for approximately 10 of 27 airports for approximately 10 percent or fewer of the 1 hour periods in 2014. Thus, the frequency with which arrival capacity benefit could be obtained from the application of the IM with Wake Mitigation concept at these airports is relatively infrequent due to their infrequent occurrence of closely-scheduled arrivals.

6.4 NAS-Wide Benefits Analysis

We estimate the NAS-wide benefits for the IM for Wake Mitigation concept by estimating the net benefit of concept for set of representative airports across the NAS. We conduct quantitative analysis to estimate the capacity of each airport under the baseline condition and application of the concept, and the frequency of concept application.

6.4.1 Airport Arrival Capacity Benefit

To estimate the arrival capacity benefit, we first estimated the baseline arrival capacity for each airport. Then we estimated the theoretical arrival capacity for each airport that might be realized with the concept. Then we compared the two values to determine the overall benefit. In turn, we sum the capacity increases realized across the airports to compute a NAS-wide arrival benefit of the concept.

We estimated the baseline (Nominal) airport arrival capacity as the average of the called arrival rates among all the 1 hour periods when the airport is operating in VMC, regardless of the demand-capacity condition, from FAA ASPM data. This serves as a proxy for an actual arrival throughput benefit for this concept due to the absence of existing benefit data.

We estimated the airport arrival capacity afforded by the concept (Reduced Wake Vortex) as follows. For each 1-hour period in VMC where there is a 3 knot or greater crosswind to the arrival runways as determined from FAA ASPM data, we enforce the average called VMC arrival rate as the minimum arrival rate afforded by the IM for Wake Mitigation concept. In turn, we compute the average of the arrival rates among the 1-hour periods of VMC, including those revised as per the minimum capacity assumed for the concept and others which were not revised, as the Reduced Wake Vortex arrival capacity. Figure 6.9 depicts the baseline (Nominal) and theoretical (Reduced Wake Vortex) arrival capacities for each airport.

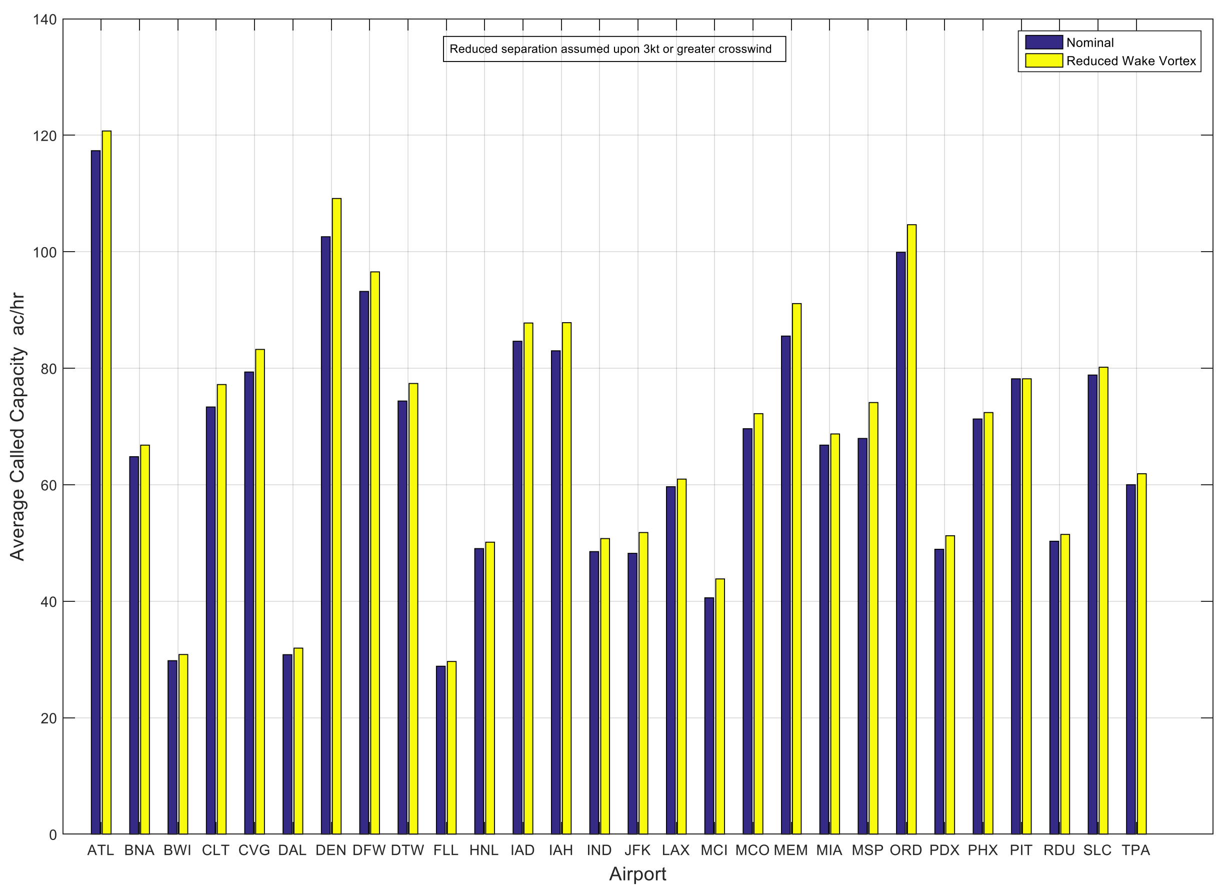


Figure 6.9. Average Arrival Rates for Parallel Arrival Runways of Airports for Historical Called Arrival Rates and Theoretical Arrival Rates using Wake Mitigation.

The results indicate that crosswind-based wake mitigation for arrivals may increase the hourly arrival capacity of airports, and that the relative increase is consistent among the airports.

6.4.2 NAS-Wide Arrival Capacity Benefit

To estimate a NAS-wide arrival benefit of the concept, we estimate the arrival capacity impact of the concept and the frequency of concept application across the airports evaluated. We estimate the arrival capacity impact as the difference between the theoretical and baseline capacities for each airport. We sum the capacity changes of the airports to estimate a NAS-wide arrival capacity increase. We estimate the frequency with which the arrival capacity increase could be realized as the number of 1 hour periods that the crosswind to the arrival runways at each airport is greater than or equal to 3 knots during 2014 from FAA ASPM data. We average the number of time periods among the airports to estimate the number of hour periods the total arrival capacity increase could be realized across the NAS.

Table 6.2 presents for each airport the average of the baseline and theoretical arrival rates, and the difference between the two. The per-airport changes are summed to estimate a total NAS-wide arrival capacity impact of the wake mitigation concept. The table also presents the number of 1-hour periods in 2014 where the crosswind conditions were met. The per-airport time period counts are averaged to estimate the number of hours that the NAS-wide arrival capacity impact of the wake mitigation concept could be realized.

Table 6.2. Comparison of Average Airport Arrival Rates for Baseline Historical and Theoretical Wake Mitigation.

Airport	Average Airport Arrival Rate (Arrivals/Hour)			Number of Hourly Periods Crosswind Conditions Were Satisfied in 2014
	Baseline, Historical	Theoretical, Wake Mitigation	Change	
ATL	117	121	4	4690
BNA	65	67	2	3488
BWI	30	31	1	4318
CLT	73	77	4	3724
CVG	79	83	4	5121
DAL	31	32	1	6031
DEN	103	109	6	6269
DFW	93	97	4	4764
DTW	74	77	3	5168
FLL	29	30	1	5295
HNL	49	50	1	3545
IAD	85	88	3	3651
IAH	83	88	5	5690
IND	49	51	2	5807
JFK	48	52	4	6841
LAX	60	61	1	1858
MCI	41	44	3	5696
MCO	70	72	2	4337
MEM	86	91	5	6292
MIA	67	69	2	4917
MSP	68	74	6	5218
ORD	100	105	5	6066
PDX	49	51	2	3316
PHX	71	72	1	2803
RDU	50	51	1	2451
SLC	79	80	1	4320
TPA	60	62	2	4137
			Sum = 76	**Average = 4660**

The results indicate that the NAS could accommodate 77 additional arrivals per hour among these airports, and that, on average, this capacity could be realized for 4660 hourly periods throughout the year.

The key caveats to these values are that the 3 knot crosswind condition is a coarse proxy for the likely more complex combination of meteorological conditions under which the concept may provide benefit, and the approximation of the theoretical capacity benefit to the concept as the average of the called arrival rates of the airport under VMC may not accurately represent the true benefit of the concept. However, we note the values estimated here are similar in magnitude to those presented for the FAA RECAT I operations [23]. Lastly, sufficient traffic levels are required to utilize the additional arrival capacity.

6.4.3 Airport Arrival Capacity Benefit, Alternative Arrival Rate Assumption

In an alternative analysis for purposes of comparison, we estimated the baseline (Nominal) airport arrival capacity as a minimum of 40 arrivals per hour per runway, consistent with our theoretical analyses of single-runway throughput under reduced wake-vortex separation minima of 2 nautical miles.

In turn, we estimated the airport arrival capacity afforded by the concept (Reduced Wake Vortex) as follows. For each 1-hour period in VMC where there is a 3 knot or greater crosswind to the arrival runways as determined from FAA ASPM data, we enforce the 40 aircraft per hour per runway as the minimum arrival rate afforded by the IM for Wake Mitigation concept. In turn, we compute the average of the arrival rates among the 1-hour periods of VMC, including those revised as per the minimum capacity assumed for the concept and others which were not revised, as the Reduced Wake Vortex arrival capacity. Figure 6.10 depicts the baseline (Nominal) and theoretical (Reduced Wake Vortex) arrival capacities for each airport.

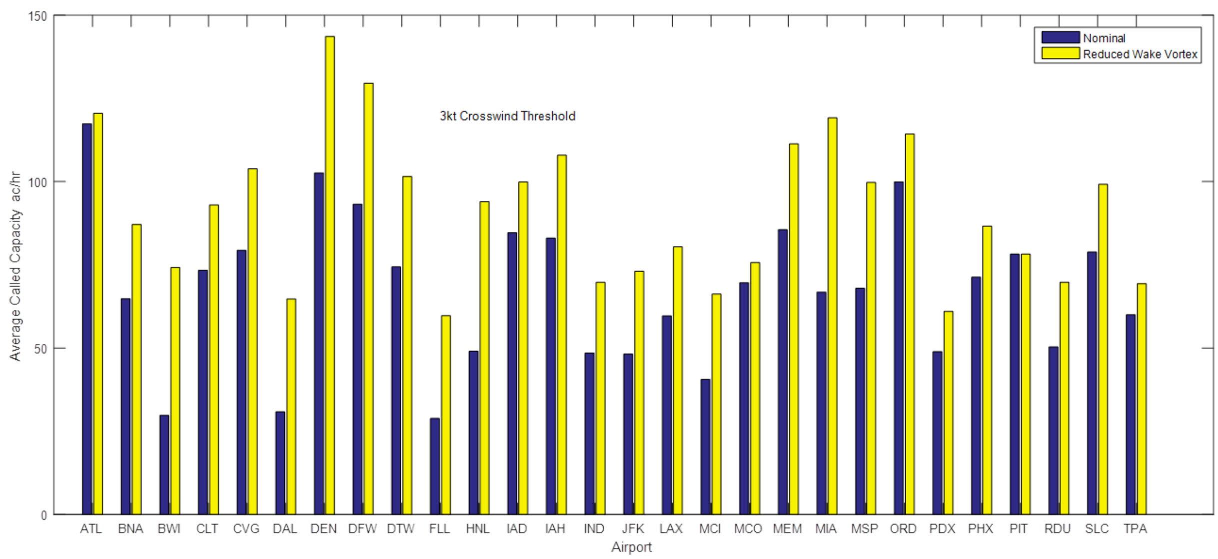


Figure 6.10. Average Arrival Rates for Parallel Arrival Runways of Airports for Historical Called Arrival Rates and Alternative Theoretical Arrival Rates Using Wake Mitigation.

The results indicate that the crosswind-based wake mitigation for arrivals significantly increases the average of hourly arrival capacity of most of the airports, in particular DAL, DEN, HNL, MIA, MSP. Because one of the typical arrival runways at BWI is too short (approximately 5000 feet) for arrivals of jet aircraft, it would likely not experience such a significant throughput increase. We note that these results represent the upper bound on arrival capacity and may not be physically realizable.

Caveats to these results include arrival runways shared with departures, dependent operation of parallel and crossing arrival-arrival and arrival-departure runways, availability of taxiway surface areas to accommodate arrivals, minimum runway occupancy times of arrivals and minimum time periods for and frequency of application of reduced separation minima. Nevertheless, we include the results as a basis for comparison.

7 Impediments and Limitations

This section focuses on the potential impediments and limitations that might prevent the implementation of the IM concepts, or the full realization of the benefit. This analysis focuses on identifying potential impediments and limitations that might occur, more than trying to completely characterize or quantify their impact. Determining the impact of any particular problem and/or its potential solution is left to future analysis. It is the opinion of the authors that the identified problems can be overcome through sufficient analysis and investment. The final remaining question therein is whether the benefit is worth the cost.

To perform the analysis, an additional review of the literature is conducted, as well as consultation with subject matter experts. Some impediments and limitations have been identified by prior researchers, and these are included in addition to our own findings. The remaining impediments and limitations are determined through the consultation of subject matter experts, and direct analysis of the concepts.

The enumerated impediments and limitations are presented in a list format, starting with problems common to all IM concepts, followed by a section on each specific IM concept studied in this analysis. Each impediment or limitation enumerated is followed by short description. One of the common themes throughout the analysis is the problem of developing the appropriate flight deck equipage to handle the IM concept, and how the IM concepts might interact or interfere with current operations. These problems warrant their own sections. Finally, a conclusion, with an overall ranking is provided.

7.1 Interval Management, General

This section provides a general description of IM functionality and discusses some of the impediments and limitations of IM concepts in general.

7.1.1 IM Functionality Description

The FAA document on preliminary concepts of operation for AIM [35] makes a clear distinction between what it considers to be *Baseline* IM capability and what it considers to be *Advanced.*

7.1.1.1 Baseline Equipage

The baseline IM has the ability to assist with the merging and spacing of aircraft in the cruise and arrival phases of flight. In the baseline, flight-deck based IM equipment calculates the speeds that IM Aircraft crewmembers use to achieve and then maintain a relative spacing behind the Target Aircraft. The baseline characteristics are summarized in Table 7.1.

Table 7.1. Baseline IM Equipage Characteristics.

Baseline Equipage Characteristics
The desired spacing goal is achieved at a common point to the routes of both aircraft
Baseline IM operations have a single target capability only
Baseline IM operations must be possible in voice-only environment

Example

An example of this type of equipage is the ACSS (Aviation Communication & Surveillance Systems) manufactured *SafeRoute* suite of software applications [39]. The SafeRoute product implements the CoSpace algorithm is developed by Eurocontrol [40]. The system makes use of Class 3 EFB (Electronic Flight Bag) equipage, but is also available as a stand-alone product. The SafeRoute applications include:

- Merging & Spacing (M&S)
- In-Trail Procedures
- CAVS (Cockpit Display of Traffic Information (CDTI) Assisted Visual Separation)
- Surface Area Movement Management (SAMM)

Figure 7.1 shows the cockpit of an Airbus A330 that has an Electronic Flight Bag installed that hosts the SafeRoute software [36].

Figure 7.1. Illustration of Class III EFBs in the A330 That Hosts SafeRoute [36]

The avionics components to support the SafeRoute system are shown in Figure 7.2.

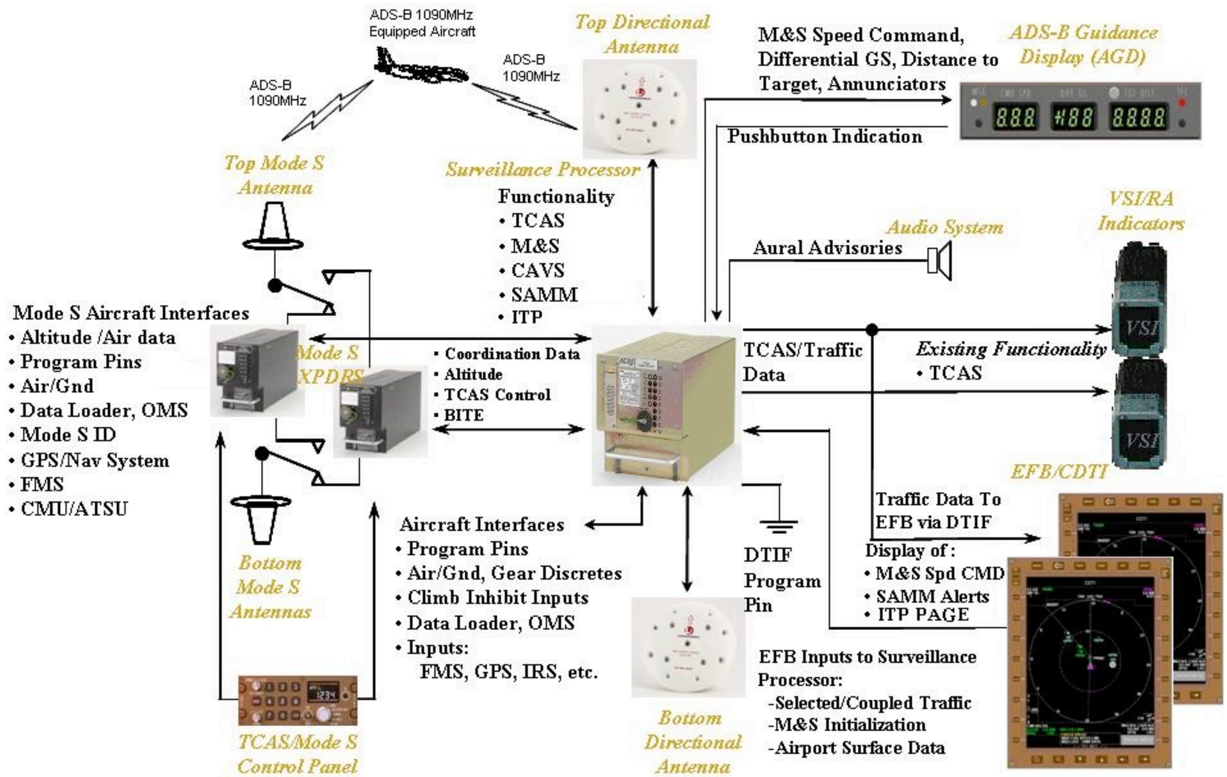


Figure 7.2. Illustration of IM Avionics Architecture to Support SafeRoute [41].

The SafeRoute main processing is performed on the TCAS (Traffic Collision Avoidance System) 3000 Surveillance Processor (SP), which also supports conventional TCAS capability. The other equipment that interfaces to the SP includes the Mode S Transponder, the CDTI, the AGD (ADS-B Guidance Display), the auto-pilot Mode Control Panel (MCP), and various aircraft sensors. A complete listing of data sources is contained in Table 7.2. A standalone TCAS display is provided either on a standalone Vertical Speed Indicator/Resolution Advisory (VSI/RA) display, a Vertical Speed Indicator/Traffic Resolution Advisory (VSI/TRA) display, a Navigation Display, or Multifunction Display (MFD). This standalone TCAS display is typically the existing aircraft TCAS display.

Limitations

The baseline equipage has several limitations that render it inadequate for some of the Advanced IM concepts. For instance, the baseline equipage does not support non-coincident paths and doesn't support two-target operations. It is limited to voice-only communications, which makes clearances difficult to issue or change. The baseline equipage does not provide effective IM speeds during climbs and therefore cannot be used during departure operations [35].

Table 7.2. Baseline IM Equipage Data Sources.

GPS Source Data	MCP (Mode Control Panel) Source Data
Own-ship Latitude/Longitude	Own-ship CAS/Mach Indicator
Own-ship Ground Speed	Own-ship Selected Airspeed
Own-ship Track Angle	Own-ship CAS/Mach Indicator
DADC (Digital Air Data Computer) Source Data	Own-ship Maximum Operating Speed
Own-ship Static Air Temperature	**FMS (Flight Management System) Source Data**
Own-ship Pressure Altitude	Own-ship Minimum Maneuvering Speed
Own-ship Airspeed	Own-ship Maximum Operating Speed
Own-ship Static Air Temperature	**RADAR Altimeter Source Data**
ADS-B (Transponder) Source Data	Own-ship Radio Altitude
Traffic Latitude/Longitude	
Traffic Ground Speed/Track Angle	
Traffic Pressure Altitude	
Traffic Identifier	
Traffic Aircraft Category	

For the three concepts considered in this research, at least two (Dependent Parallel Arrivals, Departure Operations) would require some level of advanced equipage. The Dependent Parallel Arrival concept requires non-coincident routes, and advanced versions use two-target spacing. The Departure Operations concept requires accurate climb speed predictions. The third concept, Wake Mitigation, is not explicitly precluded by baseline limitations but may be hindered due to the inability to quickly and easily alter aircraft clearances.

7.1.1.2 Advanced Equipage

Advanced IM equipage is intended to address some of the limitations associated with the functionality of baseline equipage. The FAA document on preliminary concepts of operation for AIM [35] identifies these main extensions to the baseline functionality:

- **Non-coincident Route Operations.** Advanced IM will allow an IM Aircraft to achieve spacing relative to a Target Aircraft at a point not common to both routes, including parallel or converging approaches. In these cases, where the Target Aircraft does not pass through the IM Aircraft's ABP, a new type of IM special point, the Target Reference Point (TRP), is defined and communicated to the flight crew. For time-based spacing goals, the operational objective is for the IM Aircraft to reach the ABP at a given time after the Target reaches the TRP. For distance-based spacing, the operational objective is for the IM Aircraft to be a given distance from the ABP when the Target reaches the TRP.

- **Two Target Operations.** Advanced IM will allow an IM aircraft to achieve spacing relative to two Target Aircraft. This operation allows controllers to clear an IM Aircraft to achieve and/or maintain the spacing goal that results in the greater longitudinal distance behind the two Target Aircraft, one of which is landing on the same runway as the IM Aircraft and one of which is landing on the parallel runway.

- **Achieve-by Altitude Capability.** Advanced IM will allow an IM aircraft to achieve a spacing goal at a specified altitude. This operation will allow controllers, especially during departure operations, to specify an altitude at which a spacing goal should be achieved (e.g. at a sector or center boundary).

- **Paired Approach Speed Guidance and Alerting Capability.** Advanced IM will allow an IM Aircraft to perform spacing operations behind a Target Aircraft that is landing on a closely spaced parallel runway.

- **Data Communications.** Data Communication (Data Comm) enables the uplink of more complex IM clearance information to the IM Aircraft via Controller-Pilot Data Link Communications (CPDLC), including multiple Targets, and better projected flight path information about the targets. Data Comm may also allow for the automated exchange of information between the flight deck and the ground. The delivery and acceptance of IM clearances via CPDLC also allows the IM status to be updated automatically on the controller's display and facilitates the loading of information into FIM equipment through direct load capabilities.

  Data communications may also enable more non-traditional data exchanges including *Dynamic RNP* (the ability to uplink dynamic changes in routing and/or RNP elements), *ATC Winds* (consistent understanding of wind and temperature among both ATC and aircraft), and *Improved IFPI* (Intended Flight Path Information). The Improved IFPI enables the provision of 4D path information that consists of lateral turn points expected altitudes along the lateral path, and expected (indicated) speeds along the lateral path.

7.1.2 Impediments and Limitations

The impediments and limitations that are common to IM concepts are enumerated in this section, followed by short descriptions. A more thorough discussion on selected limitations is provided in the following section.

- **Traffic density.** The IM benefit of reduced spacing and vectoring requires sufficient traffic levels to exercise the concept and realize benefit. Thus, only a subset of metroplexes where consistent demand/capacity imbalances occurs can benefit from the application of the IM capability.

- **Mixed Equipage levels.** The IM concepts require that a substantial portion of the aircraft be IM-capable sufficient to exercise IM concept. Requirements include aircraft equipage and crew training, as well as ground automation and controller training. What isn't clear, however, is what a substantial portion is (e.g. 50, 70, 100 percent equipage levels), how mixed equipage might be characterized, and how it ultimately impacts system efficiency and stability. For instance, there is likely to be a mix of capability in terms of basic-equipage and advanced-equipage IM aircraft, and it is not clear how this mixed equipage might be handled, such as in the case of parallel approaches. This area needs future research.

- **Initiation criteria.** Air traffic control and IM aircraft must agree to conduct operations and must meet the criteria to initiate operations.

- **Target aircraft Estimated Time of Arrival (ETA) prediction functionality.** IM literature implies the IM Aircraft will perform trajectory prediction of the Target Aircraft to assess meeting ASG and computing IM speed advisories. This levies significant requirements on IM aircraft equipage. It is not clear how the IM equipage will interact with the Flight Management System (FMS) or Flight Management Computer (FMC) of the IM Aircraft and how the speed advisories impact the trajectory being followed by the FMS. This is of particular concern when an aircraft has been given a 'Descend Via' clearance on a RNAV arrival procedure with Required Navigation Performance (RNP) requirements.

- **IM aircraft control envelope**. For IM Aircraft to achieve an ASG with Target Aircraft at a particular ABP, a sufficient control envelope in terms of time and distance must be provided prior to issuing the clearance. There must be some mechanism for gauging whether a particular aircraft has the control authority to meet a specified constraint in the time and distance available.

- **Pilot-in-the-loop control bandwidth.** AIM concepts do not suggest that the FMS/FMC of the aircraft has any trajectory negotiation with IM devices. Therefore, IM requires pilot intervention as part of the closed-loop speed control system for managing spacing. The requirement that the pilot constantly serve as an intermediary between the IM equipage and the primary flight deck (essentially closing the feedback loop) increases workload to perform a task much better suited for automation.

- **Mixed IM and aircraft performance.** Performance differences between the IM control systems of aircraft and the performance of the IM aircraft themselves, may lead to varied performance in meeting constraints. This might create traffic flow disruptions or conflicts due to problems one aircraft might have in terms of anticipating another's performance. Even if two aircraft meet IM spacing performance standards of +/- 10 seconds 95% of the time at the ABP, dynamics of the individual aircraft in responding to disruptions or changes in ASG or ETA could have an impact.

- **Traffic flow stability.** For longer sequences of aircraft, each conducting an IM operation (e.g., assessing spacing and making speed, and possibly path, adjustments with the next aircraft in the sequence), the question arises regarding stability of the chain of aircraft (i.e. String Stability, e.g. Weitz *et.al.*[37]) as successive responses are magnified, particularly with low control bandwidth of pilot-in-the-loop control.

- **Aircraft flight management system.** Feasibility and/or benefits of IM operations may require changes to the FMS to receive and process IM clearances, and to perform closed-loop speed and path control to meet IM spacing. This might potentially include a prediction of Target Aircraft's trajectory, and performing IM with Target Aircraft on non-coincident route.

- **Inter-facility coordination.** The ARTCC or TRACON will likely have to plan IM operations and issue IM clearances to aircraft. This requires knowledge of flight plans and airport conditions, such as the runway configuration, and current and forecast surface traffic levels.

- **Time-based metering precision.** Air traffic control must manage aircraft to their scheduled times at Flow Management Points which precede the ABP so that the IM aircraft can achieve their ASGs with the Target Aircraft while accommodating planning errors and uncertainty. Initial errors in spacing or release time of IM aircraft, in conjunction with haste/delay control envelope of IM aircraft, determine feasibility of realizing ASG.

- **Time of arrival control for Target.** The Target Aircraft will be controlled to the ABP under a time of arrival paradigm, either through Controlled Time of Arrival (CTA) capability or ground-based time of arrival control tool. The performance of the system managing the Target Aircraft to its scheduled time may impact the performance of the IM Aircraft tracking it.

7.1.3 Discussion

The overriding concern about the implementation of IM concepts is the sophisticated trajectory prediction capability that may be required for some maneuvers and how this functionality will be implemented on the flight deck. The literature suggests that the baseline IM climb prediction capability is insufficient. Climb trajectories are the most difficult trajectories to predict and are usually performed by energy-based algorithms within an FMS. IM Aircraft prediction of the climb trajectory of a Target Aircraft may be difficult and error prone if aircraft specific information is not known (e.g. weight). It would be expected that similar problems would be encountered during descents, especially if IM is implemented early, when an aircraft is just initiating the descent. Some of these concerns are addressed with the proposed datalink information of ATC Winds and Improved IFPI. Indeed, these datalinks are listed as a requirement for departure merge operations [35]. As described, these may provide enough information about the Target Aircraft, that a predicted trajectory may not be needed at all. However, it is considerable amount information to be passing from one aircraft to another, through CPDLC, the proposed link. ADS-B is only a fraction of the enabling technology for this concept.

A related problem is the simultaneous application of SIDs and Standard Terminal Arrival Routes (STARs) with all the constraints associated with the RNAV-RNP procedures, and then the addition of IM procedures. It is not clear that there is a procedure in place to operate simultaneously. For instance, if IM is employed, what treatment is given to the published speeds of the arrival procedure? Are the published speed limitations are relaxed, but the published altitudes still honored? If speeds have to be continually changed in the FMS for the procedure, it becomes workload intensive for the crew.

It would appear that there needs to be tight interaction between the IM processor and the FMS, and to some extent, some trajectory collaboration between the two systems. Additionally, it is desirable for the automation to command the IM speeds, as required, directly, without continuous pilot interaction, so that any conflict between the nominal-trajectory speeds and the IM modified speeds are resolved within the avionics. CPDLC data (clearances, etcetera) must be available to both units.

7.1.3.1 Avionics Retrofit Issues

The big concern with any change or retrofit of equipage to an aircraft's avionics package is the cost. Much of the functionality associated with FIM concepts should rightfully be tied to the FMS, but due to the extreme cost of modifying the FMS, existing IM solutions have been located on ancillary avionics.

The costs to modify and certify an Air Transport FMS, even after a simple change is on the order of $10's of millions of dollars [38]. With respect to FMS's that are installed on airline transport category aircraft, the FMS manufacturer cannot add or alter that functionality without OEM (Original Equipment Manufacturer) (e.g., Boeing or Airbus) approval.

To implement any FIM modifications to an FMS, several conditions must be established. First, the aircraft OEM must give permission, be actively supportive, and have their own business case for such implementation. The FMS manufacturer must also believe that there is a business case. A typical 'rule-of-thumb' is that operators would need to recoup their capital investment in 1 – 2 years based on either more efficient operation or cost avoidance [38].

Therefore, the modification of the TCAS system to support FIM is a much more attractive option, and is probably a small fraction (perhaps 10 percent) of the cost to modify the FMS [38]. However, ultimately, it would seem as though an integrated solution between the FMS, the TCAS surveillance processor, and the other flight deck systems is desirable.

7.1.3.2 Mixed Equipage

Any concept or procedure that requires unique equipage and that relies on the participation of other aircraft in the airspace suffers from a mixed equipage problem. Due to the cost of equipage, it is likely that any IM implementation will be working with a mixed equipage environment. The IM concepts definitely rely on a substantial portion of the aircraft be IM-capable to function properly. It is not clear to what extent the fleet will equip or what portion is needed to achieve any benefit. The problem is not as straightforward as equipped versus non-equipped aircraft, since there is likely to be a mix of capability between basic-equipage and advanced-equipage.

7.2 Interval Management for Dependent Parallel Approaches

In this section, the impediments and limitations that are unique to the dependent parallel approaches concept are identified. A short summary of the concept description is provided first, for reference.

7.2.1 Concept Summary

The parallel arrival concept makes use of Advanced IM capability to precisely space aircraft to dependent parallel runways with centerline distances up to 9000 feet during both Visual and Instrument Meteorological Conditions. This includes arrivals to runways spaced closer than 2500 feet, where such operations are either not possible today in IMC or have significant other restrictions. Three distinct types of Advanced IM Parallel Runway Operations are proposed (see Figure 7.3): IM Dependent Staggered Arrivals with One Target (IM DSA1), IM Dependent Staggered Arrivals with Two Targets (IM DSA2), and IM Paired Arrivals (IM PA).

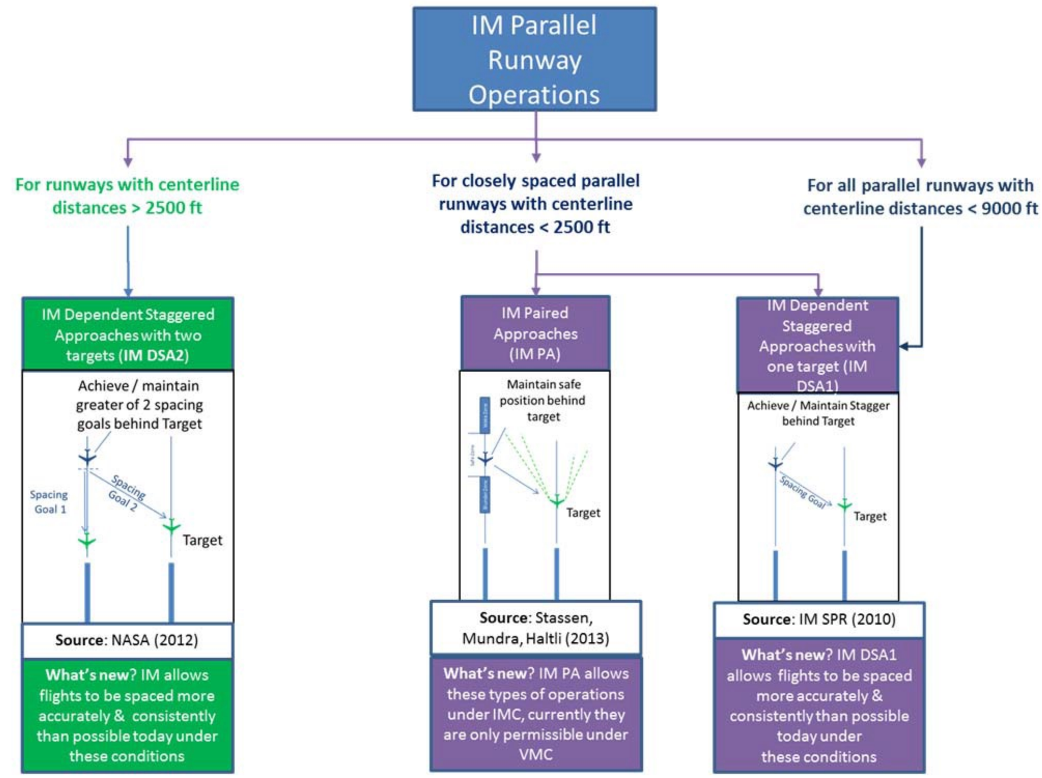


Figure 7.3. Illustration of the Three Proposed Parallel Runway Operations [35].

The primary component of advanced IM that enables parallel runway operations is the ability to space on non-coincident routes. IM for Dependent Parallel Approaches is described at a high level in [1]. Applications to staggered arrival operations with one Target Aircraft (on the same runway or the parallel runway) and two Target Aircraft (on the same runway and on the parallel runway) are described and evaluated in greater detail in [3]. A summary of the concept details is contained in Table 7.3.

Table 7.3. Summary of Parallel Arrival Operations.

Summary of Parallel Arrival Operations
Arrival airport plans to use runways with centerlines spaced 2500 feet to 9000 feet for arrivals and to support Dependent Parallel Approach operations as available.
Aircraft arriving to parallel runways are to achieve spacing goal relative to Target aircraft on parallel runway and same runway (IM DSA2) to achieve desired single-runway and stagger spacing goals.
Target aircraft has Controlled Time of Arrival (CTA) capability, or is managed to its Scheduled Times of Arrival (STAs) at Flow Management Points (FMPs) by Air Traffic Control (ATC) using ground-based tools. For IM DSA2, the Interval Management (IM) aircraft equipment includes arbitration logic to identify and select more constraining of same-runway or stagger spacing requirements, and to shift between each as one becomes more constraining than the other. Previous NASA Langley Research Center research determined IM aircraft equipage for two-target speed control and switching of target aircraft was acceptable [6]. Separation of 3-nautical miles and 1000-feet at turn onto final was key throughput constraint.
En route automation assesses conditions for conducting IM Dependent Staggered Approaches for Two Targets (IM DSA2) and suggests an IM clearance for following aircraft after crossing time-based metering freeze horizon. The Achieve By Point (ABP), Target Reference Point and Planned Termination Point are part of published IM procedure or communicated as part of IM clearance. The ABP is sufficiently close to the runway to realize the reduced separation.
The IM clearance is issued in en route airspace, prior to Top Of Descent (TOD) or during descent.
IM operations can be initiated with a single clearance to IM Aircraft for both Targets. This requires sufficient accuracy and precision of time-based scheduling to identify Target Aircraft and specify Assigned Spacing Goal (ASG). Otherwise, IM operations can be initiated by ATC identifying one Target Aircraft, then amending clearance with second Target Aircraft as traffic evolves. IM aircraft begins accounting for second Target Aircraft while spacing against the first Target.
If the IM clearance is single two-Target clearance, the initiation of IM spacing to parallel runway Target Aircraft can be delayed to some time after same runway Target. Following clearance information is proposed. • IM Initiation (Immediate, When Able, or When Able After X) • Target Aircraft, Clearance Type (Achieve Then Maintain), Spacing Goal (Time or Space) • Spacing Goal Type (Meet or No Closer Than) • IM Initiation Point along IM aircraft's flight path • Intended Flight Path (IFP) Information (IFPI) for Target 1, Target 2 • Wind Information (along flight paths of Target 1, Target 2 and IM aircraft) • ABP (where IM aircraft achieves spacing goal) • Target Reference Point (non-coincident route point for spacing) • Termination Point (where IM operations terminate).
IM operations initiate immediately upon clearance issuance or at downstream point. The IM Aircraft communicates to the controller via Controller-Pilot Data Link Communications (CPDLC) or voice that IM has initiated. IM initiation depends on the availability of Automatic Dependent Surveillance-Broadcast (ADS-B) for IM aircraft to conduct spacing

Ground automation knows IFP of Target and IM Aircraft. IM Aircraft has Data Communications (DataComm) capability to receive IFP including Predicted Final Approach Speeds (PFAS) and wind information for Target 1 and Target 2 Aircraft. IM aircraft leverages flight path and wind information of Target Aircraft to assess spacing and suggest IM speed adjustments to meet spacing.

The DSA1 concept spaces arrivals to dependent parallel runways with centerline distances less than 9000 feet and allows an IM Aircraft to achieve a spacing goal relative to a Target Aircraft arriving on the parallel runway. DSA1 provides IM speeds behind a target on a non-coincident route which requires the designation of a TRP in addition to an ABP. The DSA2 concept considers two spacing goals simultaneously and maintains the greater of the two spacing goals.

7.2.2 Impediments and Limitations

This section enumerates the impediments and limitations unique to the Dependent Parallel Arrivals concept. These include issues identified in [1] and [3], and others identified by the project team.

- **Airport operating conditions and characteristics.** This includes airport operations, runway occupancy, and airport surface capacity.
    - *Airport operations*: The airport has approach procedures to support IM operations, the parallel arrival runways in use, the airport is operationally prepared for dependent approach procedures and the called arrival rate reflects this.
    - *Runway occupancy*: A shared arrival-departure runway can impact the arrival capacity available to implement the concept. Also, arrivals must be sufficiently expedient in exiting the runway to make arrival runway capacity available to subsequent pairs of aircraft.
    - *Airport surface capacity*: The airport surface taxiway is sufficient to accommodate the influx of arrivals resulting from concept application.
- **Traffic characteristics.** The concept application requires that the IM Aircraft has one Target Aircraft on route to same runway and second Target Aircraft to parallel runway which are sufficiently proximate in time to enable concept application. Sufficient traffic density is required to achieve the proper traffic mix.
- **Scheduling precision.** The accuracy in the schedule prediction of arrivals must be sufficiently precise to identify IM and Target Aircraft, and the landing sequence prior to entering the TRACON.
- **Compatibility criteria.** The FAA AIM concept of operations calls out for arrivals to compute and communicate to the ARTCC controller the final approach speeds to support traffic planning and management. Pairing aircraft with compatible final approach speeds may present difficulties.

- **Aircraft equipage.** Arbitration logic for selecting dominant spacing goal among two Target aircraft is required. There may be cyclic chatter between two Target Aircraft that are closely spaced. Clearances related to two different Target aircraft in one operation is complex, may require data communications. Repetition and confirmation of clearances is laborious.

- **Ground-based automation.** The ARTCC must be sufficiently knowledgeable of current and forecast aircraft and airport conditions to identify IM pairings generate and issue IM clearances, assess adherence of aircraft to those clearances, and share clearance information with the TRACON and the ATCT.

  - Ground automation must have knowledge of aircraft and air crew capabilities to conduct IM Dependent Parallel Approaches. Such IM capabilities might include non-coincident route spacing capability, single- or two-target spacing capability, and supporting DataComm capabilities.

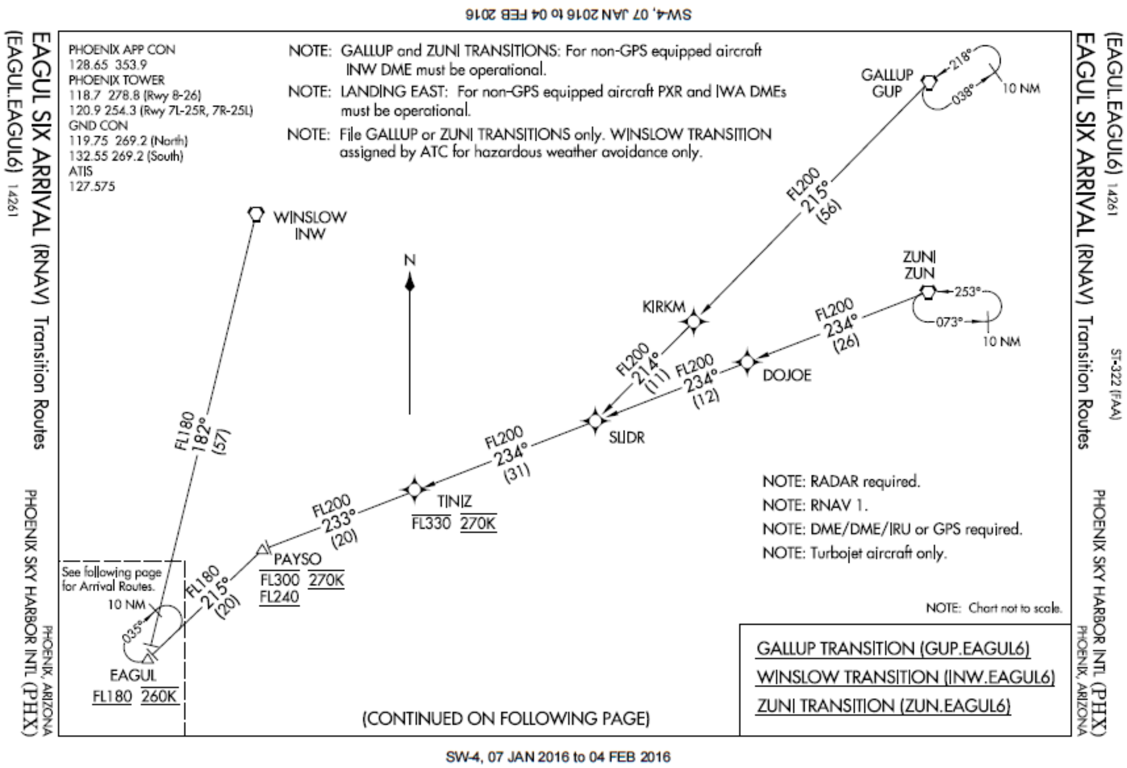
  - Ground automation must have knowledge of airport runway configuration, operating conditions, and applicability of IM for Dependent Parallel Approaches.

  - Ground automation must be able to assign the appropriate arrival procedure, airport arrival runway, runway transition and approach procedure to Target 1, Target 2, and IM Aircraft

- **Missed approaches.** The complexity and tightly spaced nature of parallel arrivals, makes the system more fragile to disturbances in the flow such as missed approaches. Challenges in discerning appropriate spacing goal may result in greater occurrence of missed approaches. The complexity of inserting missed approaches into an arrival stream of tightly-spaced, parallel-runway traffic is problematic. This may be an area warranting future research.

7.2.3 Discussion

The big difficulty with the parallel arrival concept centers on all the ground automation needed to properly sequence and schedule the aircraft into the appropriate streams. Additionally, since these decisions are made far upstream, the aircraft time of arrival estimates need to be accurate and precise. This might be achievable by assigning time constraints along particular RNAV-RNP arrival procedures along with the aircraft's communication and adherence to the PFAS speeds. One problem with IM on any type of approach is the extent to which RNAV/RNP arrival procedures are constrained. Figure 7.4 shows the EAGUL6 RNAV STAR.



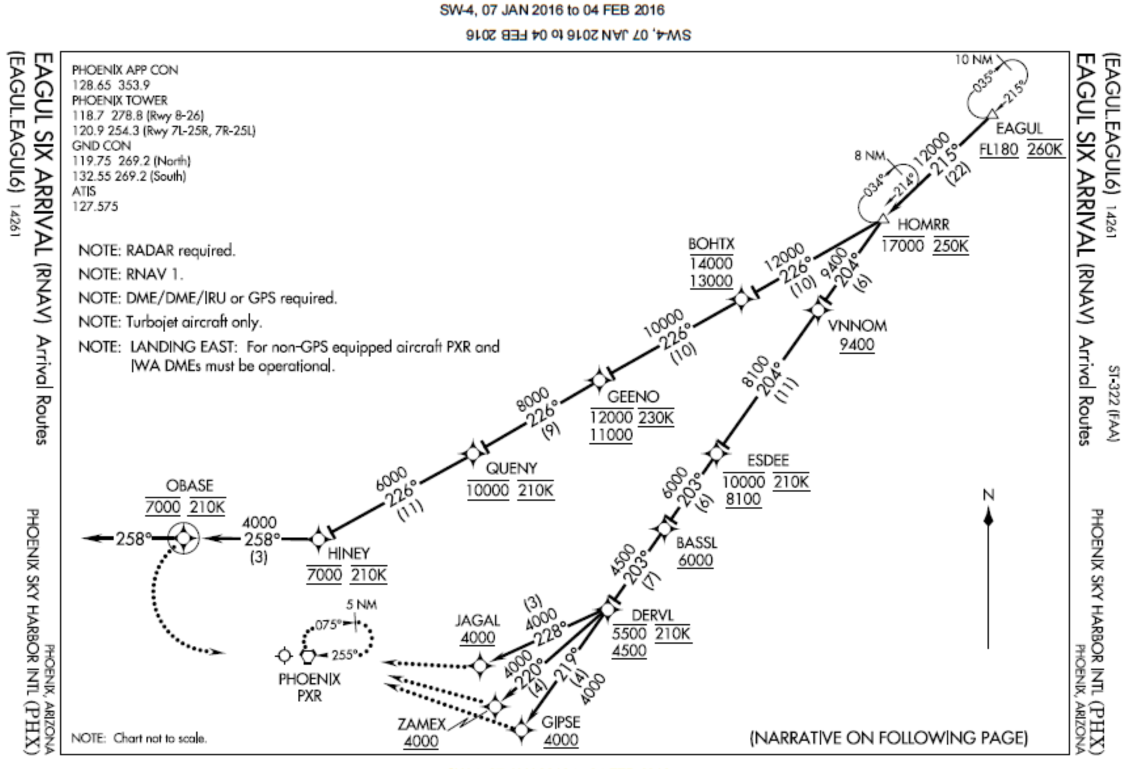


Figure 7.4. The EAGUL SIX Arrival Procedure Has Many Speed and Altitude Constraints Down to the Runways of Phoenix Sky Harbor Airport (PHX).

Nearly every fix along the route has speed and altitude constraints. When the controller assigns the STAR and then issues a “descend via” clearance, it is a clearance for the flight crew to not only follow the lateral path, but also to fly the vertical profile as depicted. Since the information for the STAR is already in the aircraft’s navigation database, this is simple for the flight crew. However, as soon as a controller makes a change to the profile, the flight crew’s workload becomes high since all the constraints will need to be manually changed. This is an even bigger problem if downstream TRACON or Airport Tower controllers implement changes to the clearance as per their local traffic management needs. This is the type of problem that needs to be avoided with the IM clearance. There must be avionics and procedures for appropriately interacting with STARS and the “descend via” clearance.

The use of non-coincident routing and two target tracking means that the concept requires features associated with Advanced IM. However, the non-coincident routing and two-target tracking are some of the easier functions to implement. The presumption in the Parallel Arrivals concept of operation is that the single target versions do not need datalink clearances, and that two target tracking will require datalink clearances. Therefore, the only feature that parallel arrivals may need is the non-coincident routing. This may make the expansion of airborne functionality fairly straightforward.

This may not be necessarily true for tracking two target aircraft, which needs datalink communications. It may be that the IM algorithms can be designed to infer the parallel aircraft given the in-trail aircraft. In this case a controller might be able to verbally assign a clearance such as: “*Maintain IM spacing from your in-trail traffic- American 391, and its parallel.”*

The problem of the missed approach or other disruption is a matter of serious concern. The complexity and tightly spaced nature of parallel arrivals, makes the system more fragile to flow disturbances such as missed approaches. Challenges in discerning appropriate spacing goal may result in greater occurrence of missed approaches. The complexity of inserting missed approaches into an arrival stream of tightly-spaced, parallel-runway traffic is problematic. This depends quite a bit on when the clearances are issued and how long the traffic runs in an IM parallel configuration. The length of the stream matters and likely impacts the string stability of the stream. Additionally, there does not seem to be any published procedure for reinserting missed approach aircraft into the stream. This is something that needs to be worked out prior to implementation and may be an area warranting future research. One interesting question is whether IM can be used to assist with reinserting an aircraft in the stream. For instance, can the ground system identify a potential gap and then issue clearances to the associated aircraft to make room for the missed approach aircraft?

7.3 Interval Management for Departure Operations

In this section, the impediments and limitations that are unique to the departure operations concept are identified. A short summary of the concept description is provided first, for reference.

7.3.1 Concept Summary

IM Departure Operations (IM DO) are intended to be used on initial climb-out between a target and IM aircraft that both have to be inserted into an overhead stream. For IM DO During Initial Climb Out, the Target Aircraft departs ahead of the IM Aircraft from the same or different runway at the same airport, or on a runway at a different airport in the vicinity. The IM Aircraft receives a clearance to achieve or maintain a particular spacing goal behind the Target Aircraft up to a specified ABP. During this time IM equipage provides advisories to the flight crew, and controller intervention is minimal. The concept is illustrated in Figure 7.5.

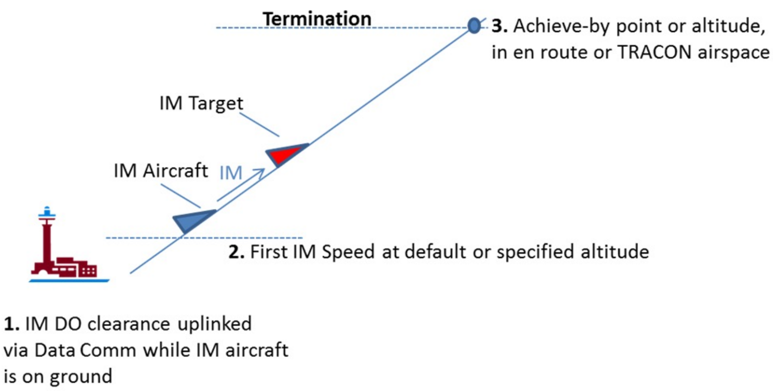


Figure 7.5. Illustration of IM during Initial Climb Out [35].

A similar concept is when the departing aircraft is given a Target Aircraft that is already established in the overhead stream. Here the departing aircraft must use IM to establish a spacing buffer behind the Target Aircraft at an En Route Flow Metering Point as shown in Figure 7.6.

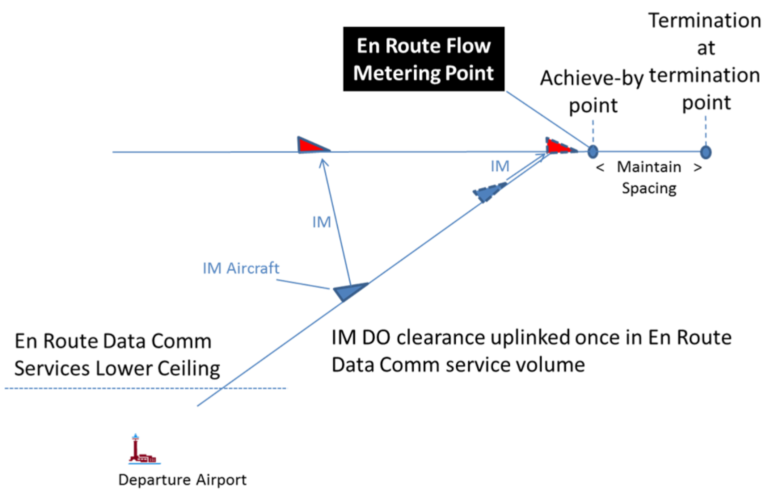


Figure 7.6. Illustration of IM Insertion into an Overhead Stream [35].

A summary of the departure operations is contained in Table 7.4.

Table 7.4. Summary of Departure Operations.

Summary of Departure Operations
Target Aircraft departs ahead of Interval Management (IM) aircraft on the same or different runway of the same airport, or runway of different airport in vicinity. IM Aircraft and Target Aircraft routes may be completely coincident, merging, or non-coincident.
Meeting Distance-based Miles-In-Trail (MIT) or time-based spacing goals at departure fixes at the Terminal Radar Approach Control (TRACON)-Air Route Traffic Control Center (ARTCC) boundary or points beyond in ARTCC.
Airport Traffic Control Tower (ATCT) automation such as Tower Flight Data Manager (TFDM) or other ground-based system identifies IM initiation conditions based on equipage, airport surface traffic information, and traffic predictions in TRACON airspace, including time-based metering of departures at Achieve By Point (ABP) to support staging operations and specifying Target Aircraft and Assigned Spacing Goal (ASG). Supporting information could include: • Departures from same airport (in-trail) or different airports in metroplex (merging) • Knowledge of departure aircraft that are IM capable • Tactical scheduling of departure fix crossing and runway takeoff times
IM clearance includes IM Initiation (altitude), Target Aircraft, Spacing Goal and Type, Intended Flight Path Information (IFPI) of Target Aircraft, Achieve-By Altitude, Termination Altitude
IM clearance uplinked to IM aircraft prior to takeoff or communicated by voice in the TRACON includes: • Fundamental clearance information is ABP and ASG • IFPI includes departure runway, Standard Instrument Departure (SID) procedure name and departure fix name; Flight-deck IM (FIM) equipment infers Target aircraft IFPI based on Target aircraft's position and ABP name • IM aircraft uplinked detailed wind information for IM and Target aircraft, IFPI of IM Aircraft • Consider issuing entire IM clearance as pre-departure clearance via Controller-Pilot Data Link Communications (CPDLC) from the Air Traffic Control Tower (ATCT) with more precise IFPI for Target Aircraft, leveraging Tower Flight Data Management (TFDM) flight plan data and Tower Data Link System (TDLS) transmission to IM aircraft • Hybrid approach communicates some IM clearance information prior to takeoff, remainder via voice after takeoff
IM aircraft equipped with closed-loop control algorithms to determine speed and turn (path) adjustments to meet the ASG • IM Turn is a proposed component to Advanced IM, explicitly called out in [1] to expand control envelope of IM aircraft to meet IM spacing, accounting for uncertainty. • Includes capability of IM aircraft to perform its own trajectory prediction. • Planned termination point may be ABP or point downstream in ARTCC; latter requires communication between TRACON and ARTCC
IM operations

- Initiate after 10,000 feet as per pilot workload considerations; explore earlier initiation
- Variability in climb profiles impacts prediction of Target aircraft's trajectory, resultant spacing; leverage Target aircraft's Estimated Time of Arrival (ETA) to ABP to improve spacing control, or assign At or Greater (AOG) spacing to accommodate uncertainty

7.3.2 Impediments and Limitations

Based on the descriptions of the concepts and other external analysis, we identify potential impediments and limitations to realizing benefit from the concept. These include issues identified in [1] and [4], and others identified by the project team.

- **Airspace structure.** The airspace structure must have departure routes that share common or proximate departure fixes. Ground-based automation planning for IM must have knowledge of airspace configuration and applicable in-trail spacing restrictions from the ARTCC and TRACON.

- **Airport departure management.** Departure control must manage departures to scheduled takeoff times to enable IM aircraft to achieve ASG at ABP from multiple airports. For multi-airport coordination, scheduling of departures may need to be done at the TRACON or ARTCC level to identify Target and IM aircraft pairs and ASGs at common departure fixes from disparate airports. Clearances must be provided to aircraft or to the appropriate local controller.

- **Departure trajectory variability.** Extensive variability in the climb-out trajectories of aircraft makes predicting and tracking the trajectory of a target aircraft very difficult for the IM aircraft. Criteria for pairing IM and Target aircraft, (e.g., similar climb profiles), may impact the opportunity for applying concept and receiving benefit.

- **IM operations below 10,000 feet AGL.** Departure operations preclude pilot heads-down time below 10,000 feet to support conducting IM operations. Without IM aircraft automation, this may limit the situations to which IM DO can be applied, or the ability to meet the ASG because of errors and disturbances.

7.3.3 Discussion

The big impediment to the implementation of the Departure Operation concept is the problem of predicting the target aircraft's trajectory. It is not clear how the IM aircraft is going to accomplish this. The difficulty in tracking a target aircraft in a climb is that the nature of the climb means that most easily observable properties (true airspeed, and climb rate) that can be used to extrapolate the future position, are constantly changing.

Figure 7.7 shows a typical climb trajectory. The climbing aircraft usually observes a CAS/Mach profile where the aircraft maintains max available thrust while holding a constant CAS (Calibrated Airspeed). In this profile the TAS (True Airspeed) and Mach constantly increase, until at some point, the aircraft makes a transition to a constant Mach profile, and then the CAS drops off. Predicting these trajectories is usually the realm of a

FMS equipped with energy-based trajectory models. However, it is not known if the IM algorithms will have this level of sophistication to apply to a target aircraft, or if the IM equipage will have access to the ownship's FMS trajectory prediction.

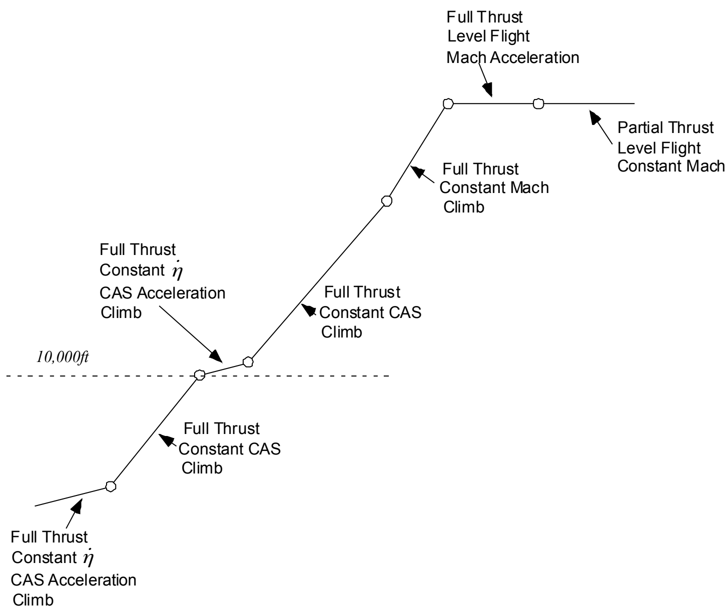


Figure 7.7. Illustration of the Vertical Trajectory Components Typically Associated With an Airline Transport Climb Profile.

The FAA IM documentation has already made clear that Baseline IM does not provide good climb trajectories. However, the Advanced IM capabilities concept of operation does not explain how it will process climb trajectories to any greater accuracy. It offers expanded datalink capabilities including ATC Winds and IFPI. ATC Winds information insures that all aircraft in the vicinity use the same wind information. The IFPI offers additional 4D path information such as lateral turn points, expected altitudes, the start and end points for altitude changes, expected indicated speed profiles, and bank angle and turn radius data. So, presumably, the method of operation depends on the Target Aircraft providing a detailed 4D trajectory to the IM Aircraft. Some combination of 4D trajectory information with energy-based trajectory modeling should support accurate departure climb trajectory prediction to enable IM for departure operations.

However, a more basic question to ask is whether IM is redundant with existing time of arrival capabilities of aircraft. In anticipation of the wide-spread adoption of Time-Based Flow Management (TBFM), existing FMSs have had the ability to predict and then meet a particular arrival time at a fix for a long time. In the IM concept, the IM aircraft is trying to meet a time spacing relative to the Target Aircraft's Scheduled Time of Arrival (STA) at the ABP. Isn't this nearly equivalent to IM Aircraft meeting its own STA at the ABP? The presumption is that the IM solution, due to its constant monitoring, will allow for smaller separation buffers than TBFM. Whether that is true is not clear, however, the existence of a competing concept creates another problem. Not only will a mixed-equipage problem exist in terms of avionics, there is also is also a mixed concept/procedure problem. Some aircraft may operate under TBFM while others may operate under IM. An IM aircraft will be unable to operate under TBFM. This multi-dimensional mixed-equipage/procedure problem further exacerbates the traffic management problem for the controller.

Interestingly, IM Aircraft's insertion into an overhead stream does not present the same complexities, due to the fact that the Target Aircraft is in a steady-state cruise condition. Here, it might be equally true that STAs could be issued for the IM Aircraft and Target Aircraft, but the ease with which the Target Aircraft's position can be predicted makes IM operations more attractive, since in this case, the Target Aircraft would not need to participate in any capacity (other than ADS-B out).

7.4 Interval Management for Wake Mitigation

In this section, the impediments and limitations that are unique to the Wake Mitigation concept are identified. A short summary of the concept description is provided first, for reference.

7.4.1 Concept Summary

In the Wake Mitigation concept, a scheduling tool in the ground automation predicts the required wake separation distance needed between arriving aircraft in an arrival stream for a single runway. Subsequent clearances are issued to arriving aircraft and then IM operations are used to allow the aircraft to space precisely at the predicted wake separation requirement. The separation distance calculation is a function of several sets of parameters, including route, weight, aircraft type, planned final approach speed, and weather conditions at the arrival runway. The operational scenario includes a 30 to 45 minute freeze horizon, where wake-separation is frozen. Aircraft outside the freeze horizon are subject to changing wake vortex spacing at 15 minute intervals to take into account observed differences from the forecast.
Figure 7.8 provides a concept diagram.

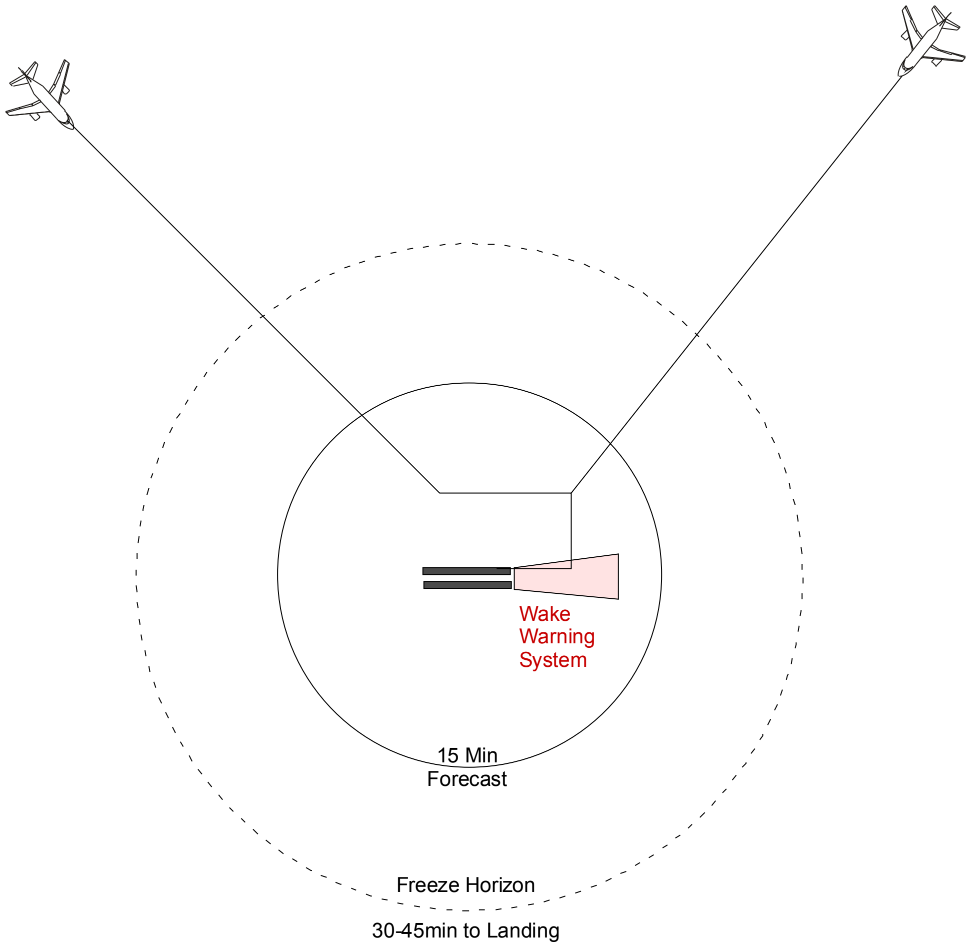


Figure 7.8. Illustration of IM Wake Mitigation Concept.

Table 7.5 provides a summary of wake vortex operations.

Table 7.5. Summary of Wake Mitigation Operations.

Summary of Wake Mitigation Operations
Time-based metering schedules arrival landings using dynamically computed wake vortex separations. At the metering freeze horizon, scheduled crossing times for aircraft at the Flow Management Points (FMPs), and the implied inter-flight spacing, are fixed. Aircraft trajectories (e.g., speed) are managed to meet the prescribed safety. • Separation established 30-45 minutes prior to the freeze horizon • Separation at runway threshold scheduled at the freeze horizon, remains static throughout arrival phase of flight
Safe in-trail separations for aircraft are specified based on fast-time models of wake transport and circulation decay from meteorological data, aircraft data, and aircraft information • Pair-wise wake turbulence separation at runway threshold specified dynamically as per actual conditions, e.g., aircraft mass and atmospheric/meteorological conditions
In the baseline condition of static in-trail spacing requirements, controllers manage trailing aircraft to meet spacing with the leading aircraft. Spacing control shortcomings introduce excessive response time to implement spacing goal reductions, limiting achievable airport throughput.
In the IM condition, the flight crew uses equipment on-board the IM aircraft to meet the assigned spacing goal, and the controller monitors the operations. The improved spacing control reduces response time to spacing goal reductions, enhancing achievable throughput.

7.4.2 Impediments and Limitations

Based on the descriptions of the concepts and other external analysis, we identify potential impediments and limitations to realizing benefit from the concept. These include issues identified in [4], and others identified by the project team.

- **Airport characteristics:** Airport operating characteristics and conditions may determine the feasibility of realizing the throughput benefits of the concept. They include runway occupancy and airport surface capacity, described below.

    - *Runway occupancy*: Arrivals must be sufficiently expedient in exiting runways to make room for the next arrival.

    - *Airport surface capacity*: Sufficient runway exits and taxiway surface area (surface capacity) are needed to absorb arrivals if aircraft separations are sufficiently reduced and traffic levels sufficiently high to overwhelm traffic capacity of the airport infrastructure.

- **Specifying safe separations.** Extensive requirements are levied on the (presumably) ground-based automation system which dynamically determines in-trail separations between aircraft.

- *Wake prediction accuracy:* The accuracy and availability of meteorological data and aircraft data needed to perform the necessary wake-vortex calculations is unclear.

- *Wake vortex separation thresholds:* The wake-vortex thresholds for feasible inter-flight spacing accounting for data and modeling errors in wake-vortex prediction is unclear.

- *Wake prediction certainty:* The certainty of a particular spacing condition duration as basis for implementing reduced spacing may need to be calculated.

- *Missed approaches:* Forecasting errors may call for missed approach if spacing must be suddenly increased to maintain safe separation from Target.

- **Time-based metering freeze horizon**. The flight time between the freeze horizon and the runway overlaps with the frequency of dynamic spacing changes of 1 hour (as per meteorological data predictions). Time-based scheduling would have to permit scheduling changes in the TRACON to accommodate dynamic spacing changes.

- **Increases in spacing:** There needs to be some way to add delay at the TRACON level automatically and instantaneously to insure safe spacing if separation standards suddenly need to increase. Having aircraft execute missed approaches to avoid spacing conflicts is undesirable.

    - IM may enable rapid response to changes in wake vortex spacing. Response dynamics of strings of aircraft, particularly with different IM performance characteristics, could be unstable.

- **Aircraft response time:** Time required for aircraft to respond to changes in assigned spacing goal may determine feasibility of reducing spacing goals, differences in times for aircraft to respond to changes in assigned spacing goal may create intermittent conflicts.

- **Controller tools and operations:** Additional controller tools are needed to support this operation. Possible functionality required includes: 1) predicting and avoiding wake-vortex interactions; 2) identifying reductions in wake spacing minima; 3) determining feasibility of changing spacing (e.g. can all aircraft respond to separation requirement changes?); 4) rescheduling aircraft and issuing new spacing goal clearances; 5) monitoring and ensuring separation during compression of traffic when meeting spacing reduction; 6) predicting and avoiding wake-vortex interactions.

7.4.3 Discussion

The major difficulty in implementing the wake vortex spacing concept is implementing the ground-based algorithms that predict the required wake vortex separation. This problem is exacerbated by the difficulty in obtaining the required aircraft data. For instance, the instantaneous weight and airspeed are needed to estimate a particular aircraft's vortex strength, and that data would need to be transmitted to the ground. If weight for each aircraft is not available, then some other approximation will have to be employed and the separation criteria will need a larger safety buffer to account for uncertainty.

Another concern is the freeze horizon for time-base metering. At 45 minutes out, the aircraft is still in ARTCC airspace and final approach spacing information would need to be transmitted (or at least known to the TRACON controller) at that time. It might be that only certain weather related parameters are established 45 minutes out, and that the final spacing can be determined at a later time, when the aircraft sequence is defined. At any rate, there needs to be a mechanism for expanding the spacing if, for instance, unforeseen weather conditions make the current spacing untenable. Indeed, this scenario may be where the IM functionality pays the greatest dividends. It might be that spacing could be expanded just on the basis of issuing new clearances. This is an area requiring further research, with a particular emphasis on the string-stability problems such a scenario might entail.

One interesting aspect of this concept is that it probably does not require what the FAA is terming Advanced IM, but rather it could possibly be accomplished with the existing *Baseline* capability. For instance, the concept assumes coincident routing (same runway) and only one target for the IM Aircraft to track. Therefore, other than for the purpose of transmitting weight, no datalink would be required. It is conceivable that if the weight information is available to the flight crew, that the single number could be transmitted over voice communications.

One concept of operations that might be viable and that would require no datalink information would be to have the TRACON controller request aircraft weight information. There is a precedent for controllers requesting numerical data from pilots (e.g., *"What is your best forward speed?"* and *"What is your heading direct destination?"*). There is already a precedent for a certain amount of information exchanged at the ARTCC/TRACON junction. For instance, checking in with the next sector always includes an altitude confirmation (e.g., "*Indy Approach, November 63112, checking in, level, one-zero (ten) thousand").* Similarly, the TRACON controller will likely insure that the landing aircraft has the appropriate weather conditions (e.g., "*Confirm you have Alpha for Indianapolis*"). In less sophisticated airspace, the TRACON controller might ask the pilot for approach requests, especially if the destination airport is unmonitored. If the Air Terminal Information Service (ATIS) information or the published arrival procedure indicates that aircraft weight information is requested, pilots could query it and provide it along with the altitude confirmation and the ARTCC/TRACON transition. This would be no more cumbersome than the additional information that often accompanies ATIS broadcasts, such as taxiway closures, bird activity, or land/hold-short operations. The rest of the aircraft data would have to be in a ground-based database that would be queried based on the aircraft's identification code.

8 Conclusions and Next Steps

This section presents a summary of the benefits analysis, and provides metrics for straightforward comparison of the three concepts. Here, the expected capacity benefit of each concept is balanced against the overall difficulty to implement.

8.1 Summary of NAS-Wide Benefits

To compare the potential benefit provided by each of the concepts, the overall NAS-wide benefit, in terms of increased capacity for each concept, is tabulated. In this analysis, the number of potential sites for application, plus the expected frequency that the concept might be applied are used to tabulate a collective capacity increase for each concept. Table 8.1 summarizes the NAS-wide benefits estimated from the range of sites evaluated for each concept.

Table 8.1. Comparison of NAS-wide Benefits of Concepts as per Capacity Increase and Frequency of Application.

Concept	Number of Sites	Frequency of Application	Collective Capacity Increase
IM Dependent Parallel Arrivals	27 airports	1691 hours per year (19% of the time)	237 arrivals per hour
IM Departure Operations – Spacing Precision	21 metroplexes: 8 evaluated, 13 others estimated	18 hours per day → 6570 hours per year (75% of the time)	176 departures per hour
IM Departure Operations – Missed Slots	21 metroplexes: 8 evaluated, 13 others estimated	18 hours per day → 6570 hours per year (75% of the time)	93 departures per hour
IM Wake Mitigation	27 airports	4460 hours per year (51% of the time)	77 arrivals per hour

The results indicate that the IM Dependent Parallel Approaches concept is estimated to have the greatest increase in NAS-wide capacity with 237 arrivals per hour, followed by the increased precision of IM Departure Operations which is estimated to increase NAS-wide capacity by 176 departures per hour. IM Departure Operations, missed slots, is estimated to have less of an impact, with an increase to NAS-wide capacity of 93 departures per hour. Finally, IM with Wake Mitigation is anticipated to have the least impact with an increase of 77 arrivals per hour, however we note the lack of available data for estimating the throughput increase afforded by reduced separation.

In addition to the aforementioned caveats to each analysis, we note that each of these results assumes that all aircraft in the NAS can participate, or that otherwise approximately equivalent spacing performance can be achieved by means other than IM for all aircraft.

8.2 Summary of Impediments and Limitations

This section summarizes the limitations of and impediments to implementing Advanced IM concepts and realizing benefits of those concepts. Table 8.2, Table 8.3, Table 8.4 and Table 8.5 provide a basic ranking to the relative risk and impediments.

Table 8.2. Impediments and Limitations Common to IM Concepts.

Impediment or Limitation	Description	Type of Impact	Impact
Traffic density	Sufficient traffic to apply IM	Implementation	H
Capability levels	Portion of aircraft capable of IM operations	Implementation, Level of benefit	M
Initiation criteria	Cooperation of air traffic control and flight deck	Implementation	L
Inter-facility coordination	ARTCC and TRACON knowledge of airport surface conditions for planning and execution of IM operations	Implementation	L
Target Aircraft ETA prediction - functionality	Flight deck- or ground-based trajectory prediction of Target Aircraft's ETA to achieve-by point	Level of benefit	H
Target Aircraft ETA prediction - accuracy	Accurate ETA prediction to realize reduced spacing or trajectory benefits	Level of benefit	M
Time-based Metering Precision	Appropriately staging operations to realize reduced spacing	Level of benefit	M
IM Aircraft control envelope	Sufficient haste or delay control envelope to achieve reduced spacing in light of errors or disturbances	Level of benefit	M
IM Aircraft control bandwidth	Sufficient frequency of haste or delay control changes to achieve reduced spacing in light of errors or disturbances	Level of benefit	M
Mixed IM aircraft performance	Consistency and feasibility of meeting reduced spacing given differences in performance of aircraft	Level of benefit, implementation	L
IM Aircraft FMS changes	Automated trajectory planning and management capability which supports IM operations	Level of benefit	M
Target aircraft Time of Arrival	Performance of non-IM aircraft in meeting times of arrival impacts IM aircraft in	Level of benefit	L

Control	achieving spacing		
Overall Score:			22

Impediments and limitations common to all IM concepts are listed first, followed by impediments and limitations of each concept. Each limitation or impediment is characterized by the type of impact, either on implementing IM operations or the level of benefit obtained from implementing the IM operations, and the estimated level of impact on the benefit obtained from the concept. A simple ranking system of (3 (H) = High, 2 (M) =Medium , 1 (L) = Low) to help with comparisons of risk between the three concepts.

Table 8.3 and Table 8.4 show that based on the ranking, the Parallel Arrival Concept and the Departure Concept have roughly the same amount of risk. Table 8.5 tallies the IM for Wake Mitigation concept at a slightly lower risk than the others.

Table 8.3. IM for Parallel Arrival Impediments and Limitations.

Impediment or Limitation	Description	Type of Impact	Impact
Airport operating conditions	Airport utilizing parallel arrival runways, with infrastructure and operational characteristics facilitating their use	Implementation	H
Traffic characteristics	Relative routing and timing of Target and IM aircraft to enable concept application	Implementation	H
Time Based Metering Precision	Time based metering sufficiently accurate to pair aircraft and identify spacing goals	Level of benefit	M
Aircraft pairing criteria	Compatible final approach speeds or other criteria	Implementation	H
IM aircraft equipage & capability	IM aircraft capable of processing complex clearances and conducting 2-target operations	Implementation	H
ARTCC arrival management	Knowledge of airport operating conditions to plan operations and issue clearances	Implementation	M
Missed approaches	Complexity of managing and recovering from off-nominal conditions	Implementation, Level of benefit	M
Overall Score:			18

This analysis has some clear limitations and should be treated accordingly. For instance, the need for extensive datalink communications, beyond what would normally be provided by ADS-B, to perform the departure operation may very well be a much larger impediment than what it is scored. Similarly, while the parallel runway operation has many identified problems, many are relatively minor. In fact, extensive new development may not be needed for all variations of the Parallel Arrival concept. The wake vortex mitigation concept scores lowest on the risk level. This would agree with general intuition. For instance, the concept, as defined only applies to a single runway with a single arrival stream. Furthermore, while the concept is not fully defined, it is conceivable that the operation could be carried out with no more than voice communications. Therefore, most of what would be needed to support the wake vortex mitigation concept already exists in the baseline IM capability. This represents a huge advantage.

Table 8.4. IM for Departure Operations Impediments and Limitations.

Impediment or Limitation	Description	Type of Impact	Impact
Airspace structure	Proximity of departure gates and fixes may be required for IM; i.e., same quadrants	Implementation	H
Traffic characteristics	Relative routing and timing of departures to enable concept application	Implementation	H
Inter-facility coordination	ARTCC or TRACON knowledge of current & forecast multi-airport traffic and operating conditions	Implementation, level of benefit	H
Airport departure management	Airport management of departures to successfully stage IM operations	Level of benefit	M
Departure trajectory variability	Trajectory prediction sufficiently knowledgeable and accurate to identify pairs and spacing goals	Level of benefit	M
IM operations below 10,000 feet	Limits application of IM operations, or errors and disturbances that can be accommodated	Implementation, Level of benefit	M
Datalink Required	Considerable datalink data needed	Implementation	H
		Overall Score:	18

Table 8.5. IM for Wake Mitigation Impediments and Limitations.

Impediment or Limitation	Description	Type of Impact	Impact
Airport characteristics	Operating conditions and characteristics conducive to operations, e.g., runway occupancy times, sufficient taxiway capacity	Level of benefit	M
Specifying safe separations	Wake prediction accuracy and certainty, separation criteria and thresholds, missed approach procedures	Implementation, Level of benefit	H
Time-based metering freeze horizon	Horizon for freezing scheduled times may preclude spacing reductions or result in unsafe spacing	Implementation, Level of benefit	H
IM aircraft response	Differences in response times to spacing	Implementation,	M

to spacing changes	changes may yield intermittent violations	Level of benefit	
Controller tools and operations	Specifying and implementing spacing changes, monitoring current and forecast traffic and atmospheric conditions	Implementation, Level of benefit	H
		Overall Score:	13

Overall, the intuition of the authors is to rank the concepts in terms of highest risk as 1) Departure Operations, 2) Parallel Arrivals, and 3) Wake Vortex Mitigation.

8.3 Summary of Benefits and Impediments and Limitations

Table 8.6 summarizes the benefits estimated for each concept, and the quantified impact of the impediments and limitations identified for each concept. The benefits for each concept include its frequency of application its NAS-wide capacity increase. The impact of the impediments and limitations is the sum of the high, medium or low impacts of the individual impediments and limitations to each concept.

Table 8.6. Comparison of NAS-wide Benefits of Concepts as per Capacity Increase and Frequency of Application.

Concept	Number of Sites	Frequency of Application	Collective Capacity Increase	Impact of Impediments and Limitations
IM Dependent Parallel Arrivals	27 airports	1691 hours per year (19% of the time)	237 arrivals per hour	22 + 18 = 40
IM Departure Operations – Spacing Precision	21 metroplexes: 8 evaluated, 13 others estimated	18 hours per day → 6570 hours per year (75% of the time)	176 departures per hour	22 + 18 = 40
IM Departure Operations – Missed Slots	21 metroplexes: 8 evaluated, 13 others estimated	18 hours per day → 6570 hours per year (75% of the time)	93 departures per hour	22 + 18 = 40
IM Wake Mitigation	27 airports	4460 hours per year (51% of the time)	77 arrivals per hour	22 + 13 = 35

The results indicate that IM Dependent Parallel Arrivals yields the highest capacity benefit when the concept is applied, however instances of concept application are less frequent, limiting overall benefit. The weight of the impediments and limitations to concept implementation are among the highest. The IM Departure Operations—Spacing Precision concept may provide the greatest potential capacity benefit on the NAS due to its frequency of application, and the fairly high benefit realized when the concept is applied. The weight of the impediments and limitations to concept implementation are equivalent to IM Dependent Parallel Arrivals. IM Wake Mitigation appears to have the least capacity impact of the concepts evaluated, however more detail regarding the concept baseline and its application would enhance the benefit estimate. However, impediment and limitations to this concept scored the lowest among the concepts, indicating that, despite remaining research and development, this concept may be more readily implementable the others.

8.4 Next Steps

There are several areas where future research would be appropriate. This section provides a short listing of areas that the authors think may require additional research along with some initial suggestions on how that research might be attempted.

8.4.1 Parallel Arrivals

The Parallel Arrival concept is the most thoroughly developed concept and considerable modeling and simulation has already been applied to its operation. In that sense, it is fairly mature. What is not completely clear is how these parallel arrivals, and the overall descent-based IM concepts will interact and properly overlay with the RNAV-RNP based arrival procedures that are now in use at most major airports. These published procedures are heavily constrained from the point of speed/altitude crossing points, and procedures need to be developed to relax these constraints under IM operations. Informal discussions with flight crews have indicated that changes to the vertical profile in the FMS, after a particular STAR has been selected, are very workload intensive. The authors recommend some analysis to determine the breadth of the problem. This might start with interviews of flight crews and controllers. Next, some examination of the equipage available for them to use is in order. From there, an analysis of typical RNAV-RNP procedures into airports likely to use parallel arrivals should be performed. An examination of how these airports operate under VMC conditions might help draw some conclusions.

8.4.2 Departure Operations Future Work

The departure operations concept is the one that seems to hold the most uncertainty. The concept as described requires a considerable amount of CPDLC-based data transfer between aircraft to insure that the IM aircraft is able to adequately track the target aircraft. This information is all in addition to the ADS-B data which presumably enables IM. There is a trade-off to be considered between the cost in bandwidth and complexity of the additional messaging and what might be possible through additional algorithmic complexity. From the literature review, it is not obvious that the additional data is absolutely necessary. To be sure, it is one way to solve the problem, however it may also be possible to infer target aircraft trajectories with a minimal amount of information. The viability of the concept is improved when the required datalink information is reduced.

One possible method for conducting this research might be as follows: If the ADS-B information contains the aircraft type and the final destination, it may be possible for an

IM avionics algorithm to infer a weight for the aircraft and hence some measure of performance. Furthermore, target-aircraft, past-state information (speed, rate of climb etc...) might be used to estimate future climb performance. Experiments could be set up to see how well algorithms could infer climb profiles, first in simulation, and then perhaps using actual aircraft departure track information. The proposed IM algorithms could then simulate aircraft flight on IM climb profiles behind actual track data. NOAA RUC/RAP data corresponding to the day of the actual operations could be used to correctly replicate the original ambient conditions.

8.4.3 Wake Vortex Spacing Reduction

From the authors' perspective, the wake vortex concept details could be developed further and tested in simulation to assess the difficulty of implementation. This should be performed first with automated, Monte-Carlo type simulations, followed by HITL (Human in the Loop) simulation to assess human factors issues.

The concept sketches out an implicit methodology where the individual aircraft aerodynamics might be employed to estimate the minimum spacing, in real time. This idea is definitely intriguing, and is worthy of future examination.

The analysis of this concept, as performed in this document, has made some very simplifying assumptions about the concept behavior, and how it is utilized in conjunction with IM. For instance, it is assumed that IM offers a benefit when spacing needs to be adjusted due to varying weather conditions. Perhaps it would, but it would be at best ancillary to the real benefit mechanism, namely the spacing reduction. The concept really is about wake prediction, not IM. The presumption is that IM might be able to space the aircraft with greater precision (probably true), but the real benefit comes from the reduction of the wake vortex spacing, which is not IM dependent.

To pursue research on this concept, it would be best to first study the real-time spacing reduction concept, itself. This could be done in simulation of aircraft arriving at a single runway, and exposed to real-world weather conditions (e.g. using NOAA's RAP (RAPid Refresh) data for prediction of atmospheric conditions). The simulation could provide a truth-estimate of the wake vortex strength based on aircraft configuration and weight. This would provide a truth estimate of the actual required spacing. Then, either a simulated ground system, or simulated avionics could estimate wake strength based on the incomplete data likely to be available to aircraft/controllers in the real world. Once simulation is able to properly characterize the dynamics of this problem, IM simulations might be in order.

To perform the simulations including IM, IM aircraft would space off the target aircraft based on the estimated minimum safe spacing. As the spacing estimates vary, it could be tested if IM based spacing offers benefits over traditional spacing. Elements of the concept that need further consideration include the freeze horizon, which should be tested with different values, if it is needed at all. Also, emergency scenarios need to be tested, such as if an estimated spacing value is too small and an aircraft must perform a missed approach.

8.4.4 Aircraft Equipage

The problem of aircraft equipage is two-fold. First, is the pervasive mixed-equipage problem. Not all aircraft will equip and procedures must be designed to accommodate these aircraft. The other problem is how best to leverage existing flight-deck equipage to provide as much advanced IM capability as possible.

Due to the extreme expense of modifying an existing FMS, an important area of research will be to determine how best to use the FMS (all of its existing features and input/outputs), without actually changing it. It is unlikely that the FMS can or will be changed to accommodate IM procedures in a retrofit environment. Therefore, other avionics boxes, such as the EFB, or the TCAS computer, or other new LRU (Line Replaceable Unit), will have to be used. The main trick will be to make the most of the FMS trajectory prediction capability while at the same time, 1) not interfering with the FMS's primary job of guiding the autopilot, and 2) not increasing pilot workload. Developing an integrated concept for smooth IM avionics interaction with the existing flight decks is a persistent challenge.

8.5 Final Remarks

This effort accomplishes the initial evaluation of three IM concepts including IM for Dependent Parallel Arrivals, IM for Departure Operations, and IM for Wake Mitigation. Evaluations included: 1) summarizing and further defining theory of operation for each concept, 2) developing and applying first-principles analysis techniques to estimate the maximum benefit of each concept, 3) developing and applying operational data techniques to estimate the frequency of application of each concept, and 4) extending the methods to estimate the benefits at major airports and metroplexes across the NAS. The results indicate that all three concepts could benefit numerous airports and metroplexes to varying degrees across the NAS.

The evaluations also included detailed assessment and identification of the impediments and limitations to implementing the IM concepts in general each of the IM concepts individually. The impediments and limitations identified are technical requirements that require further evaluation and refinement, and subsequent research and development to fulfill, thus represent significant opportunity for future work towards implementing these concepts.

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This document is the final report for the NASA Langley Research Center (LaRC)-sponsored task order "Possible Benefits for Advanced Interval Management Operations." Under this research project, Architecture Technology Corporation (subcontractor to Saab Sensis Corporation) performed an analysis to determine the maximum potential benefit to be gained if specific Advanced Interval Management (AIM) operations were implemented in the National Airspace System (NAS). The motivation for this research is to guide NASA decision-making on which Interval Management (IM) applications offer the most potential benefit and warrant further research.

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