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NOTE TO THE FINAL REPORT UPDATE

This final report update is based on the final report for the Option Year 1, submitted to NASA on July 29, 2012. In addition, this update includes 1) a new chapter, Chapter 19, documenting all research activities conducted during the three-month extension between July 30 and October 29, 2012, and 2) a modified Chapter 20, Conclusion, to address additional research efforts conducted during the extension period.

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1 Introduction

NASA has been conducting Concept & Technology (C&T) research to enable capacity, efficiency, and safety improvements under the Airspace Systems Program, Aeronautics Research Mission Directorate (ARMD). These C&Ts provide various benefits (e.g., improved airport departure/arrival throughputs, fuel saving, and taxi efficiency) with costs and benefits apportioned among various Air Traffic Management (ATM) system stakeholders (e.g., FAA, aircraft operators, or public).

1.1 Description of Analysis

Saab Sensis has been awarded a two-year contract by NASA Langley Research Center, Task Order NNL10AB83T under Blanket Ordering Agreement NNL08AA17B, to conduct C&T assessment, evaluation, integration, and benefit analysis to support NASA in understanding the potential impacts of the NASA C&Ts. This report addresses the efforts made in the second year of the contract.

In the second year, the Saab Sensis team performed concept evaluation for an additional concept, Controller Managed Spacing (CMS), in addition to the three concepts evaluated in the base year: Efficient Descent Advisor (EDA), Terminal Area Precision Scheduling System (TAPSS), which includes Terminal Metering (TM) and , and Flight-based Interval Management (FIM). TM is the main feature of TAPSS that is assessed in our analysis.To complement the evaluation and analysis of the four individual concepts listed above, the central effort in the second year was to perform benefit and cost analyses of the integrated concepts and assess the incremental benefits for different concept migration paths to an integrated concept. Benefits for three concept migration paths are assessed in this report:

Migration Path 1

- Traffic Management Advisor (baseline)
- TMA + TM + CMS
- TMA + TM + CMS + FIM

Migration Path 2

- TMA (baseline)
- TMA + EDA
- TMA + EDA + TM + FIM

Migration Path 3

- TMA (baseline)
- TMA + EDA
- TMA + EDA + TM + CMS
- TMA + EDA + TM + CMS + FIM

Two types of benefits for the concepts and for migration paths for the concepts are evaluated in this report: benefits of time savings and benefits of fuel savings from flying Optimal Profile Descents (OPD). The benefits of time savings include operating costs and value of passenger time; the benefits from flying OPDs are the value of fuel saved. The operation cost savings from

time savings includes fuel reduction from the lower flight time; the OPD benefit include fuel savings from flying more fuel efficient arrival routes.

1.2 Description of Evaluation Approach

Section 1.2 summarizes the approach to estimate the benefits and the costs. The sections that cover the various topics in the analysis are also indicated.

1.2.1 Approach to Estimate Time Savings Benefits

The steps for estimating the time savings benefits are:

1) Describe the concepts and define their benefit creating mechanisms. This is covered in Sections 2 through 5 for EDA, CMS, TM, and FIM, respectively.
2) Estimate the key change in performance resulting from EDA, CMS, TM, and FIM. This key performance change is in the conformance of aircraft to meet scheduled times of arrival at the meter fix and/or runway threshold scheduling points got EDA, CMS, and FIM. For TM (or TAPSS) the key performance change is in throughput. These changes in conformance and throughput enable the time savings benefits. Section 6 describes how previous studies were used to estimate the performance changes for the four concepts.
3) Adapt airports for simulation analysis for time savings benefits. This adaption of the analysis airports consists of assembling such airport-specific data as arrival configuration, meter fixes, terminal merge points, traffic composition by weight class at each meter fix, time-to-fly between meter fixes, merge points, and runway ends by aircraft type. Then the airports are ready for simulation analysis to estimate the time savings from the concepts. Section 7 describes the airport-specific adaptations.
4) Before conducting the simulations to determine delay time savings at each airport, we need to investigate such simulation parameters as demand sets, flight schedules, controller intervention rates, and mixed equipage where some of the aircraft are FIM equipped while the rest use CMS. Section 8 discusses these issues.
5) Simulations were conducted for each of the 16 ASDE-X airports to determine the increase and throughput and delay reduction. The delay reductions provide the time savings benefits at each airport. Section 9 explains these airport-specific simulations that provide the average per flight delay at each airport under the different concept configurations.
6) In order to determine the national benefits, the delay savings results from 16 ASDE-X airports are extrapolated to other TMA airports. In addition, delay savings simulations results for single day are expanded to annual delay savings. Section 10 presents this analysis.
7) Once the delay time savings for the TMA airports are determined, calculations are made to account for total flight time savings for each future year, adjustments for ground and airborne equipment implementation schedules, and monetary values of time savings. Section 11 explains these calculations.
8) The monetary time savings benefits are presented in Section 14.

1.2.2 Approach to Estimate OPD Fuel Savings

The fuel savings for aircraft flying OPDs are estimated separately from the time savings benefits.

1) The results of a previous study on OPD benefits, John E. Robinson III and Maryam Kamgarpour, "Benefits of Continuous Descent Operations in High-Density Terminal Airspace Under Scheduling Constraints," NASA Ames Research Center, estimated the maximum potential per aircraft average fuel savings from flying OPD arrival trajectories at 14 of the airports we are studying. This step, as well as Steps 2 and 3 below, is explained in Section 12.
2) Maximum potential per aircraft average OPD fuel savings were estimated for the remaining TMA airports using the results of this study and three other studies.
3) The percent of the maximum per aircraft average fuel savings obtainable by the sets of concepts was estimated using the controller intervention rate analysis from Step 4 above (explained in Section 8).
4) The monetary OPD fuel savings are presented in Section 14.

1.2.3 Approach to Estimate Concept Costs

The costs for EDA, CMS, TM, and FIM are estimated using standard FAA Work Breakdown Structure (WBS) categories. The costs were estimated from information gathered from NASA concept researchers and from similar cost analysis performed for the FAA. The costs estimation approaches for EDA, integrated TM and CMS, standalone TM, and FIM are presented in Sections 15, 16, 17, and 18, respectively.

1.3 Benefit and Cost Results

The combined benefit and cost results are presented in Section 18 for the three concept migration paths assessed. Section 19 covers some work to still be conducted, and the last section, Section 20, lists references. The Appendix includes the airport adaptation and simulation results for all airports.

2 Efficient Descent Advisor (EDA) Concept Description

Sections 2 through 5 introduce the four concepts evaluated (i.e., EDA, CMS, TM, and FIM) and review some literature and developments involving the concepts.

EDA is a decision-support tool that computes advisories to enable OPDs to the runway without the loss of the throughput normally associated with OPDs. EDA can tailor arrival solutions to accommodate individual aircraft performance, atmospheric conditions, and operational restrictions in congested airspace environments [C07]. EDA is a research component of the CTAS that works in conjunction with the CTAS TMA to provide controllers with combinations of speed, altitude and path-stretching advisories [C07]. EDA advisories help deliver aircraft to an arrival-metering fix in conformance with a scheduled time-of-arrival constraint, while preventing separation conflicts with other aircraft along the arrival trajectory [C04].

2.1 Assumptions

EDA assumes all aircraft are equipped with a flight management system (FMS). It works with existing voice communication, but its capability and usability should be significantly enhanced for Data Comm enabled aircraft. EDA is intended for the ARTCC sector controller working at the Radar position (i.e. “R side”) [C04].

EDA requires atmospheric input data (e.g., forecasted wind speed, wind direction, temperature, and pressure).

2.2 Concept Equipage

EDA is adaptable to the current ATM/ATC environment.

2.3 Experiments and Related Research

The 3D PAM project is a multiyear project, originally conceived by Boeing and, through collaboration with the FAA, NASA, and Saab Sensis, continues to evolve [S08]. The 3D PAM project involves ground automation in the form of the EDA. While the overall 3D path concept can be extended to include both terminal and en route airspace and can utilize either voice or – Data Comm for air/ground communications, the scope of the current 3D PAM project is targeting the en route airspace and a voice communication environment [S08]. The 3D PAM concept is based on the utilization of existing FMS capabilities, namely the RNAV with low levels of RNP and Vertical Navigation (VNAV); and the utilization of advanced ground automation support through the use of existing TMA and EDA automation tools [S08].

Under the 3D PAM project, EDA HITL simulations began in April 2009 and were scheduled to continue through June 2011. After the HITL simulations, EDA will be tested in the field in front of sector controllers for real-time, operational decision support. The field test was scheduled for the fall of 2011, and will include commercial (United and Continental) flights into Denver.

In 2006, Landrum & Brown Worldwide Services, Inc. performed a NAS-wide potential benefits assessment of EDA. Potential benefits were estimated for the year 2005 based on simulation results from July 2004. The July 2004 simulation environment emulated a simplified version of the Dallas (ZFW) northeast arrival corridor, with emphasis on the high and a low ZFW arrival

sectors, Sectors 42 and 37 respectively. The July 2004 simulations focused on evaluating EDA performance metrics, such as meet-time performance, workload measures, and fuel utilization. Researchers compared meet-time performance of a TMA only operating environment versus TMA with EDA, and showed that EDA delivers aircraft to the meter fix with less variability than TMA without EDA (See Table 1). EDA also exhibited a significant reduction in the total number of controller-to-pilot communications necessary to deliver the aircraft to the meter fix (See Table 2). Lastly, it was estimated that EDA provided 7% - 10% fuel savings from the time the aircraft entered the high sector to the time it arrived at the meter fix (approximately 130 miles). The fuel savings estimate was derived from a sample set of 12 MD80 aircraft.

Table 1: Meet-Time Performance Results [S04]

Operating Environment	Maximum Early Deviation (sec)	Maximum Late Deviation* (sec)	Standard Deviation (sec)	Mean* (sec)
TMA Only	57	-35	24	8
EDA w/250	24	-38	12	-11

* Negative numbers refers to late arrival

Table 2: Controller Workload Measurements [S04]

Operating Environment	Average # of Communications Per Aircraft	Standard Deviation
TMA Only	9.9	1.8
EDA w/250	5.8	1.0

The Landrum & Brown Worldwide Services, Inc., EDA benefits assessment identified three potential benefit mechanisms [W06]:

1. Predictive capabilities of EDA, which allow for better distribution of workload between downstream and upstream sectors, as well as fewer clearance instructions.
    - EDA is expected to facilitate the early detection and resolution of metering-related problems, which could lead to a more equitable distribution of controller workload between upstream and downstream sectors.
    - Difficult to convert this benefit to a dollar value
2. Minimum-fuel trajectory planning algorithms
    - EDA is expected to improve fuel efficiency since controllers can issue strategic, more fuel efficient maneuver advisories, and delay can be shifted from the TRACON to Center airspace where aircraft are at higher altitudes.
    - These benefits (i.e., reduced fuel burn) will only occur during “at capacity” periods. Benefits are proportional to the number of operations during periods where demand exceeds airport capacity. If demand never exceeds capacity at a

particular airport, or if this does not occur often, then the potential EDA benefits at that airport will be limited.

3. Accurate TRACON delivery in accordance with a TMA plan that is optimized for maximum throughput to the runway.
    - EDA is expected to improve the meter fix meet-time accuracy, which could lead to reduced meter fix separation buffers (buffer = in excess of minimums).
    - If EDA was combined with a DST that provided sequencing and spacing to the final approach fix or runway threshold (i.e., TAPSS), then improved runway meet-time accuracy could lead to reduced runway threshold separation buffers.
    - Reduced runway threshold separation buffers could lead to increased airport throughput.
    - These benefits (i.e., reduced excess inter-arrival separation and increased throughput) will only occur during "at capacity" periods. Benefits are proportional to the number of operations during periods where demand exceeds airport capacity. If demand never exceeds capacity at a particular airport, or if this does not occur often, then the potential EDA benefits at that airport will be limited.

The Landrum & Brown Worldwide Services, Inc. EDA benefits study evaluated only the second and third potential benefit mechanisms. The methodology and results of these evaluations are briefly described below.

EDA Capacity Benefits Assessment [W06]:

- Project constraints: quick simulation turnaround
- Assumptions: combined effect of DSTs (TMA+EDA+aFAST) can always bring arriving aircraft to the runway at a desired inter-arrival distance.
- Simulation was designed to bring successive aircraft to a metering fix with a given inter-arrival separation distribution, then to bring successive aircraft to a desired runway with a given inter-arrival separation distance distribution. It simulated EDA performance for all arrival flights at an airport during a period of time.
- Methodology:
    1. Ran baseline simulation to let the aircraft arrive at the metering fixes at their observed times, and matched their inter-arrival distance distribution to the best observed mean and standard deviation.
    2. Simulated EDA scenarios by controlling the inter-arrival separation distribution at the metering fixes and at the runway thresholds. Ran each simulation 50 times with different randomly generated standard normal distribution for the inter-arrival distance distributions to match.
    3. After running the simulations, compared the landing times of each aircraft and the differences averaged to assess the time savings per operation.
    4. Converted time savings per operation into economic benefits using the direct operating cost rate developed by the FAA for investment and regulatory programs.

- Results:
    - When EDA's accurate TRACON meet-time performance can result in reduced inter-arrival distance at the runway threshold and there is a DST that works with EDA to take advantage of the opportunity, there will be EDA capacity benefits.
    - By assuming that the combined effect of EDA and an additional DST can reduce the inter-arrival distance at the runway threshold so that the observed proportion below the wake turbulence standard is matched and the standard deviation is reduced by half, the EDA capacity benefits is about $28 million for the whole NAS in the year 2005.
    - These estimates are conservative and assumed that many of the airports considered have little potential EDA benefits.

EDA Fuel Savings Benefits Assessment [W06]:

- Assumptions: all arrival flights during the "at capacity" period have the potential of fuel burn savings, specifically those that are MD-80s can save 140 lbs to 200 lbs of fuel when EDA is in operation.
- Fuel savings of other aircraft types were estimated using the Fuel Scale Factor (FSF), where high-fidelity aircraft performance simulations were conducted to determine accurate fuel burn values for both MD-80s and B-747s during descents.
- The Fuel Scale Factors (FSF) for a number of different aircraft types were calculated based on Eurocontrol's Base of Aircraft Data (BADA) aircraft models.
- The fuel savings were then converted into dollar amounts using jet fuel price index.
- Results:
    - EDA's annual fuel savings potential is between $97 million to $138 million dollars in 2005 dollars.
    - The biggest uncertainty of this result is the percentage of operations expected to have EDA fuel savings potential.

In collaboration with the FAA and United Airlines, Oceanic Tailored Arrivals (OTA) trials with a prototype EDA decision-support tool were conducted in January 2007 for a single United Airlines Boeing 777 flight in commercial service between Honolulu and San Francisco (SFO) [C07]. Results from these field trials suggests Boeing 777 fuel savings of approximately 200 to 3,000 lbs per flight – depending highly upon baseline traffic conditions (See Table 1)– together with a corresponding reduction in CO2 emissions of approximately 700 to 10,000 lbs per flight (See Table 2) [C07].

Table 3: SFO Field Trial Results - Fuel Burn

Baseline Traffic Congestion	**Average Fuel Savings (lbs)**
Light	234

Medium	365
Heavy	3221

Table 4: SFO Field Trial Results - Emissions

Baseline Traffic Congestion	**Average CO_2 Savings (lbs)**
Light	738
Medium	1,151
Heavy	10,144

EDA is tied to RNP and 3D path concepts. The 3D Path concept requires ATM automation technology enablers (e.g., EDA) and communication, navigation, surveillance (CNS) automation technology enablers (e.g., voice and Data Comm communication, RNP capability, and automatic dependent surveillance).

Boeing performed a benefits assessment which focused on assessing the potential NAS-wide benefits of RNP and the 3D path concept [H06]. According to this assessment, RNP provides increased arrival and departure throughput in all weather conditions. The 3D path concept, in combination with the necessary ground-based (e.g., EDA and TMA) automation equipment, provides further increases in arrival throughput. The estimated airport capacity benefits of RNP, represented as an average across all 35 Benchmark airports, is an increase of almost 9% in VMC and MVMC and an increase of 4% in IMC. The estimated airport capacity benefits of RNP combined with 3D paths, represented as an average across all 35 Benchmark airports, is an increase of almost 16% in VMC and MVMC and an increase of 7% in IMC. The sector capacity benefits of RNP are estimated to be between 25% and 60%–depending on the type of sector (i.e., arrival, departure, transitional, and ultra high sectors). The sector capacity benefits of RNP combined with 3D paths are estimated to be between 60% and 100%.

The 3D path concept is technically feasible for implementation in the 2008-2012 timeframe [H06]. The 3D path concept requires RNP approach procedures to be defined in US and European operations (i.e., published approach transition procedures would need to be available in both aircraft and ground system navigation databases) [H06]

Boeing also studied the benefits of RNP and the 3D path concept and its potential application to an airport and airspace area such as Houston [S06]. According to their analysis, airspace redesign and the use of 3D paths suggest capacity benefits on the order of an additional 58 flights per hour, and fuel savings on the order of 500 lbs.

2.4 EDA Benefit Creating Mechanism

The benefit creating mechanism for EDA as used in our study is shown in Figure 1.

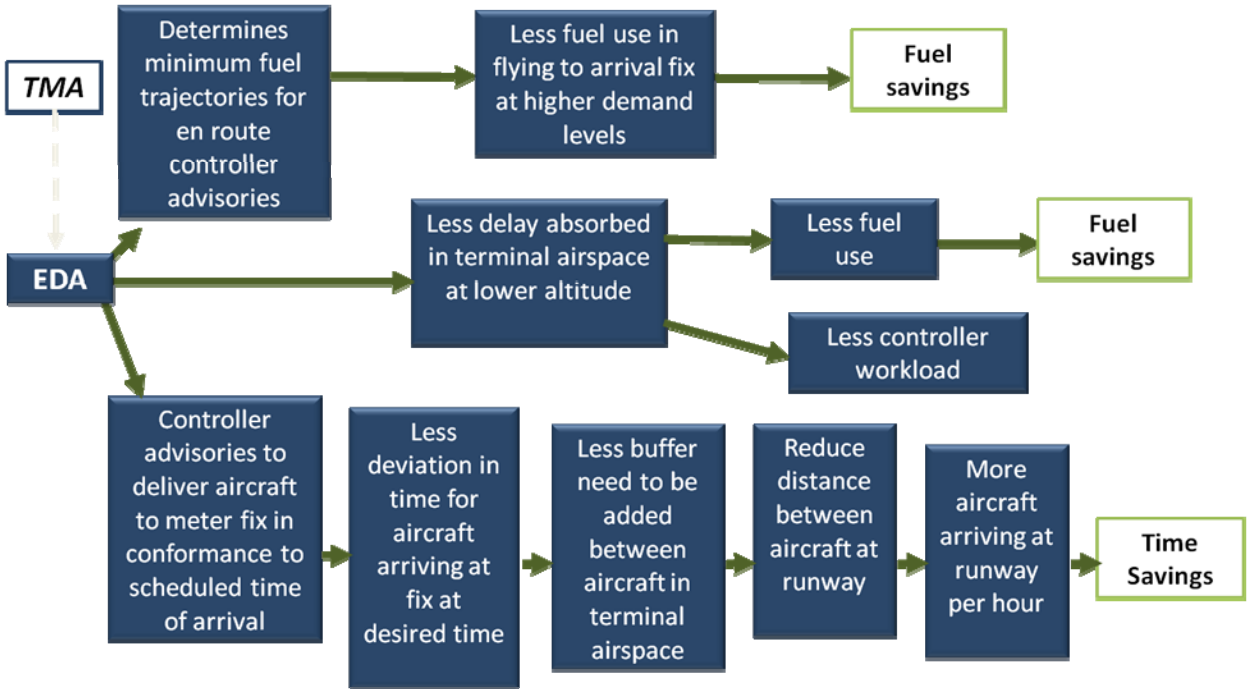


Figure 1: EDA Benefit Creating Mechanism

For EDA, the EDA benefit creating mechanism offers two functions:

- Determines minimum fuel trajectories that are provided as advisories for the en route controller
- Controller advisories to deliver aircraft to meter fix in conformance to scheduled time of arrival.

The first function will lead to less fuel use in flying to arrival fix during higher demand levels and result in fuel savings compared with procedures without EDA.

The second function will provide for aircraft to arrive at the meter fix with less deviation from desired time at the meter fix. The system can then support more flights in a time period because less buffer is needed between aircraft in terminal airspace. The distance between aircraft at runway can then be reduced and allow more aircraft arriving at runway per hour. As a result, this functionality offers time saving, or throughput improvement, that can be revealed on the runway.

3 Controller Managed Spacing (CMS) Concept Description

Controller Managed Spacing (CMS) is a collection of decision support tools for ground-based controller management of arrival aircraft terminal airspace trajectories from the meter fix to meet scheduled times of arrival at the runway threshold. It uses accurate predictions of future aircraft position to provide controllers with traffic schedule and aircraft speed advisories to meet inter-flight spacing requirements and aircraft scheduled times of arrival to the runway threshold. With CMS, the controller issues advisories via voice or data communication. This tool is similar to Flight Interval Management (FIM) in that it assists with spacing between aircraft; but unlike FIM, which is an airborne-based spacing tool, CMS is a ground-based tool.

The CMS tools are similar to the Final Approach Spacing Tool (FAST). FAST was a Center/TRACON Automation System decision support tool for terminal area air traffic controllers. It used trajectory predictions to compute and display heading and speed advisories to allow for sequencing and spacing of arrival aircraft to their assigned runways. However, these tools were too complex for controllers to use, so CMS tried to overcome this difficulty through the application of Required Navigation Performance (RNP) procedures and improved decision support to achieve its goals.

CMS tools assume that the aircraft are flying Optimal Profile Descent (OPD) vertical profiles along Area Navigation (RNAV) routes and will be delivered to the meter fix with relatively good spacing. For example, one study assumed en route facilities delivered aircraft to the Los Angeles International Airport (LAX) terminal-area entry fixes with nominal runway-schedule errors no greater than 60 seconds early or 30 seconds late. Another study assumed aircraft were delivered to entry fixes with no more than ±40 seconds nominal spacing error from schedule. CMS permits trajectory management only via speed control in order to minimize deviations from the RNAV OPD arrival routes' lateral paths and vertical profiles.

The three main CMS support tools under development are: 1) Timelines, 2) Slot Markers, and 3) Speed Advisories. The functionalities of these three components described as follows:

1) Timelines

Timelines provide a graphical representation of an aircraft's estimated time-of-arrival (ETA) relative to its scheduled time-of-arrival (STA) for a given waypoint. This tool allows the controller to verify quickly whether an aircraft is flying on schedule and, if not, whether the aircraft's ETA is behind or ahead of its STA, along with the difference in time between them. This information in turn aids the controller in formulating any necessary changes for the aircraft to meet its schedule.

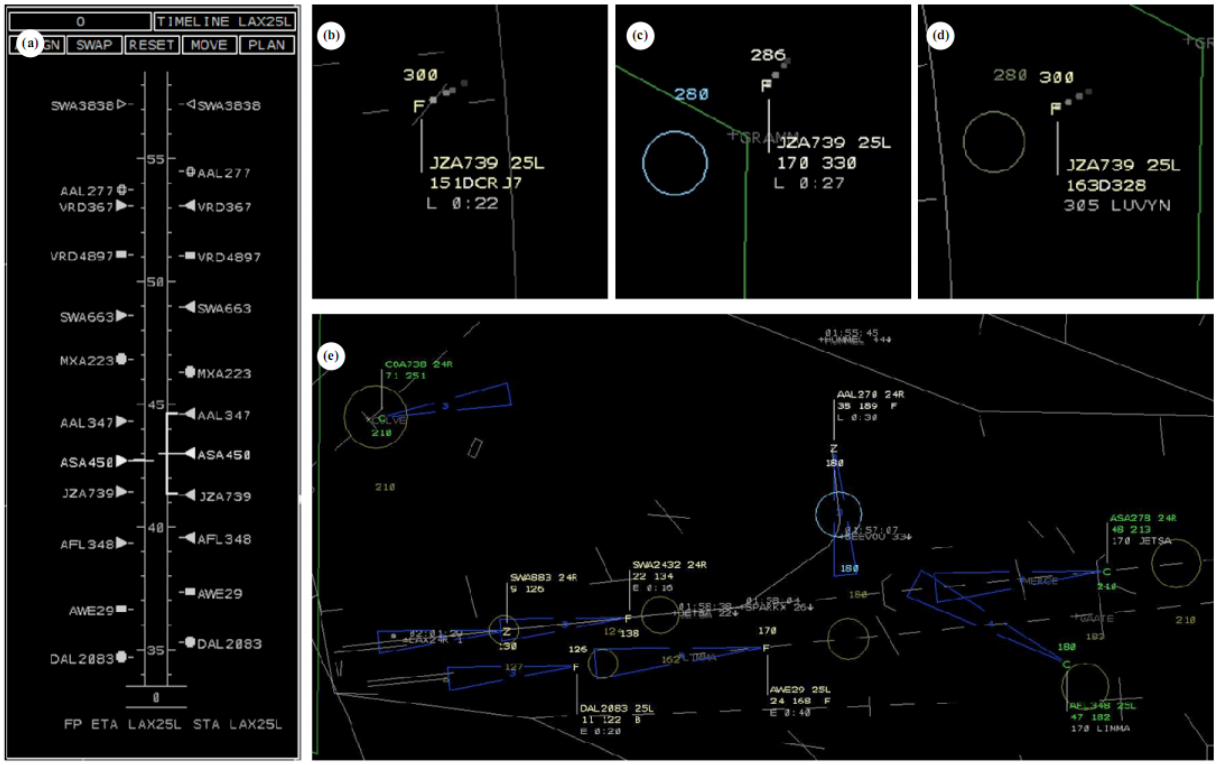
2) Slot Markers

Slot markers are circles that present time-based schedule information spatially on the traffic display. The center of the circles shows the controller where the aircraft will be if it flies the nominal RNAV route through forecast wind conditions and adheres to all known restrictions. The slot markers inform the controller how far the aircraft is from its desired position. The controller uses this information to adjust the aircraft's path to ensure it arrives on schedule.

3) Speed Advisories

Speed advisories generated by CMS calculate the speed required to be flown by the aircraft to meet its schedule. This calculated speed is displayed to the controller. The display of this requisite speed aids the controller in formulating speed clearances that will keep the aircraft on schedule.

Additional CMS support tools were evaluated using information gathered in a human-in-the-loop (HITL) simulation conducted in 2010 at NASA Ames. These tools included aircraft ETA early/late advisories, spacing cones which indicate minimum inter-flight distance spacing as per minimum separation, J rings, spacing ('splat') tool, route display, ground speed in flight data block, and IAS indicator of aircraft target.



In clockwise order, from left: (a) timeline incl. a spacing bracket, (b) FDB in timeline condition, (c) dwelled FDB and slot marker in slot marker condition, (d) FDB and slot marker in advisory condition, (e) spacing cones and route display.

Figure 2: Different Controller Managed Spacing tool displays including Timeline, Early/Late Indicator, Slot Marker, Speed Advisory, and Spacing Cones

Controllers are supposed to use these tools to help assess conformance with runway schedules, manage the spacing of scheduled arrival aircraft flying OPDs, and cope with disturbances, without resorting to vectoring strategies typical of current terminal-area control practices (see Figure 2).

CMS works with existing voice communication but will presumably evolve when Data Comm becomes the predominate means of communication. In the current implementation, CMS utilizes the established air traffic control paradigm of voice and radio-based arrival clearances. However, having Data Comm would allow more flexible path changes whenever the route conformance cannot be achieved with speeds alone. Without Data Comm, the reroutes would need to be pre-defined along named waypoints. Also, Data Comm can help reduce controller workload by

allowing controllers to obtain information directly from the aircraft instead of having to relay information via voice communications.

The main benefit of CMS is that it enables the reduction of spacing buffers compared to conditions without CMS tools, thereby allowing higher throughput and tighter schedules. The spacing conformance at the final approach fix is improved. Additionally, it also enables the conformance of flights to RNAV/RNP routes which will enable more OPDs. The higher route conformance will reduce uncertainty and improve predictions.

3.1 CMS Benefit Creating Mechanism

The CMS benefit creating mechanism as assessed in our study for the three functionalities of timelines, slot markers, and speed advisories is shown in Figure 3.

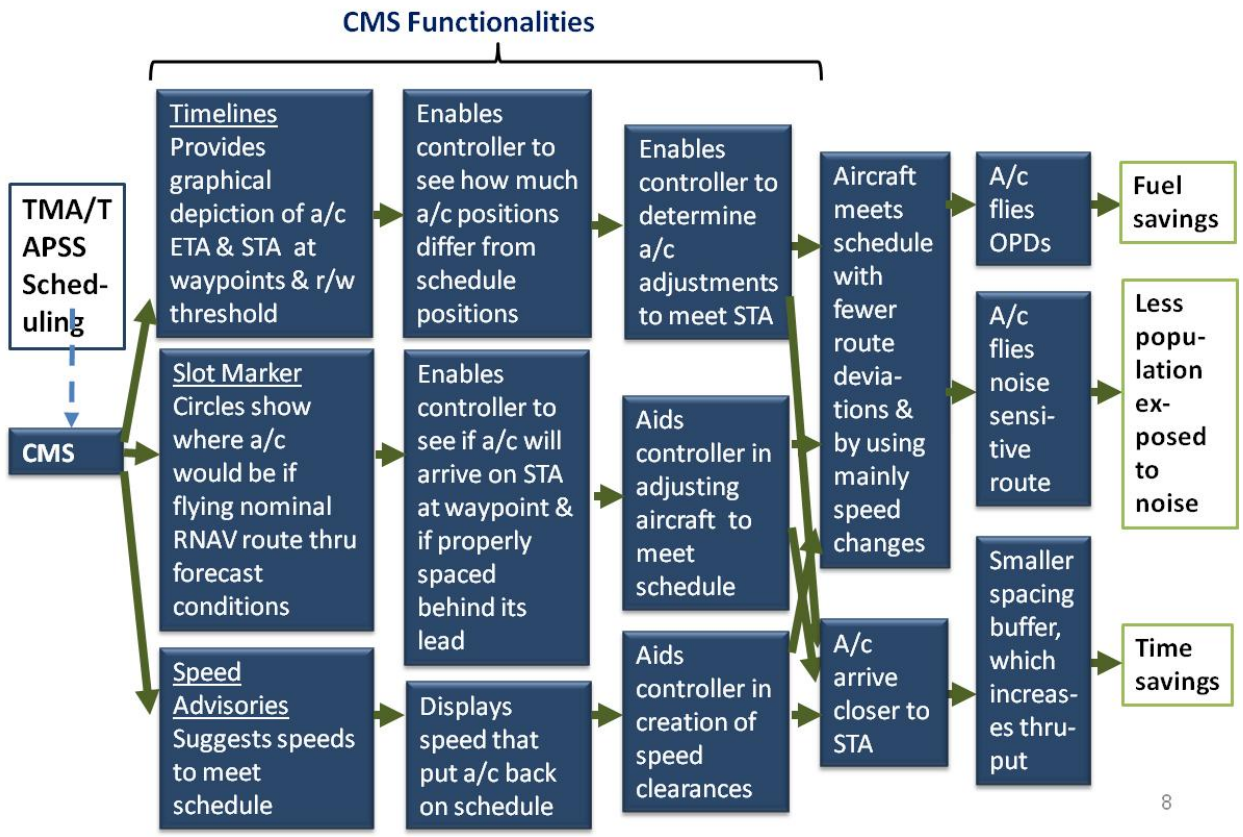


Figure 3: Controller Managed Spacing Benefit Creating Mechanism

The three capabilities (timelines, slot markers, speed advisories) will result in aircraft more likely arriving on schedule at each waypoint and at the runway with the controller generating fewer route deviations and using mainly speed changes. Thus, aircraft will better adhere to OPDs that are fuel efficient and less noise sensitive, resulting in fuel savings and less noise pollution.

These three capabilities will also enable aircraft to arrive closer to their STAs at terminal waypoints and at the runway threshold. This will allow the use of a smaller spacing buffer, which will increase throughput and result in times savings for flights.

3.2 Experiments and Related Research

A 2008 study was performed at NASA Ames using the Atlanta TRACON airspace environment. Slot markers and runway timelines were used by controllers to see if they could reduce controller workload. The results from this study showed that slot markers did not significantly reduce spacing violations and excess spacing. There were no significant differences between the tools and no-tools condition in the runway spacing. However, the CMS tools are necessary since they allow controllers to achieve RNAV OPDs by having better route conformance and tighter runway spacing. Without the tools, controllers can only achieve one or the other, which limits the overall throughput.

A HITL simulation of terminal-area operations was performed in 2010 at NASA Ames with and without advisory tools to determine how well controllers could handle the demand. The experiments were based on LAX airspace, depicted below, with arrivals to LAX 24R, 25L. The experiments evaluated a number of different control variables and conditions, including Tools vs. No Tools (i.e., current-day vs. CMS-based traffic management practices), Forecast Wind Errors (Minus, Plus Bias Conditions), Demand Level (Scenarios A and B), and a Merge Conflict scenario under a fixed 0.5 nmi schedule buffer.

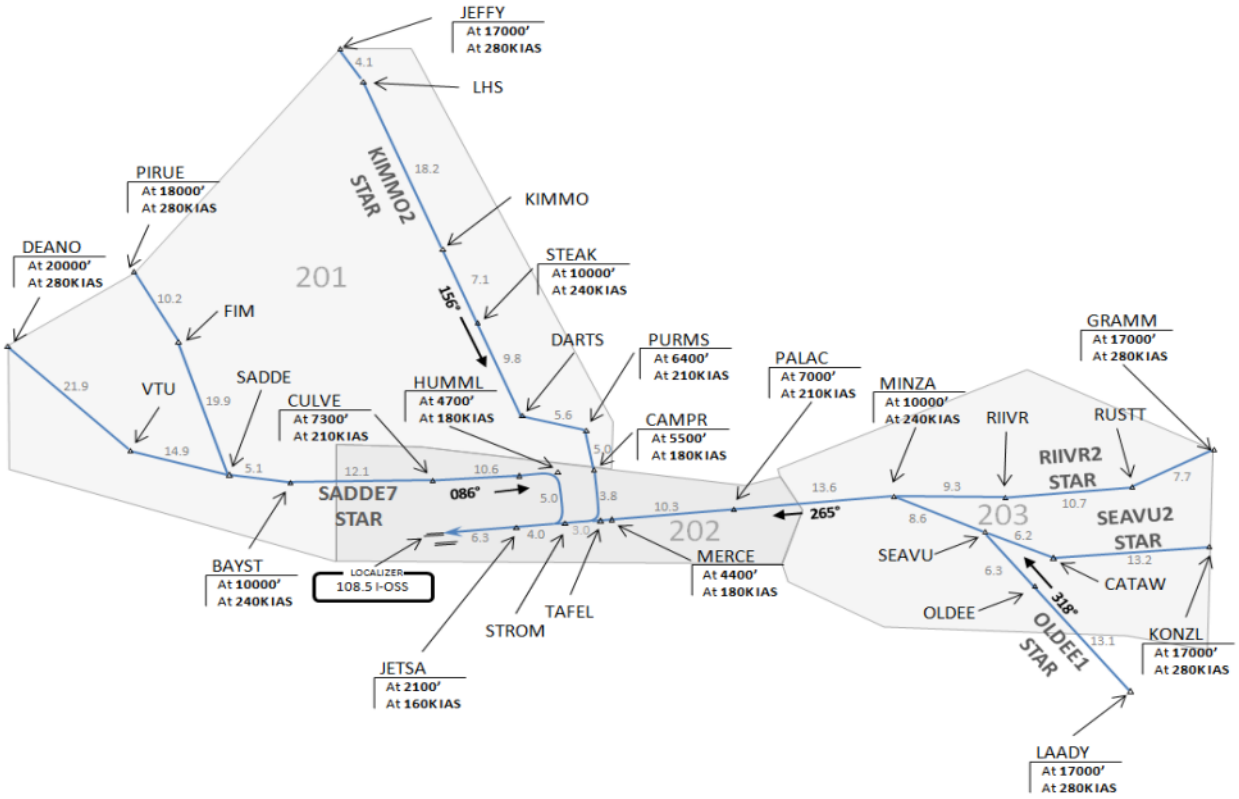


Figure 4: LAX RNAV OPD arrival routes and airspace sectors for CMS HITL simulation-based evaluations.

Off-nominal situations such as ties at merge points were also evaluated. The results of the study showed that controllers were able to keep aircraft on their routes while maintaining similar throughput levels to the no-tools condition, but without the tools there were more route deviations recorded. There was no difference in controller workload in the with-tools case compared to the no-tools case. However, the research hypothesized that the demand levels may

not have been high enough to tax the controllers. These results were conducted as part of research dealing with super-density terminal airspace operations. Additional research needs to be done for this study, since the simulation results may have been biased because of the unexpectedly large ETA-STA difference due to wind forecast errors.

Another follow-up HITL was performed in 2011 at NASA Ames that tested various tools for managing relative spacing (e.g. timeline, slot markers, slot cones, etc.). The tools were tested to see how controllers managed traffic given different forecast wind errors and other disturbances. The results of this study showed that all the tools helped controllers keep aircraft on their routes, mitigate schedule errors, and ensure sufficient wake-vortex spacing between the aircraft. The controllers preferred the slot markers and found the speed advisories to be the least usable of the tools. The main reason why speed advisories were not useful was because they provided the controller with speeds for the aircraft to fly only until the subsequent waypoint. Once the aircraft reached that waypoint, the aircraft resumed the charted speeds and ignored the controllers' speed advisory. This method was counter to the controllers' speed adjustment strategies, which was to mentally average the desired speed change across multiple downstream waypoints. Given these results, the speed advisory algorithm is being changed to match the controllers' strategies.

The study also included human factors to enable further consideration of possible improvements to the tools in future operational implementations.

4 Terminal Metering (TM) and Terminal Area Precision Scheduling System (TAPSS) Concept Description

TAPSS, as shown in Figure 5, is an extension of the Center-TRACON Automation System (CTAS) TMA, and it supports Super Density Operations (SDO).

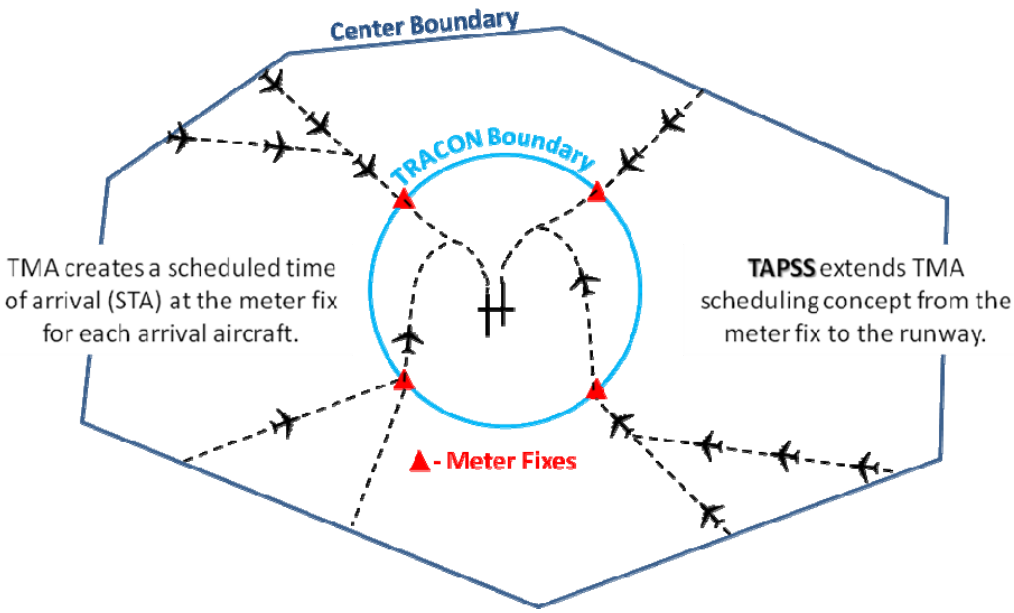


Figure 5: TAPSS Concept Diagram

TAPSS schedules aircraft to both the meter fix and the runway, and creates a schedule that adheres to minimum separation requirements and arrival rate constraints [T10]. Controllers are expected to meet meter fix and runway arrival times produced by the TAPSS scheduler within 30 and 15 seconds respectively, while using speed adjustments as the primary means of control [T10]. The precision scheduling component of TAPSS has a 20 to 60 minute time horizon, and the spacing component has a 2 to 20 minute time horizon.

By applying simple variations in speed from cruise altitude to landing, instead of vectoring in the terminal area, small amounts of delay are distributed over the length of a flight, relieving some of the congestion that builds up near the airport [ASD10]. This leads to a much more efficient flow into busy terminal areas, less fuel burn, and reduced workload for pilots and controllers [ASD10]. Efficient flows in the terminal airspace also provide benefits in terms of reduced noise and emissions. This concept affects airspace utilization and could also have a positive impact on metroplex operations. For example, if metroplex airspace was used more efficiently through TAPSS then metroplex airports could potentially accept higher arrival rates.

4.1 Assumptions

The TAPSS system assumes that flexible but precise routes are defined from the en route airspace, through the terminal airspace, and from the meter fix to the runway. In today's operations, routing between the meter fix and runway is not adhered to precisely. Instead,

controllers and pilots follow general rules and guidelines to conform to a set of altitude and lateral constraints.

The TAPSS system assumes that a number of control points exist between the meter fix and the runway (e.g., meter fix in center airspace, merge or diverge points in the terminal airspace, final approach fix, and runway threshold). The system relies on the knowledge of aircraft intent for accurate trajectory and demand predictions [I10]. Precision scheduling and spacing in the terminal area require surveillance and wind field information to ensure accurate trajectory predictions. Table 5 summarized the assumptions and the capabilities of TAPSS.

Table 5: SDO Concept Assumptions and Functional Capabilities – TAPSS Elements

	Near-Term	**Mid-Term**	**Far-Term**
Assumptions	• Compatible with existing fleet equipage • Mixture of RNAV OPD and step-down arrivals • Departure ops rely primarily on RNAV-based procedures • Current controller and pilot procedures, technologies, capabilities employed • RNP procedures are limited to acute problems of terrain, procedural separation and noise abatement.	• Mixed equipage with increasing numbers of aircraft equipped for RNP, data communication • RNAV/RNP SIDs and STARs with altitude and speed restrictions • Aircraft controlled to meet STAs at runway threshold and key merge points • Controller responsible for aircraft separation • Limited number of aircraft capable of Flight Deck Managed Spacing at controller's discretion • Communication via voice, with limited data	• 3D and/or 4D RNP routes within TRACON • Aircraft controlled to meet STAs at runway, key merge points, and where inter-flow coordination is required • Generation, transmission, and execution of clearances for routine ops largely automated (pilot acceptance required) • Most aircraft capable of Flight Deck Managed Spacing • Routine communication via data, voice as backup
Precision Scheduling Along Routes	• Expanded use of TMA • Modification of TMA for RNAV OPDs and RNP procedures • Timeline-based decision support for pairing very closely-spaced approach operations	• TMA extended to include merge point scheduling • Time advance to close gaps in arrival streams • Partial slot recovery to mitigate arrival variance • Constrained position shifting from FCFS	• Automatic transmission of STAs • Automatic transmission of pairing assignment for very closely-spaced approaches • Automatic rescheduling as needed
Merging and Spacing	• Largely unchanged • Controllers use situational display aids to space aircraft with speed instead of vectors	• Decision support for controller-managed spacing • Delegated spacing at controller's discretion	• Ground-based spacing instruction via data communication • Automatic transmission of delegated spacing assignment

4.2 Concept Equipage

TAPSS is envisioned to be implementable in near-term NextGen timeframe and therefore utilizes much of the current air traffic control paradigm of voice and radio-based arrival clearances [ASD10]. TAPSS can accommodate airborne merging and spacing into its schedule for aircraft with merging and spacing capability. Similarly, TAPSS can accommodate ground systems that enable controllers to issue merging and spacing clearance using ground based automation.

Additional concept equipage information can be found in Table 5 above.

4.3 Modeling and Simulation

Two TAPSS human-in-the-loop (HITL) simulations were conducted this year at NASA Ames to evaluate the performance of SDO technologies (i.e., RNAV/RNP, precision scheduling, and

controller merging and spacing tools). The HITL simulations were focused on the Los Angeles Air Route Traffic Control Center and the Southern California TRACON. The simulation results suggest that precision scheduling and metering, coupled with known terminal routing (i.e., RNP from the center boundary to the runway) and enhanced controller decision support tools, enables ODPs from top of descent to the runway threshold in high density traffic with no loss in throughput. Results also suggest that when separation buffers and delay distributions are properly balanced, controller workload is predictable and balanced between the Center and TRACON controllers.

NASA researchers also studied terminal area arrival traffic scheduling logic and accuracy using a fast-time simulation tool called Stochastic Terminal Area Scheduling Simulation (STASS). The STASS tool was used to evaluate the benefits of improved scheduling accuracy for an arrival traffic rush period at Dallas/Fort-Worth (DFW) airport. In these studies, they compared the performance of four systems designed to provide conflict free trajectories that will meet scheduled arrival times: 1) a completely manual system, 2) a system utilizing Decision Support Tools (DSTs) to assist the controller, 3) a highly automated system, and 4) an ideal system with perfect conformance of flights to scheduled positions [M05]. Results from the STASS simulations suggest that schedule accuracy can have a significant impact on airport efficiency. For delays equivalent to those produced by the manual system under today's demand, the system which utilized DSTs to assist the controller could accommodate a 19% increase in demand; the highly automated system could accommodate a 42% increase in demand; and the system with perfect conformance to an automated schedule could accommodate a 69% increase in demand [M05].

4.4 TAPSS Benefit Creating Mechanism

The benefit creating mechanism used in our study for TAPSS is shown in Figure 6. It starts with TAPSS' main functionality, which is to determine scheduled times of arrival at meter fixes, runway thresholds, and terminal merge points. There are three major outputs of this functionality:

1) Controller advisories provided to deliver aircraft more accurately to meter fixes, thresholds & merge points in conformance to STA,
2) TAPSS advisories designed to produce fuel efficient trajectories, and
3) TAPSS advisories designed for faster TRACON speeds thus reducing terminal area flight time.

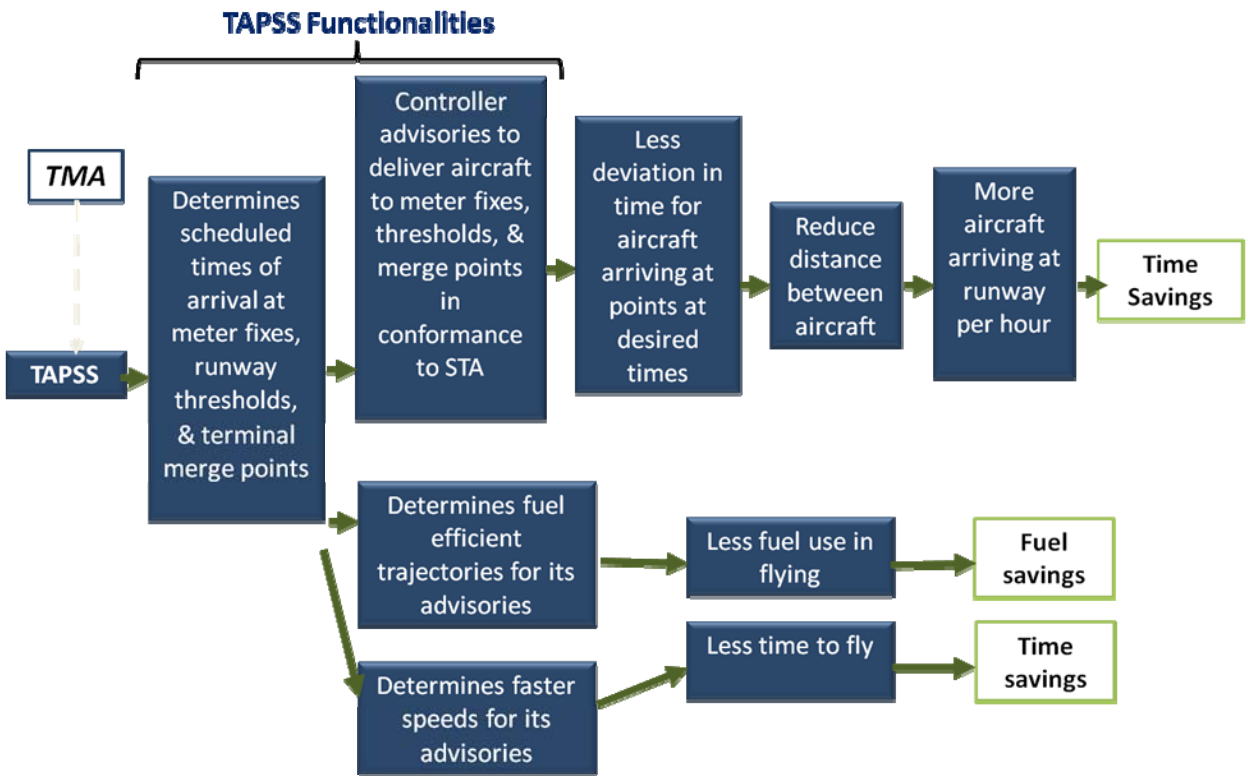


Figure 6: TAPSS Benefit Creating Mechanism

The first function output, controller advisories, is intended to result in less variance in the time for aircraft to arrive at points at desired times and thus enables reducing the distance between aircraft. This in turn enables more aircraft to arrive at a runway per hour. As a result, this functionality produces time savings, or throughput improvement, for aircraft arriving at the runway.

The second function output, fuel efficient trajectories, will achieve fuel savings when flying the arrival trajectory. This fuel efficiency benefit occurs when the demand is near airport capacity and fuel efficient routes cannot be planned without a planning aid (i.e., TAPSS). At lower demands, fuel efficient routes can be planned and flown without a DST. Similarly, the third function output, faster speeds, allows an aircraft to fly faster and reach its final destination quicker for time savings.

5 Flight-deck Interval Management (FIM) Concept Description

The Flight-deck Interval Management (FIM) concept calls for a following, or in-trail, aircraft to achieve and/or maintain precise in-trail spacing, called the Assigned Spacing Goal, with a leading Target Aircraft [FA2012-1]. The concept may be applied to the terminal and en route domains to flights in the arrival, departure, or cruise flight phases. The Assigned Spacing Goal is specified in units of time or distance. Extensive previous research has demonstrated time-based spacing to be superior for terminal airspace arrival aircraft applications [BA2006]. Interval Management may call for achieving the Assigned Spacing Goal at a particular point or for maintaining the assigned spacing goal over a portion of the in-trail aircraft's trajectory. The goal may be short-term or long-term [AB2009]. A short-term goal focuses on meeting immediate spacing needs, such as spacing between an in-trail arrival flight pair as they enter the terminal airspace. A long-term goal focuses on downstream spacing needs, such as the required spacing between two arrival flights at the runway threshold as they enter the terminal airspace.

FIM typically exists in two alternative operational paradigms: Spacing or Delegated Separation [FA2012-1][FAA2012-2]. In the spacing paradigm, the controller delegates, to the in-trail aircraft, the responsibility for precisely maintaining the assigned spacing goal with a specified target aircraft. In the delegated separation paradigm, the controller delegates overall separation responsibility to the in-trail aircraft, including responsibility for maintaining assigned spacing goal with a specified target aircraft. In either paradigm, the controller issues a clearance to the in-trail aircraft which specifies the target aircraft and the required spacing relative to the target aircraft. The in-trail aircraft is responsible for generating and implementing its own speed and, possibly, vector clearances to meet or maintain the assigned spacing goal with the target aircraft.

The FIM concept is a pair-wise spacing operation. With aircraft arriving in sequence to the same runway, the controller can assign each following aircraft in the stream to arrive at the runway threshold at a specific interval, either time or distance, behind an assigned lead aircraft [A09]. Control of the following aircraft's speed is delegated by ATC to the flight crew in order to precisely achieve an assigned inter-aircraft spacing [BAR08]. The FIM concept assumes the flight crew can make minor speed changes computed by onboard software that uses broadcast aircraft state data. By combining airborne spacing with OPDs, the environmental benefits of OPDs can be realized while maintaining or increasing capacity relative to current-day levels [A09].

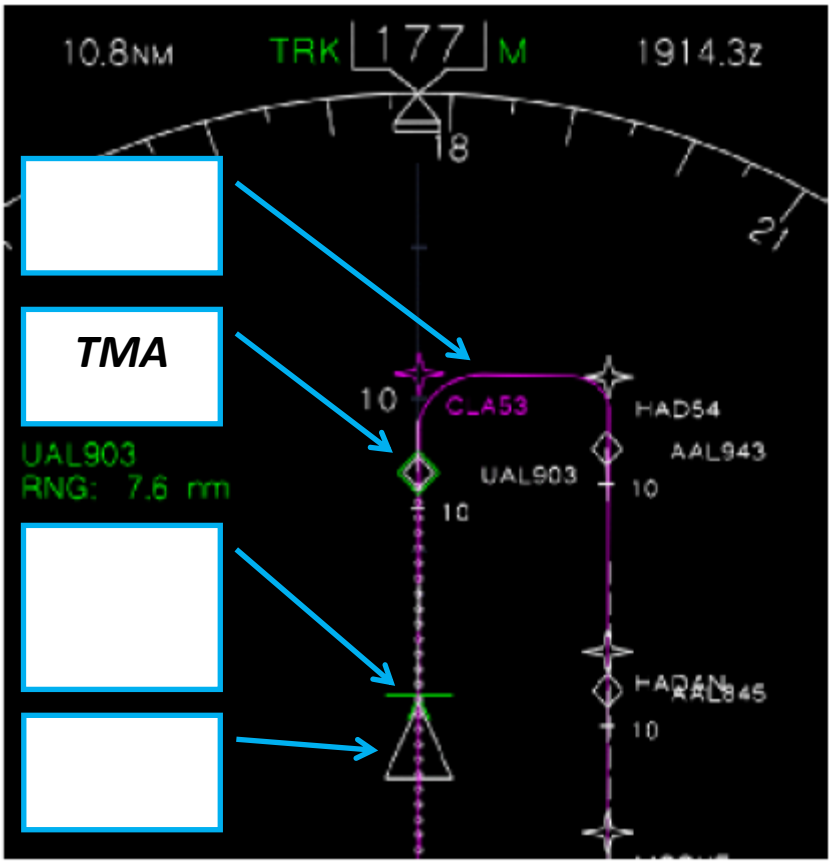


Figure 7: Prototype Navigation Display for Arrival Flight In-Trail Distance Spacing Relative to Target Aircraft along RNAV Arrival Route [LO2006].

The application of FIM to arriving aircraft in the terminal airspace is a particularly challenging application. Complexities include changing flight path geometry, crew interface dependence, premature deceleration of follower aircraft in applications to terminal airspace arrivals, and excessive follower aircraft speeds when lagging the assigned spacing goal [AB2009].

FIM is an instantiation of the Airborne Precision Spacing (APS) concept [BAR2008]. The APS concept is complimentary to the OPD procedural concept. OPDs can reduce fuel consumption, noise, and emissions. However, more airspace is required around an aircraft on an OPD than on a conventional arrival procedure due to less active control of the aircraft spacing by the Terminal controllers during the descents. In turn, the additional spacing decreases the overall capacity of the destination airport [BAR08]. APS supports higher runway throughput when OPD procedures are used by enabling the flight deck to actively manage the spacing during the descents, thereby increasing the throughput.

The benefits of FIM include increased airport and airspace throughput via reduced and more consistent inter-aircraft spacing, and reduced controller workload via elimination of speed and vector clearance formulation and communication to the cockpit to achieve and maintain inter-aircraft spacing [AB2009][BAR2006]. Regarding the former, the flight crew is able to manage their speed more precisely and with a tighter control loop than a controller [BAR2006]. Regarding the latter, each flight crew is responsible for a single spacing interval instead of a single human (i.e., the controller) being responsible for the spacing between several pairs of aircraft [BAR2006]. FIM has been demonstrated to mitigate the airport arrival throughput

detriment characteristic of arrivals conducting OPD procedures [AB2009]. Due to the "hands-off" nature of OPD arrival operations, streams of airport arrivals conducting OPD arrival procedures typically demonstrate greater inter-arrival time spacing than non-OPD arrivals, thereby curtailing airport arrival throughput [BAX2008].

5.1 FIM Benefit Creating Mechanism

The benefit creating mechanism for FIM used in our study is shown in Figure 8. It contains two main functions: 1) maintaining proper spacing between the lead aircraft and following aircraft, and 2) offer longer planning horizon to allow for speed change at higher altitude where there is less fuel consumption.

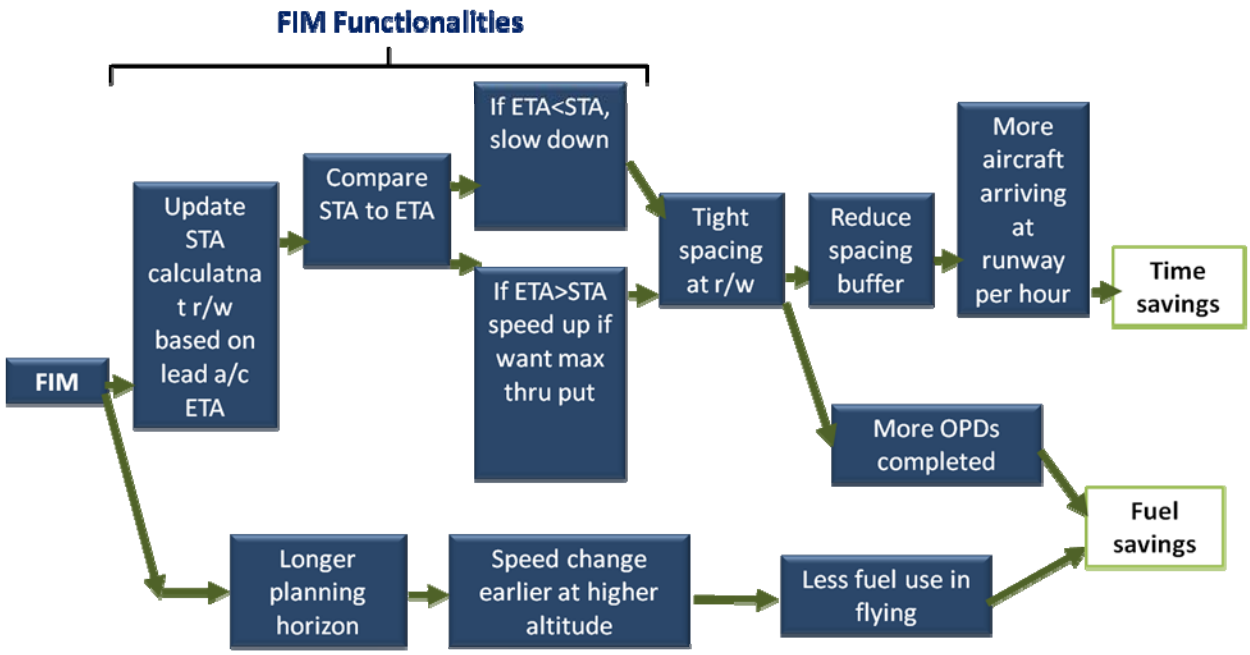


Figure 8: FIM Benefit Creating Mechanism

The first function, maintaining proper spacing between the lead aircraft and the following aircraft, will result in tighter spacing at arrival runway that will in turn reduce the spacing buffer at runway end and allow more aircraft to arrive at runway per hour. As a result, this functionality offers time saving, or throughput improvement, that can be achieved at the runway. In addition, the tighter spacing at runway end means more OPDs can be completed and thus reduce the fuel consumption for flights that are operating OPDs in the terminal airspace.

5.2 Assumptions

FIM assumptions include Automatic Dependent Surveillance – Broadcast (ADS-B), RNAV routes and navigation capability, accurate forecasts of wind data, Data Comm, and crew training. FIM systems require both ADS-B In and Out, and it is expected that the name of each aircraft's arrival route will be broadcast by that aircraft via ADS-B. FIM implementation may be enabled by continuous RNAV arrival paths from en route merge points to the runway threshold with support of self-spacing flight in predicting its target aircraft's trajectory [BA2008]. FIM aircraft prediction of its target aircraft's trajectory relies on forecast winds for accurate time of arrival estimates. The concept assumes that such data will be available, and of sufficient accuracy, to

support accurate estimation. A significant issue facing the deployment of a viable FIM system is the elimination of the effect of wind forecast error [BAR2008]. FIM may work with existing voice communication. However, controller communication of assigned spacing goal and target aircraft clearances, as well as transmission of target aircraft intent data, is greatly enhanced with Data Comm [FAA2008]. The crew of the in-trail aircraft must be appropriately trained to receive and process controller clearances and to determine and/or implement trajectory adjustments to achieve the assigned spacing goal [AB2009].

5.3 Concept Equipage

The concept requires appropriate aircraft capabilities and aircrew training, as well as ground-based automation to support conducting the operations. At minimum, the self-spacing aircraft must have equipage which supports the aircrew in specifying speed advisories to meet Assigned Spacing Goal, which may include Data Comm to obtain the Target Aircraft's trajectory intent information, ADS-B to obtain the Target Aircraft's current state estimate, Cockpit Display of Traffic Information (CDTI) to display the position of the self-spacing aircraft relative to others [MO][SO2000][FAA08], and algorithms to assess relative positioning and compute required speed adjustments [BAR2006] For an initial implementation of this FIM concept, such technology was not planned to be integrated into the existing aircraft systems, especially the autoflight system, but was planned to be an independent add-on implemented in an Electronic Flight Bag (EFB) [AB2009].

FIM operations may supported by additional ground-based equipment to support the controller in specifying FIM clearances and managing FIM operations [AB2009][BAT2000]. In addition, the FIM concept requires ATC ground-based technology capable of providing a reasonably accurate arrival schedule for the landing aircraft [AB2009]. For FIM to be successful, aircraft need to be sequenced and spaced during the en route phase of flight so that they can transition to FIM in an appropriate configuration. The sequencing and spacing during the en route phase needs to be performed by someone who has a global picture of the aircraft and access to flight plans, such as an AOC or ATC [BAR2008]. In October 2006, the UPS AOC in Louisville Kentucky evaluated a sequencing and spacing tool called Airline-Based En route Sequencing and Spacing (ABESS) [MO2006]. ABESS can provide appropriate spacing for the initiation of FIM [MO2006].

5.4 Experiments and Related Research

FIM has been extensively researched over decades to develop flight deck interfaces, decision support tools, and Data Comm technologies to support FIM, concepts of operations to implement FIM, and to apply FIM to OPD operations.

[AB2009] provides a comprehensive summary of the history of FIM applications and key technical issues in FIM development. Significant prior research has served to evaluate position- versus time-interval following; evaluate short-term versus long-term goal paradigms; evaluating applications in en route and terminal domains to arrival and departure aircraft; and to developing human interfaces, identifying appropriate tracking data, and developing control algorithms to support the follower aircraft in meeting its assigned spacing goal with the target aircraft tracking.

[BA2006] provides a comprehensive summary of the history of the NASA-developed Airborne Precision Spacing (APS) concept development for leveraging FIM. It includes a summary of the concept of operations, flight crew procedures, supporting flight deck and ground-based automation. The APS concept calls for the follower aircraft to meet target time spacing with its

runway predecessor at the runway threshold. The Airborne Spacing for Terminal Arrivals (ASTAR) speed control law provides real-time speed advisories to the follower aircraft's auto-throttle system or flight crew based on its predicted difference between its runway ETA and that of its runway predecessor. RNAV arrival routes are a key FIM enabler in supporting the ETA prediction. The target aircraft flight path and final approach speed may be communicated to the follower via ADS-B. Designated follower and runway time spacing clearances are issued by the controller to the follower prior to the metering fix. The leader and follower may be on different flight paths, thus the operation applies to paired aircraft flight phases prior to merging, during merging, and during in-trail flight. Extensive research has gone into demonstrating the concept of operations. The overall spacing performance of APS has been assessed in fast-time and human-in-the-loop simulation experiments and field evaluations, and found to achieve mean time-spacing accuracy within 1 second, with standard deviations of 4-5 seconds. ADS-B reception range does not affect the distribution statistics but may introduce more extreme values. Wind forecasting errors in follower flight ETA prediction can significantly disrupt operations. Air traffic control delivery inaccuracies to STAs (yielding initial spacing errors) do not impact the spacing performance statistics, but do introduce more extreme values. Follower flight knowledge of the Target Aircraft's spacing speed greatly reduces spacing deviation at the runway threshold, and helps to compensate for spacing errors at the final approach fix. Extensive investigation into the stability of long sequences of up to 100 arrival aircraft has demonstrated acceptable schedule deviation and quantity of speed changes, with spacing performance independent of aircraft position in the sequence.

Extensive previous research has been conducted regarding application of FIM to OPD operations. [MU2009] conducts human-in-the-loop simulations of inter-arrival spacing performance of arrivals conducting OPDs under merging conditions at Louisville Standiford Airport (SDF). The study uses high-fidelity aircraft simulators in its evaluations of multiple aircraft in two arrival streams merging to a common runway under nominal and different off-nominal scenarios. Off-nominal scenarios included off-path vectoring and ATC speed intervention. [BAR2008] conducts fast-time simulation-based evaluations of the inter-arrival spacing performance of APS with OPDs under merging conditions at Dallas-Ft. Worth Airport. Aircraft are assigned runway threshold target aircraft and associated spacing goals prior to top of descent, then expected to conduct flight deck merging and spacing during the OPD to the runway threshold. [PE2008] conducts medium fidelity HITL simulations of to assess the impact of flight deck merging and spacing operations on flight crew operations during OPD operations to SDF. [PR2007] conducts HITL simulation-based evaluations of OPDs to SDF to evaluate the impact of flight deck spacing, advanced ATC scheduling and spacing tools, and flight deck-controller Data Comm on controller workload, airport arrival throughput and flight energy management.

[LE2011] presents the Required Interval Management Performance (RIMP) concept to be used in the design, management, and certification of IM operations. RIMP comprises four components: the FIM tolerance, the quality of the FIM and target aircraft state data, the performance of the speed control algorithm in the environment, and unique functional capabilities to specify the aircraft performance required for a given IM operation. [BAX2007] documents the operational concept of Flight Deck Merging and Spacing, including automation requirements, controller roles, flight deck roles and responsibilities, information communicated between the leader aircraft, follower aircraft and controller, and other information critical to conducting the operations. [BO2008] documents pilot and controller tasks, roles, and

responsibilities for flight deck merging and spacing in sufficient detail to allow for the specification of required capabilities to enable the performance of these tasks.

6 Concept Conformance Comparison and Analysis

A key to estimating the benefits for EDA, CMS, and FIM is the conformance of aircraft to meet scheduled times of arrival at the meter fix and/or runway threshold scheduling points. This conformance determines the buffer needed between aircraft, which affects throughput, and the arrival time, which affects time savings. This section summarizes the conformance demonstrated in flights for EDA, CMS, and FIM. As is discussed in Section 6.1, throughput is the key for the benefits assessment of TM, which is part of TAPSS, and TAPSS throughput is discussed in this section.

Performance of the concepts is, thus, measured by either conformance (i.e., for EDA, CMS, and FIM) or throughput (i.e., for TAPSS). Conformance is defined to be the precision with which arrival flights are able to meet their scheduled times of arrival to the meter fix and/or runway threshold scheduling points. Conformance is measured as the standard deviation of the differences between flights ATA and STA to the scheduling points. Accurate conformance to scheduled times of arrival permits reduces inter-flight spacing for a given frequency of controller separation to enforce separation between flight pairs, yielding airport capacity gains. Throughput is measured as the average number of arrivals per hour.

Conformance or throughput performance parameters for each concept were specified through review of literature documenting one or more evaluation studies for each C&T and through discussion with key NASA researchers. The following sections compare the performance parameters of all the concepts.

6.1 Performance Summary

This section summarizes the conformance values of the EDA, CMS, and FIM concepts, and the throughput values of the TAPSS and TMA concepts. EDA, CMS, and FIM are concepts and associated technologies for managing aircraft trajectories to meet assigned STAs to scheduling points, thus their performances are described in terms of conformance. TAPSS is a concept incorporating both traffic planning (sequencing and scheduling flights to scheduling points) and trajectory management (managing aircraft trajectories to meet assigned STAs), and includes the EDA and CMS concepts, thus its performance is evaluated in terms of throughput.

Table 6 below summarizes the conformance values, the key reference, and other relevant information for EDA, CMS, and FIM. Because EDA is a concept and associated technology for meeting STAs at the meter fix, a runway conformance is estimated via extrapolation. Because CMS is a concept and associated technologies for meeting STAs at the runway, a meter fix conformance is not specified. FIM is typically engaged prior to the meter fix until just prior to the runway threshold, and thus has conformance parameters at both scheduling points. FIM demonstrates slightly better performance than EDA and CMS at the meter fix and runway threshold, respectively.

Table 6: Conformance values for trajectory management concepts.

Concept	Scheduling Point	Std. Dev., Sec	Reference	Comments

EDA	Meter Fix	12.0	Sweet, D., et. al., 2004	N/A
	Runway			
CMS	Meter Fix		Kupfer, M., et. al., 2011	Conditions-specific value corresponding to aircraft runway ETA – STA error within -60/+30 sec.
	Runway	5.2		N/A
FIM	Meter Fix	10.4	Murdoch, J., 2009	Inter-flight spacing conformance at TRACON entry point equivalent to MF STA conformance
	Runway	3.6		Inter-flight spacing conformance at runway threshold equivalent to RW STA conformance

The table below summarizes the average arrival throughput values for TAPSS, and for the Traffic Management Advisor (TMA), which serves as a performance baseline.

Table 7: Throughput values for traffic management concepts.

Concept	Average Throughput (aircraft/hour)
TMA	68
TAPSS	75

Sections 6.2 through explain in detail the studies used to derive the conformance and throughput values for the different concepts shown in Tables 6 and 7.

6.2 EDA and TMA Performance Evaluations

Reference [SW08] documents experiments which compared the conformance of arrival flights in meeting their meter fix STAs under speed and path advisories computed by EDA versus those formulated by controllers in conjunction with TMA meter fix schedules. Table 8 below summarizes the performances identified in those experiments.

Table 8: Conformances for TMA and EDA.

Concept	Scheduling Point	Std. Dev., Sec	Comments
TMA	Meter Fix	24.0	Figure 3, Without heavy traffic scenario

	Runway		
EDA w/ 250 knot restriction	Meter Fix	12.0	Figure 3
	Runway		

The study was a simulation-based HITL experiment focused on managing arrivals in the ZFW northeast arrival corridor via the KARLA meter fix. The studies evaluated three different tool conditions: TMA (as a baseline), EDA with a 250-knot minimum speed restriction, and EDA without a 250-knot minimum speed restriction (which permitted a wider range of aircraft performances). Each tool was evaluated under three test runs. The experiment conditions included two demand conditions differing in aircraft and traffic flow, and one high demand condition. Traffic was comprised of a mix of jet traffic arriving to ZFW through the northeast arrival to the KARLA meter fix. Delays were induced by setting the TMA meter fix arrival rate at KARLA to 30 aircraft an hour and having an aircraft demand that exceeded 30. In addition to the arrival aircraft, a set of over-flights was included to create additional workload for the high sector controller.

Figure 9 shows the schedule conformance measured when aircraft crossed the meter fix, averaged over all runs. This indicates meter fix schedule conformance distributions for TMA and EDA with the 250-knot restriction across all 3 experiment conditions.

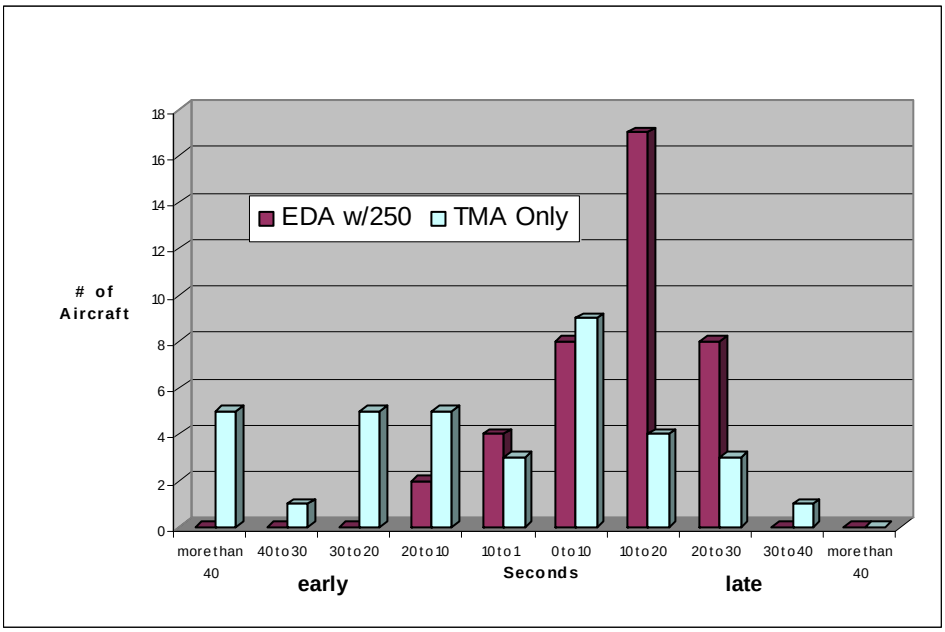


Figure 9: Representative Meet-Time Performance Histograms for TMA only and EDA

The distribution statistics are as follows. For EDA (μ = -11 s, σ = 12s), the distribution peaks within 10-20 s late. For TMA (μ = -8 s, σ = 24s), the distribution peaks within 0-10 s late; however, with a broader distribution.

6.3 TAPSS and TMA Performance Evaluations

Reference [SW11a] documents experiments which compared the conformance of arrival flights in meeting their meter fix and runway STAs and airport throughput under control of the TAPSS system versus under control of TMA only. Table 9 below summarizes the STA conformance parameters exhibited under each system in these experiments.

Table 9: TMA vs. TAPSS Conformance

Concept	Scheduling Point	Std. Dev., Sec	Comments
TMA	Meter Fix	25.0	DEANO meter fix, Figure 11
	Runway	95.0	Runway 24R, Figure 12
TAPSS	Meter Fix	30.0	DEANO meter fix, Figure 11
	Runway	30.0	Runway 24R, Figure 12

Table 10 below summarizes the airport arrival throughputs exhibited under each system in these experiments:

Table 10: TMA vs. TAPSS Average Arrival Throughput

Concept	Average Throughput (aircraft/hour)
TMA	68
TAPSS	75

The study was a simulation-based HITL focused on arrivals to LAX to runways 24R and 25L under Instrument Meteorological Conditions (IMC), encompassing the Los Angeles Center (ZLA) and the Southern California TRACON (SCT). The TAPSS system comprised a collection of traffic management tools including TMA extended with merge points and airport runway STAs assignment capability, EDA to support flight trajectory management to meter fix STAs, and CMS to support flight trajectory management to flight STAs to merge points and the runway threshold. Arrivals were flying OPDs along RNAV routes. Arrival traffic demand represented a 10% increase over the JPDO current-day high-traffic scenario. The scheduling used a 0.4 nmi inter-flight spacing buffer. The conformance achieved by TAPSS and TMA are shown in Figure 10 below.

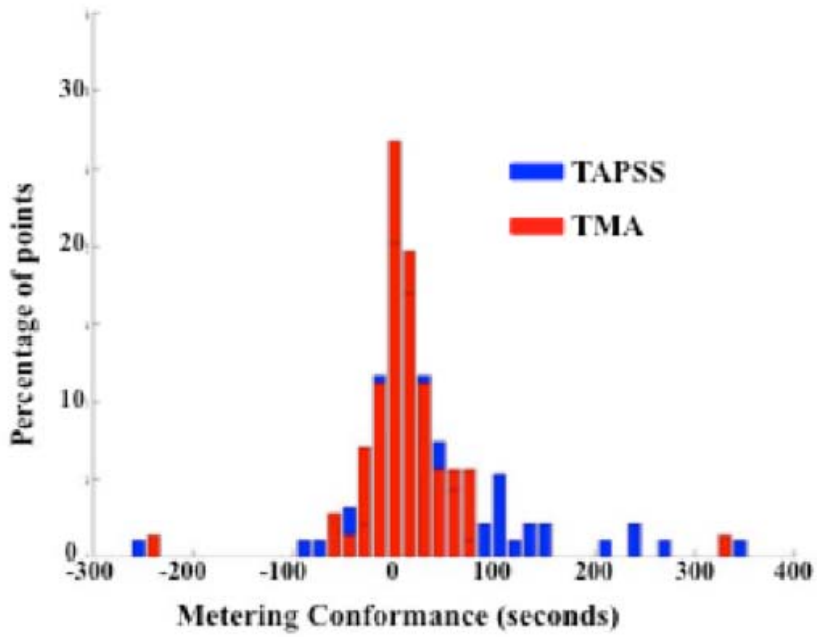


Figure 10: TAPSS and TMA Meet Time Conformance Error Distribution at Meter Fix DEANO

The TAPSS distribution (μ = -2 s, σ = 25 s) exhibits similar conformance characteristics to the TMA distribution (μ = -7 s, σ = 30 s).

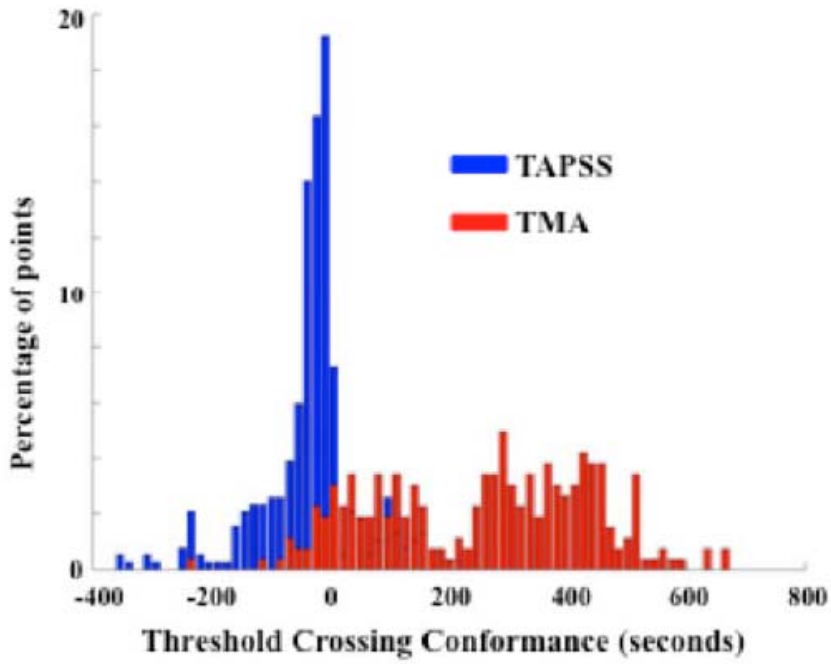


Figure 11: TAPSS and TMA Meet Time Conformance Error Distributions at LAX runway 24R

The TAPSS distribution (μ = -15 s, σ = 30 s) exhibits more accurate conformance than the TMA distribution (μ = --277 s, σ = 95 s).

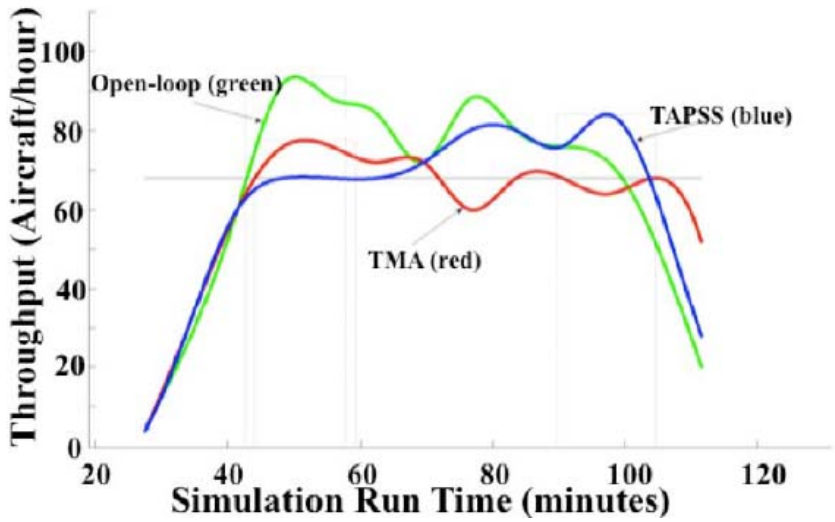


Figure 12: Throughput Distribution For LAX.

TAPSS exhibits higher mean throughput (74 aircraft/hour) than TMA (68 aircraft/hour), and a higher peak throughput (84 aircraft/hour) than TMA. The open loop line in Figure 12 shows the maximum achievable throughput.

6.4 CMS Performance Evaluation

The two CMS evaluations by Kupfer et. al. document experiments which assessed the conformance of arrival flights in meeting their runway STAs under control of the CMS system.

Table 11: CMS Evaluation Results

Concept	Scheduling Point	Std. Dev., Sec	Comments
CMS	Meter Fix	13.3	As per +/- 40 sec error tolerance in Kupfer 2010; however site, aircraft-type, winds, and operations dependent
	Runway	5.2	Figure 13 data statistics

The study was a simulation-based HITL focused on arrivals to LAX to runways 24R and 25L, encompassing the SCT airspace up to the meter fixes. Arrivals were flying OPDs along RNAV routes. CMS supported management of arrival flight trajectories to meet their runway threshold STAs. Trajectories were managed via speed control using CMS tools including Timeline, Slot Markers, and Speed Advisories. It was assumed that en route facilities deliver aircraft to the terminal-area entry fixes with runway-schedule errors no greater than 60 seconds early or 30 seconds late. The range of experiment conditions included trajectory management tools, forecast wind errors, demand levels, and conflict scenarios. A fixed 0.5 nmi schedule buffer was used.

Figure 13 shows the runway schedule conformance measured when aircraft crossed the runway threshold, averaged across all 18 simulations (900 aircraft).

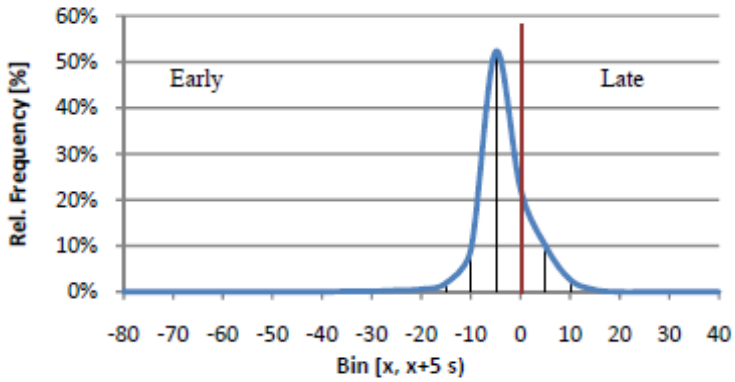


Figure 13: Runway Meet-Time Error Distribution With CMS For All Experiment Conditions and Scenarios

The distribution in Figure 13 (μ = -1.21 s, σ = 5.21 s) peaks around -5 s. The curve is steeper on the left, indicating controller effort not to exceed the 0.5 nmi schedule buffer. The curve is more gradual on the right. Excess spacing is somewhat inefficient, but safe.

6.5 TAPSS and CMS Performance Evaluations Comparison

This section compares and contrasts the two studies to explain the exhibited performance differences. The TAPSS system uses the CMS controller support tool to manage trajectories to their meter fix, merge point, and runway threshold scheduled times of arrival computed by the TMA scheduling system augmented with scheduling to merge points. The two studies indicated very different performances for traffic management using the CMS decision support tool. Table 12 below highlights the key experiment conditions documented:

Table 12: TAPSS and CMS Experiment Results

Data		TAPSS Experiment [SW11]	CMS Experiment [KU11]
Performance			
Delivery Accuracy	Meter Fix	Mean= -7 sec, Std. Dev.= 30 sec MF = DEANO	Not applicable
	Runway	Mean= -15 sec, St. Dev= 30 sec RW = 24R	Mean= -1.21 sec, St. Dev.= 5.21 sec
Conditions			
Capabilities		Scheduling to meter fix, merge points, runway threshold; runway balancing	Scheduling to runway threshold
		Controller Speed, path	Controller speed advisories to

Data		TAPSS Experiment [SW11]	CMS Experiment [KU11]
		advisories to meter fix STAs; speed advisories to merge point, runway STAs	meet runway STAs
Airspace		Arrivals to LAX 25L, 24R via NW, E, S RNAV OPD routes; 3 feeder, 2 final sectors	Arrivals to LAX 25L, 24R via NW, E, S RNAV OPD routes; 3 feeder, 2 final sectors
Traffic Demand	Level	55-72 aircraft/hour (1.1x JPDO 2004 baseline)	50 aircraft/hour, 25 aircraft/runway
	Duration	180 min	60 min
	Entry condition	As per meter fix delivery	Runway STA – ETA error range of -60/+30 sec at meter fix
Scheduling Parameters	Runway Buffer	0.4 nmi	0.5 nmi
	Delay margin	70% of range provided by aircraft nominal & slow speeds	Not available
Winds		Condition	Zero, plus, minus forecast bias conditions

NASA researchers Harry Swenson and Todd Callantine were consulted to gain further understanding/explanation of the key differences between the two studies. Findings are summarized below.

- Traffic volume
  - Biggest difference between the two studies, which most likely explains their exhibited performance differences:
  - CMS used a landing rate ~60-64 aircraft/hour
  - TAPSS used a landing rate ~84 aircraft/hour
    - Approaching LAX two-runway configuration saturation level
    - Significantly higher controller workload, attention to STA conformance was traded for the attention to separation
    - Early small conformance errors in the late direction can only be carried until the end of the saturation period
  - Achievable delivery accuracy depends on workload

        - Function of traffic load, winds and forecast wind errors, and how well the flows are conditioned

- Traffic composition
    - TAPSS: included turbo-prop traffic also increased the variability
- Aircraft initiation points
    - TAPSS: well prior to the TMA scheduling freeze horizon (~145 nm from the meter fix); active participation of Center controllers yielded real controller conformance errors at the meter fix
    - CMS: much closer to airport; used model of "Center" controller conformance errors at meter fix
    - An observation is that the conformance errors in the Center usually include a backward bias; thus, during saturation levels, you cannot push aircraft forward, only delay, leading to greater delivery errors at the runway
- Scheduling algorithms
    - TAPSS: multi-point scheduling to runway, merge points, meter fix; schedule frozen prior to meter fix
    - CMS: single-point scheduling to runway, schedule frozen closer to the airport
- Scheduling buffers
    - Different scheduling buffers combined with the demand levels can make a huge difference

6.6 FIM Performance Evaluations

A paper by Murdoch et. al. documents experiments which assessed the inter-flight spacing variability of arrival flights under control of the flight deck-based ASTAR automated interval management system. The inter-arrival time spacing variability at the meter fix and runway identified in the study are listed below:

Table 13: FIM Conformance Parameters

Concept	Scheduling Point	Std. Dev., Sec	Comments
FIM	Meter Fix	10.4	Figure 15, Inter-arrival time statistics at TRACON entry point CBSKT
	Runway	3.6	Figure 14, Inter-arrival time statistics

The experiments were simulation-based HITL evaluations of arrivals to Louisville (SDF) runway 17R. The experiments captured two arrival streams merging to single OPD prior to top of descent (TOD). Interval management was provided via the ASTAR speed advisories to achieve target spacing of 150s at runway threshold. The experiment conditions included fixed forecast wind error, three off-nominal events varied among aircraft in sequence, and large initial spacing

errors. Time spacing conformance was assessed across all 8 simulations, each including 3 off-nominal scenarios. The data are for 191 aircraft, which excludes 1 outlier flight exhibiting an anomalous late gear deployment in preparing for approach.

Figure 14 summarizes the inter-arrival time spacing statistics at the runway threshold.

Scripted Conditions		*N*	*M*	*SD*	Median	Min	Max
Following speed	12	10	151.4	2.5	150.7	147.6	157.0
Nominal	84	75	151.3	2.9	151.2	141.3	159.1
All	192	118	150.8	3.6	151.2	135.5	159.1

Figure 14: Inter-Arrival Time Statistics at Runway Threshold

Statistics for All Scripted Conditions are used as representative values for FIM performance (μ = -150.8 s, σ = 3.6 s) at the runway threshold. This includes the Following Speed off-nominal experiment condition, in which pilots flew speeds at their discretion, in lieu of the spacing guidance speed advisory. Use of the All Scripted Conditions values ensures the representative FIM performance value covers the broadest range of operational conditions, ensuring robustness in the benefits assessed for this project.

Figure 15 summarizes the inter-arrival time spacing statistics at the meter fix CBSKT.

Waypoint	*N*	*M*	*SD*	Median	Min	Max
ENL	78	156.1	7.8	154.1	143.4	170.0
PRINC	119	149.3	7.6	149.7	131.6	165.8
CBSKT	108	151.3	11.9	149.3	117.8	190.2
BRYDL	119	154.1	7.5	153.6	134.6	172.6
SLEWW	119	156.7	6.8	156.4	141.7	173.1
SECRY	119	153.6	6.2	153.6	137.6	168.3
CHRCL	119	146.6	6.2	146.4	131.5	162.4
RW17R	118	146.3	4.2	146.6	123.6	157.2

Figure 15: Inter-Arrival Time Statistics At Arrival Route Waypoints

The statistics for waypoint CBSKT are used as representative values for FIM performance (μ = -151.3 s, σ = 11.9 s) at the meter fix. The arrival procedures used in the study are depicted in the figure below. Waypoint CBSKT is visible.

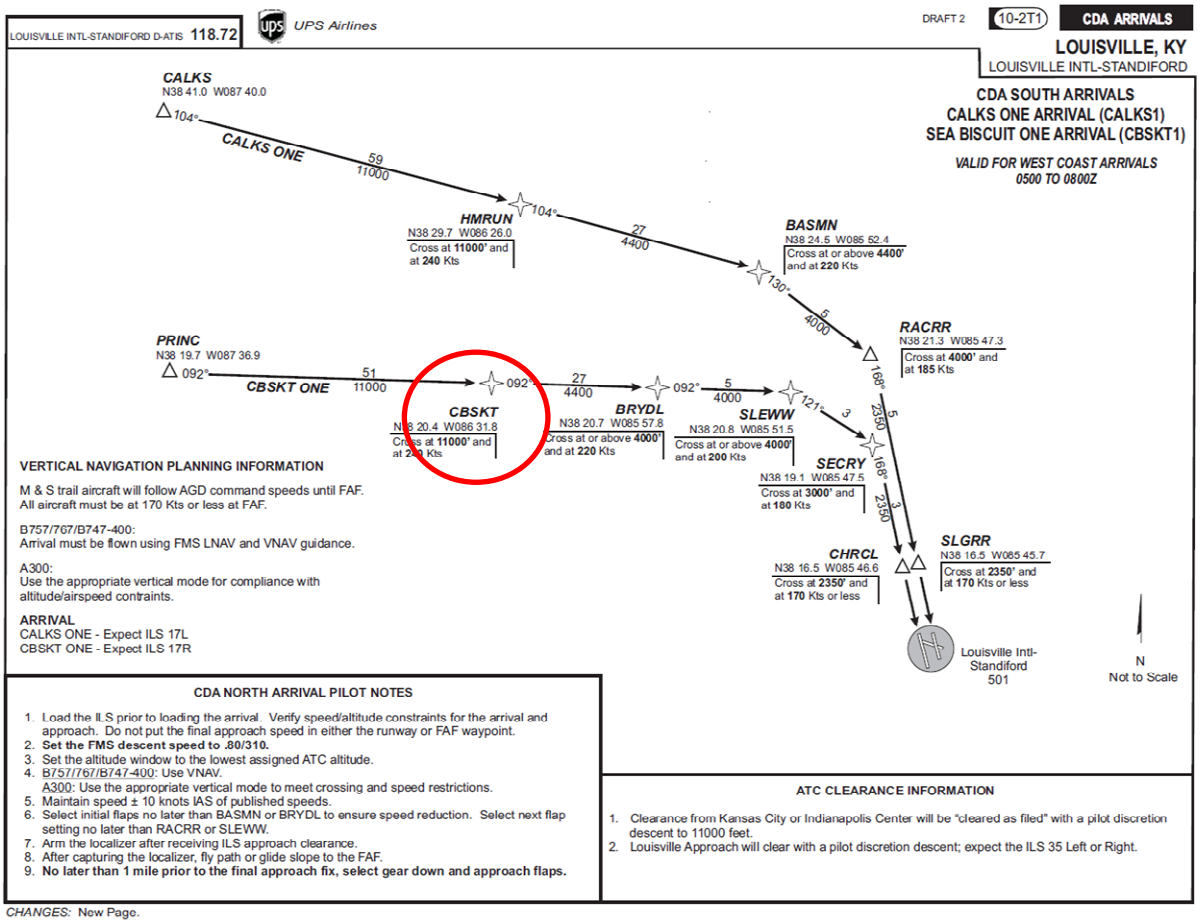


Figure 16: FIM Evaluation Experiment Arrival Routes with Meter Fix CBSKT.

7 Airport-Specific Adaptation for Benefit Analysis

This section addresses the method used to create each airport's adaptation for the time savings benefit analysis. This airport-specific adaptation consists of the airport's arrival configuration, meter fixes, terminal merge points, traffic composition by weight class at each meter fix, time-to-fly between meter fixes, merge points, and runway ends by aircraft type.

The top TMA airports are analyzed to determine the throughput benefits at each airport. Since each airport has different characteristics, the percent improvement will vary. Thus, each airport has to be modeled and analyzed separately. In order to facilitate the benefits analysis over the 30 plus airports, an airport adaptation approach has been created to make it easier to model each airport. This method allows for an airport to be plugged into the concept modeling approach without having to make any modifications in the concept modeling stage.

The concept modeling requires an airport adaptation that contains several points of data: fixes, navigational aids, and runway thresholds; arrival fixes; runway configurations; high demand track data; merge points; average altitude, speed, and spacing restrictions at each waypoint separated by weight class or stream class; route data, including usage percentage and TRACON time-to-fly from every arrival fix to every runway. Any anomalies in airspace design were handled manually and iteratively during the following process.

The first step in creating the airport adaptation was to import the arrival fixes and runway thresholds for a single airport into MATLAB. All fixes, navigational aids, and runways were imported from the FAA National Flight Data Center (NFDC) database. This database provides the position and name of the NAVAIDs and runways. Arrival fixes were imported from the CTAS TMA adaptation for every airport.

ATL is used as an example airport to show the steps taken to create its airport adaptation. The arrival fixes identified for ATL are CANUK, DIRTY, ERLIN, HERKO, HONIE, and PECHY.

Actual track data (ASDE-X track data from March 28 to April 28, 2009) was used to realistically model the TRACON usage. It was important to filter the track data using certain criteria. FAA Aviation System Performance Metrics (ASPM) data were analyzed to determine the most used runway configuration. The track data were filtered by time periods that used this particular runway configuration. Then the track data was sorted by demand, from highest to lowest. Only the high demand time periods were considered for this analysis because it was assumed TMA only operates during periods of high demand. For ATL, the most used runway configuration for arrivals was 26R, 27L, and 28. Thus, the aircraft track data were filtered to look only at arrival aircraft going to any of these three runways.

7.1 Finding Merge Point Suggestions

Finding the merge points required analyzing how the track data interacted during high demand time periods for a particular runway configuration. A merge point can be found by comparing the track data from a meter fix and runway pair with another meter fix and runway pair. In a simplified version, the first intersection of these tracks may be considered the merge point. Then, the merge point is selected by locating the nearest fix or navigational aid to that intersection. However, at any airport there are many combinations of meter fix and runway pairs to compare. Manually checking every combination would be slow so automation was used to help speed up

this process. There were some previously developed algorithms to compare radar track histories in the terminal airspace to find anomalies, clusters, and intersections. This process used a clustering algorithm to identify intersections and automatically generate merge point suggestions.

In Figure 17, there are seven blue tracks from the meter fix DIRTY to runway 27L and seven cyan tracks from the meter fix CANUK to runway 27L. The seven selected tracks for each route are considered to be a set of nominal tracks found by the clustering algorithm. These tracks are representative of all the tracks from a meter fix to a runway. The cyan and blue tracks intersect at the red circles, resulting in 49 intersections in this case. As can be seen, there is a merge zone directly before the final approach fix.

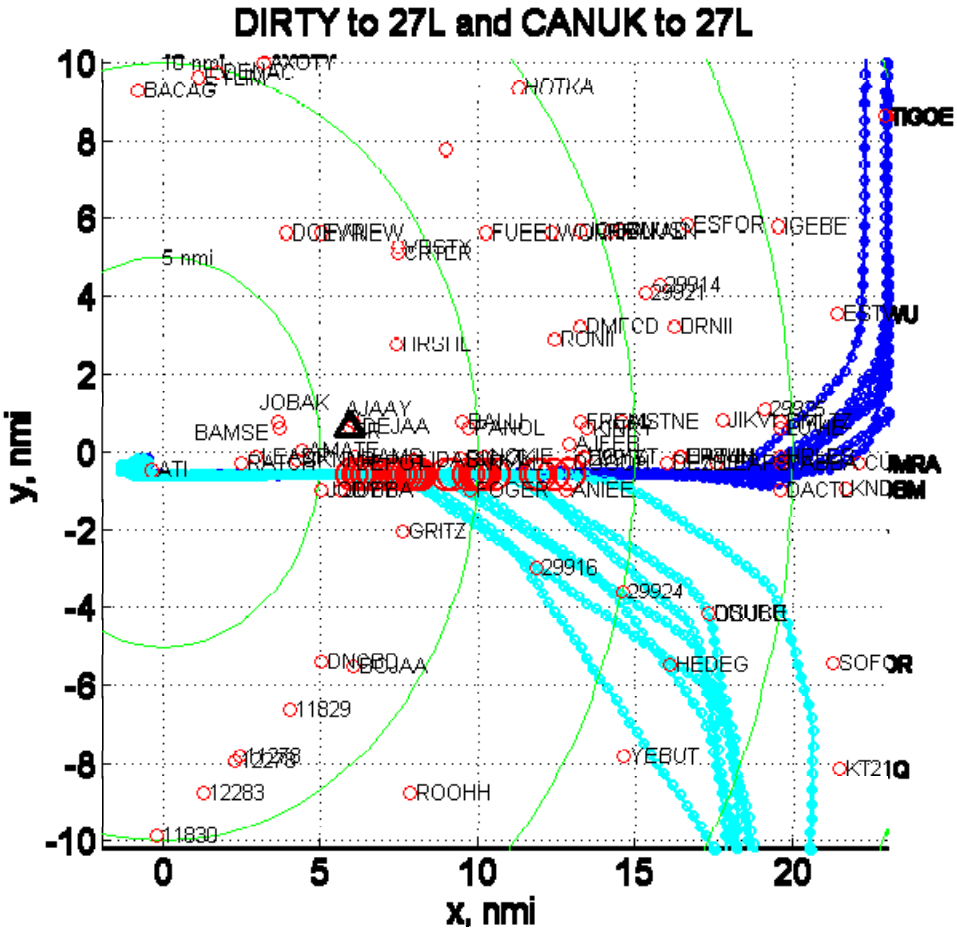


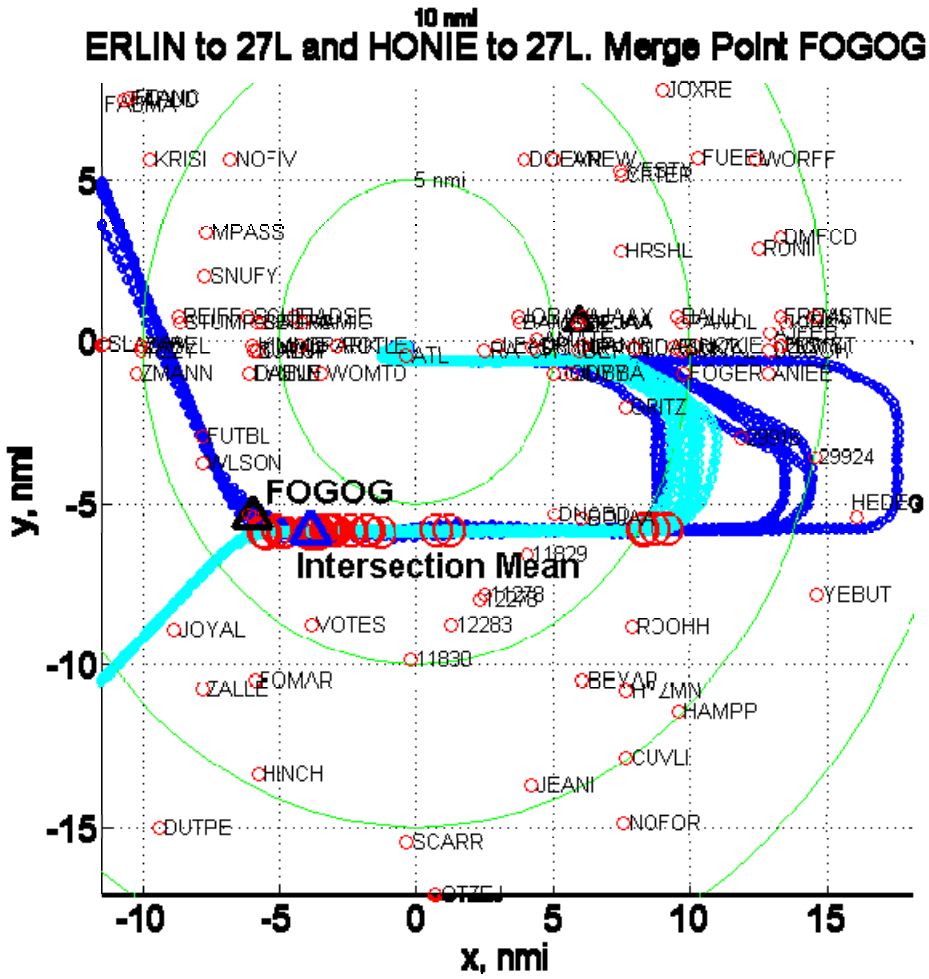
Figure 17: Seven blue tracks from DIRTY to runway 27L and seven cyan tracks from CANUK to runway 27L. The seven selected tracks for each route are considered a set of nominal tracks found by the clustering algorithm. The cyan and blue tracks intersect at the red

The algorithm to identify tracks for selection has roughly seven steps:

1. Load relevant airspace data: arrival fixes, final approach fixes, and airports.
2. Load radar track data, filter, and group tracks according to arrival fix-runway pair.
3. Calculate the ground plot area difference between each pair of flights for the section of each trajectory between the arrival fix and final approach fix. This is combinations of n things taken two at a time. It is total n^2 in the number of flights.

4. Using some area criterion, rank the flights by closeness to other flights. For each pair, if the area between them is less than the criterion, increment a counter for each flight in the pair. Then sort the counts by flight in descending order.
5. Extract the top m flights from the sorted list from step 4. These are the flights that are most similar to the other flights. They represent the nominal path between an arrival fix and final approach fix. Repeat this for each arrival fix-runway pair.
6. Find the first intersection between each pair of flights, one from each set of m flights. If all tracks intersect, there will be m^2 intersections.
7. Plot the intersections, the tracks, and all fixes and navigational aids in the area. Choose a fix or navigational aid near the mean of the intersections.

Figure 18 shows a merge point suggestion for the track comparison between ERLIN to runway 27L and HONIE to runway 27L. This figure was saved in both picture and MATLAB figure format. This analysis was done for every combination of meter fix and runway pairs. At ATL, this resulted in 90 pairs. Not all pairs result in a merge point suggestion and not all merge point suggestions are consistent. A user must untangle this complication iteratively while reviewing the pictures. The merge point suggestion review process was repeated for every airport as part of the adaptation process.



8.

Figure 18: The blue tracks are from ERLIN to runway 27L and the cyan tracks are from HONIE to runway 27L. The intersections occur over a wide area, therefore a mean excluding some outliers was found. The nearest fix or navigational aid was selected as the merge point suggestion, in this case FOGOG. As can be seen, all fixes and navigational aids are shown in case this suggestion is incorrect.

7.2 Route Definitions and Metrics

A route consists of an arrival fix, zero or more merge points, and a runway. In the previous analysis, a merge point near the final approach fix was ignored. The routes found at ATL are listed in Table 14.

Table 14: All identified routes for ATL.

Meter Fix	Merge Point	Merge Point	Runway
DIRTY	COSEL	BRNII	26R
PECHY	COSEL	BRNII	26R
CANUK	-	-	26R
HONIE	NOFIV	-	26R
ERLIN	NOFIV	-	26R
HERKO	NOFIV	-	26R
DIRTY	BYRDS	-	27L/28
PECHY	BYRDS	-	27L/28
CANUK	HEDEG	-	27L/28
HONIE	FOGOG	HEDEG	27L/28
ERLIN	FOGOG	HEDEG	27L/28
HERKO	FOGOG	HEDEG	27L/28

The next step was to determine the route properties. The percentage usage of each route was calculated from the track data and is shown in Table 15 for ATL.

Table 15: Route and meter fix usage percentages for ATL.

Meter Fix	26R % Usage	27L % Usage	28 % Usage	Total % Usage
CANUK	0.67%	22.71%	13.14%	36.52%
DIRTY	25.47%	7.00%	0.01%	32.48%
ERLIN	12.13%	1.28%	0.33%	13.74%
HERKO	0.91%	0.34%	0.16%	1.41%
HONIE	2.73%	5.16%	7.32%	15.22%
PECHY	0.46%	0.17%	0.00%	0.63%

In addition to the route characterization, the other variables describing aircraft behavior in the TRACON include the spacing, altitude, speed, weight class, and stream class. These attributes were captured, to help model each airport, by analyzing the ASDE-X track data.

The weight class and stream class show which types of aircraft land at the airport of interest. Weight classes include Heavy, Large, Small, and B757. The speed at every waypoint is obtained by taking the average speed for every weight class when the aircraft crosses the arrival fix, merge point, or runway threshold. The altitude is obtained in a similar fashion for each of those points.

The spacing shows how far apart the aircraft are when they cross the arrival fix. Some airports have tighter spacing than others, so this variable allows the concept modeling to capture the baseline throughput. For the spacing characterization, the aircraft tracks are analyzed to

determine how far apart flights are when they cross a waypoint. This information is then subdivided based on the stream class: jet, turboprop, or piston. The separation was recorded by looking at the 5th percentile of the spacing distribution to find the unimpeded distances. If the mean spacing was used, the calculated separation could contain information about delayed aircraft. This result would not accurately represent a baseline throughput level and would underestimate the amount of aircraft at the airport.

Table 16: Meter Fix separation and usage percentage observed from track data.

Meter Fix	Observed Separation (nmi)	Total % Usage
CANUK	5 nmi	36.52%
DIRTY	5 nmi	32.48%
ERLIN	8 nmi	13.74%
HERKO	14 nmi	1.41%
HONIE	9 nmi	15.22%
PECHY	23 nmi	0.63%

With all these factors captured, the airport-specific adaptation was created for each airport and was then used in the next step described in Section 8 to determine the benefits of each C&T. ASDE-X track data was available for 16 TMA airports during the time period of March 28 to April 28, 2009, so airport adaptations were generated for the list of airports in Table 17.

Table 17: Airports with available simulation results

ATL	CLT	DEN	DTW	EWR
IAH	JFK	LAX	MCO	MEM
MIA	MKE	ORD	SDF	SEA
STL				

8 Concept Modeling Approach

In a later section, the time savings benefit will determined by applying a simulation model to determine the reduction in average per flight delay at each airport under the different combinations of concepts. But before conducting these simulations to determine delay time savings, we need to investigate such simulation parameters as demand sets, flight schedules, controller intervention rates, and mixed equipage where some of the aircraft are FIM equipped while the rest use CMS. Section 8 discusses these issues.

Modeling fidelity, scenarios, and evaluation metrics are three important simulation and evaluation components that are highly coupled. The modeling fidelity determines the types and scope of the scenarios used in the simulation, as well as the metrics generated by the simulation model. The chosen scenarios affect the simulation models, the modeling fidelities used for analyses, and the appropriate metrics to be generated. Likewise, the metrics of interest can also drive the model's tools and fidelity, and thus impact the scenarios input to the modeling tools.

A scheduling model was used to measure controller intervention rate (CIR) and throughput using a set of Concepts and Technologies (C&T). These two metrics allow a comparison between each C&T, producing a throughput comparison. Each C&T is assumed to improve metering conformance at the meter fix and the runway when compared to TMA. If each C&T improves metering conformance, then it may be possible to pack aircraft more tightly without adding additional controller interventions. This model will compare the CIR of each C&T to TMA to locate how many more aircraft per hour each C&T can provide without exceeding the measured TMA CIR.

There were four steps involved in measuring the CIR and throughput for each C&T. The first was to use the airport model to create a set of Estimated Times of Arrival (ETA) for a saturated demand. The second step required the creation of a schedule (STA) from these ETAs over a variable set of scheduling parameters. During the third step, each STA was run through a Monte Carlo simulation with each C&T's conformance level, creating an Actual Time of Arrival (ATA) for each aircraft. In this step, CIR was calculated. The smallest scheduling parameters such that the CIR for every other C&T does not exceed TMA's calculated CIR. These parameters were used in step four to create a comparison between the maximum airport throughputs for each C&T.

8.1 Saturated Demand Set

The airport model provided several metrics: usage statistics of runway configurations to select the most used configuration; usage statistics at each meter fix to balance the saturated demand set; and maximum runway capacity and meter fix separation under high demand to compare the baseline TMA versus other C&Ts. The routes from each meter fix to each runway were sorted by usage percentage. The most used route from a meter fix to each runway was considered the primary route during the scheduling algorithm in step two described in Section 8.2.

The first step was to create a saturated demand set. The saturated demand was set to 1.5 times the FAA Operational Information System (OIS) maximum arrival capacity. As seen in Table 18, the observed maximum capacity from ASDE-X data and the FAA OIS capacity differ greatly at some airports. Thus, the FAA OIS capacity was used instead to ensure sufficient traffic at each

airport. While the difference at ATL may not be very large, some airports have an observed throughput at half the FAA OIS number. The observed usage statistics for each meter fix in the TRACON were used to balance the demand set such that as the number of aircraft per hour is increased, it still matched the observed balance of aircraft types and percentage usage at each meter fix.

Table 18: Most used runway configuration, FAA OIS aircraft per hour, and observed ASDE-X max aircraft per hour for all airports.

Airport	Runway Configuration	FAA OIS VMC ac/hr	ASDE-X Max ac/hr
ATL	26R/27L/28	126	114
CLT	23	35	36
DEN	34R/35L/35R	114	88
DTW	21L/22R	76	57
EWR	22L	38	39
FLL	9L/9R	46	42
IAH	26L/26R/27	108	78
JFK	31L/31R	58	56
LAX	24R/25L	80	60
MCO	17L/18R	80	38
MEM	18L/18R	72	58
MIA	8L/9	72	39
MKE	25L	32	23
ORD	27L/27R	72	72
PHL	26/27R/35	60	59
PHX	25L/26	78	65
SDF	35L/35R	52	44
SEA	16R	24	21
STL	12L/12R	64	41

8.2 Generate Schedules

For the second step, the available scheduling algorithms need to be defined. TMA-only will schedule to the meter fix and runway with a static TRACON delay absorption limit. Runway separation is calculated by the minimum wake vortex plus an additional Runway Buffer. An airport acceptance rate may also be set, e.g. 58 aircraft per hour. Separation at the meter fix is set by miles-in-trail. For the TMA-only case, each meter fix has an observed miles-in-trail. A TRACON merge point scheduler, or Terminal Metering (TMA-TM), may be turned on or off. If a C&T requires it, the TRACON Delay Distribution Function (DDF) will replace the static TRACON delay absorption limit by calculating the maximum delay available to each aircraft, depending on aircraft type and TRACON transit time. A dynamic runway allocation algorithm assigns aircraft to the runway minimizing the TRACON delay time. At ATL, the most used airport configuration has three runways. During a saturated demand, the algorithm will usually

rotate runways in this configuration. During a demand less than or equal to capacity, it will prefer to use the primary runway as found by the route usage percentages.

Given the scheduling algorithms, step two can now be explained. There were two schedules created over a variable set of runway buffers and meter fix buffers, one for TMA-only without merge point scheduling and one for TMA-TM with merge point scheduling. There were a set of ten ETAs generated and thus a set of ten STAs for both TMA-only and TMA-TM. The saturated demand sets were fed into the schedulers over a range of runway buffers between zero and two nautical miles, with all other scheduling parameters fixed. When varying the runway buffer, the meter fix separation is set to its minimum of five nautical miles. The saturated demand sets were also fed into the schedulers for a range of meter fix buffers between five nautical miles and the maximum observed separation at any meter fix, fixing a minimum wake vortex separation at the runway. The observed unimpeded meter fix separation is listed in TMA-only case in Table 19.

8.3 Monte Carlo Simulation to Generate Actual Times of Arrival

For the third step, TMA-only was compared to the other C&Ts using a Monte Carlo simulation. Each C&T has a conformance level defined as an expected standard deviation of arrival times at the meter fix and runway, as listed in Table 19. For a particular C&T, a randomly generated conformance number was added to an aircraft's STA at the runway, merge points, and meter fix, creating an Actual Time of Arrival (ATA). If the ATA of two subsequent aircraft results in a loss of separation, this was counted as a controller intervention. The Controller Intervention Rate (CIR) is the percentage of aircraft whose ATAs caused a controller intervention. A Monte Carlo simulation generating these ATAs was run one hundred times at each metering point at each runway and meter fix buffer increment, for each C&T listed in **Error! Reference source not found.**. The resulting average CIR over the one hundred simulations at each of the schedules was saved for the next step.

Table 19: The conformance for each Concepts and Technology configuration tested in the Monte Carlo simulations.

Scheduler Name	Conformance standard deviation	Description
TMA-only	Meter Fix: 24s Runway: 26s	Used observed meter fix miles-in-trail. Used to compare with all other tools.
TMA + EDA	Meter Fix: 12s Runway: 16s	The runway buffer requirement and meter fix miles in trail were smaller than TMA only case.
TMA-TM + CMS	Meter Fix: 24s Runway: 5.2s	The runway buffer requirement was smaller, while the meter fix miles-in-trail remains the same.
TMA-TM + EDA + CMS	Meter Fix: 12s Runway: 5.2s	The runway buffer requirement and meter fix miles in trail were smaller than TMA-only case.
TMA-TM + FIM	Meter Fix: 10.4s	The runway buffer requirement and meter fix miles in trail were smaller than TMA-only case.

	Runway: 3.6s	

8.4 Calculate Controller Intervention Rate to Create a Comparison Metric

The fourth step used the mean CIR to generate plots for each C&T over the variable runway and meter fix buffers. The TMA-only runway buffer was found such that it is equal to or less than the maximum observed airport capacity for a runway configuration. The goal is to compare TMA with EDA, CMS, and FIM to find a reduced runway buffer requirement based on the CIR of each tool. If a tool has a smaller conformance level than TMA, then it may show a reduction in the runway buffer required to maintain the same level of CIR. In the ATL model, the FAA OIS capacity is 126 arrival aircraft per hour, which was approximately equal to a runway buffer of 0.8 nautical miles for the TMA-only case. The TRACON CIR at that point was found to be approximately 24%. In Figure 19, the CIR curve is shown for each C&T, calculated from the mean at each runway buffer increment from the Monte Carlo Simulation. The runway and meter fix buffers were found for each C&T based on the comparison with TMA-only's CIR and are shown in Table 20.

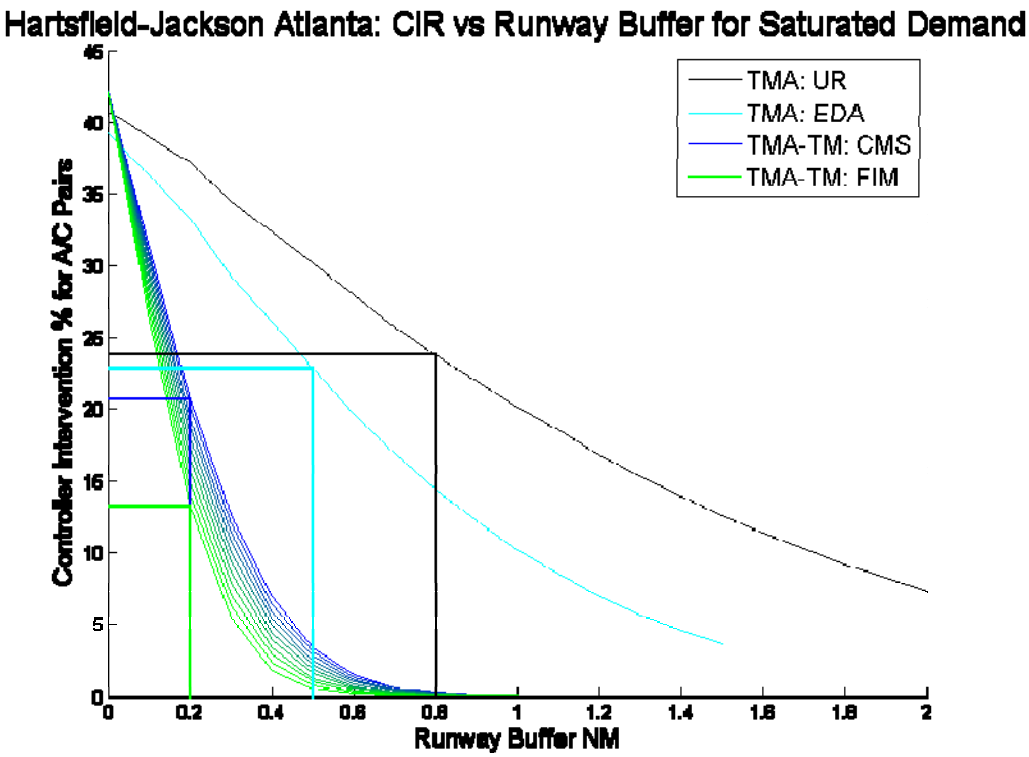


Figure 19: Controller Intervention Rate for each C&T at the ATL model.

Table 20: Potential arrival throughput capacity for ATL given the CIR analysis and resulting meter fix and runway buffers.

Concept and Technology	Throughput Capacity (ac/hr)	Percentage of Theoretical Max	Runway Buffer (nmi)	Meter Fix Separation (nmi)
TMA-only	124 ac/hr	86%	0.8 nmi	(5, 5, 8, 14, 9, 23)

TMA+EDA	132 ac/hr	91%	0.5 nmi	(5, 5, 7, 9, 7, 9)
TMA-TM+CMS	138 ac/hr	96%	0.2 nmi	(5, 5, 8, 14, 9, 23)
TMA-TM+ CMS+EDA	138 ac/hr	96%	0.2 nmi	(5, 5, 7, 9, 7, 9)
TMA-TM+FIM	138 ac/hr	96%	0.2 nmi	(5, 5, 7, 9, 7, 9)
Theoretical Max	144 ac/hr	100%	0	(5, 5, 5, 5, 5, 5)

8.5 Mixed Equipage

In addition to the Monte Carlo simulation comparing EDA, CMS, and FIM with TMA, it was also possible to create a mixed equipage simulation where some of the aircraft are FIM equipped while the rest used CMS. If there was a difference in runway buffer between CMS and FIM, there was the possibility that if enough aircraft were FIM equipped, there could be a reduction in the runway buffer.

This was simulated by generating actual times of arrival given a percentage of randomly distributed FIM equipped aircraft. In Figure 20, there are nine lines between the CMS curve, which is blue, and the FIM curve, which is green. Each line represents a set amount of FIM-equipped aircraft, in this case, every 10%. Since there are nine lines, this means 10%, 20%, ..., and 90% FIM-equipped aircraft were simulated. In the ATL case, there was no reduction in runway buffer; however, in Charlotte Douglas airport (CLT), there was a 0.1 nautical mile difference in the runway buffer found for CMS and FIM, as seen in Figure 20. By comparing the CIR for each increase in FIM-equipped aircraft with the TMA-only CIR, it was found that if 30% FIM of aircraft are FIM-equipped, there can be reduction in the runway buffer. Table 21 shows this analysis for all airports.

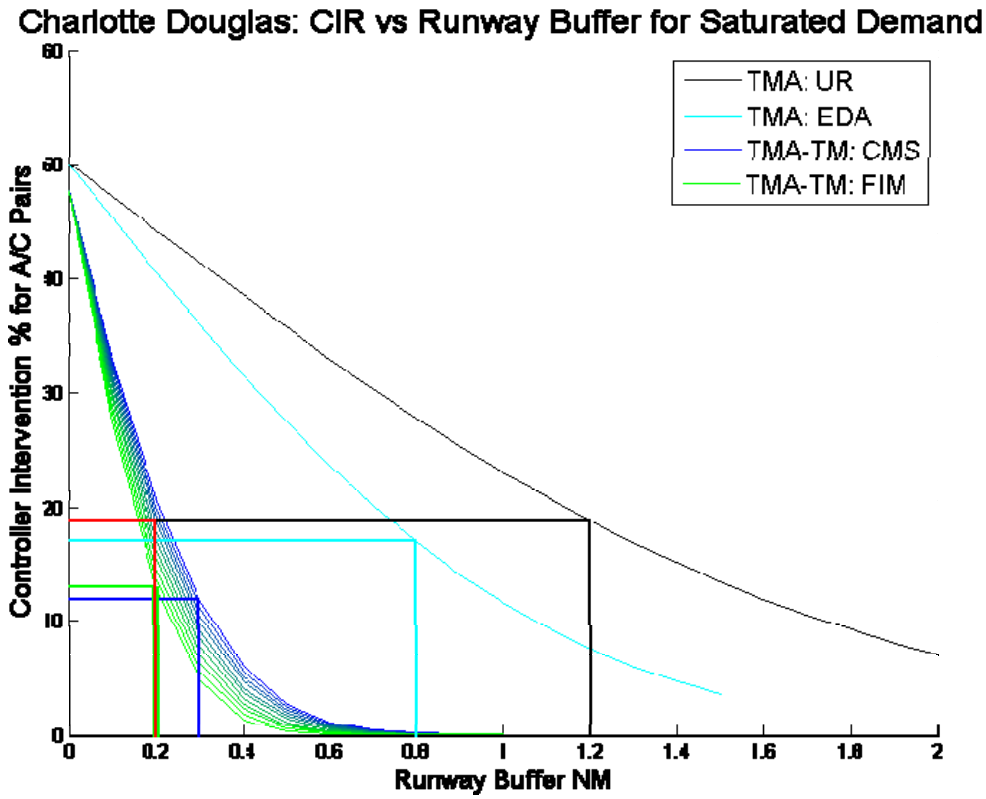


Figure 20: Controller Intervention Rate for each C&T at the CLT model. The red line shows, with 30% FIM equipped aircraft, there can be a reduction in the runway buffer.

Table 21: Summary of runway buffers for all airports, including mixed equipage results. If a percentage of FIM equipped aircraft can reduce the runway buffer, it is shown here. If the CMS and FIM runway buffers are equivalent, there can be no reduction in runway buffer via mixed CMS and FIM traffic.

Airport	TMA Buffer (nmi)	EDA Buffer (nmi)	CMS Buffer (nmi)	FIM Buffer (nmi)	Mixed Equipage Buffer (nmi)	FIM Equipped Percentage
ATL	0.8	0.5	0.2	0.2	N/A	N/A
CLT	1.2	0.8	0.3	0.2	0.2	30%
DEN	0.9	0.6	0.2	0.2	N/A	N/A
DTW	1.0	0.6	0.3	0.2	0.2	20%
EWR	0.7	0.5	0.2	0.1	0.1	80%
IAH	1.3	0.9	0.4	0.3	0.3	10%
JFK	1.2	0.8	0.3	0.2	0.2	60%
LAX	0.2	0.2	0.1	0.1	N/A	N/A
MCO	0.6	0.4	0.2	0.1	0.1	50%
MEM	0.4	0.3	0.1	0.1	N/A	N/A
MIA	0.5	0.3	0.2	0.1	0.1	50%
MKE	0.6	0.4	0.2	0.1	0.1	40%
ORD	0.9	0.6	0.3	0.2	0.2	50%
SDF	1.3	0.8	0.3	0.2	0.2	10%

SEA	2.0	1.3	0.4	0.3	0.3	20%
STL	0.9	0.6	0.2	0.2	N/A	N/A

8.6 Conclusions

Each C&Ts shows an improvement in the number of arrival aircraft per hour and a reduction in the runway buffer when compared with the TMA-only case. The results for all 16 airports are listed in Appendix A. Louisville (SDF) and Seattle (SEA) resulted in odd findings. Explanations and details are in the appendix.

There are some limitations to this model. This model assumes all runways are independent, there are no departures, the runway occupancy time has no effect on the separation of incoming arrivals, and each route is independent of each other besides at the merge points, arrival fixes, and runway. These arrival aircraft per hour improvements are not likely to be achieved in real situations; however, smaller runway buffers will increase airport efficiency.

Section 9 explores the possibilities of increasing the airport arrival capacity.

9 Time Savings Benefit Evaluation through Simulation of Delay Reduction at each Airport

Section 9 explains details for estimating how much delay reduction each C&T can provide at various airports. This delay reduction provides the time savings benefits. The delay reductions are a function of the increase in throughput at the airports

9.1 Introduction

The delay reduction benefits from C&T were calculated based on the assumption that the arrival demand level was set high enough to saturate the airport. For example, JFK's improvements with each C&T are shown below in Table 22.

Table 22: Arrival throughput in aircraft per hour by different decision support tools at JFK Airport

Technology	Arrival Throughput (AC per hour)
TMA (Baseline)	57
TMA + EDA	63
TMA-TM + CMS	72
TMA-TM + CMS + EDA	72
TMA-TM + FIM	74
Theoretical Max	79

The improvement from the baseline TMA technology to the TMA-TM+FIM technology is quite high at JFK in Table 22. However, these increases only occur at certain time periods when the arrival demand saturates the airport. Airports generally do not operate under these conditions all the time. To properly assess the actual benefit that these technologies have at each airport, a more realistic demand set should be used.

Thus, these throughput numbers are used to perform a NAS-wide operational benefit analysis by applying the percent improvement, compared to the baseline scenario, to the Pareto frontier at different airports. Then, a JPDO demand set is used as an input to perform a delay analysis for a given airport, where the Pareto frontier establishes the arrival and departure capacity, and the benefits are determined by calculating the delay for each C&T.

The Pareto frontier describes the capacity of an airport. One axis shows the arrival capacity and the other axis shows the departure capacity. The slope shows the maximum capacity of the airport, which is generally smaller than the departure capacity plus the arrival capacity.

An envelope is created, using these three numbers, that describes the maximum amount of arrivals and departures the airport can handle. Figure 21 below shows the Pareto frontier for JFK. JFK has a maximum arrival capacity of 20 aircraft per 15 minutes and a maximum departure capacity of 22 aircraft per 15 minutes. The total amount of aircraft it can handle in a 15 minute time period is 27. So the sloped line connecting the departures and the arrivals shows the trade-off that occurs whenever the airport is operating in a region with mixed arrivals and departures.

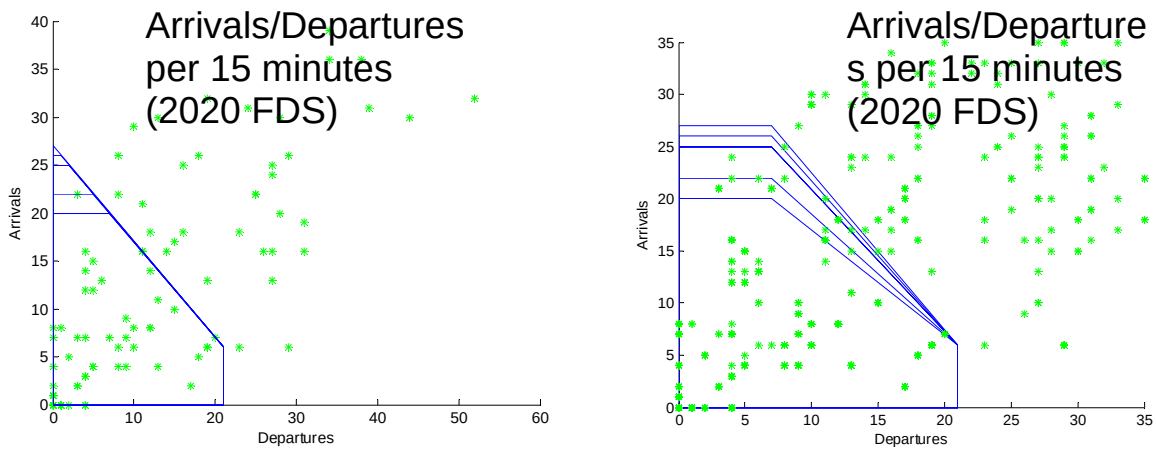


Figure 21: 15-min Pareto frontier for JFK

9.2 Pareto Frontier Approaches

The different C&Ts improve the arrival capacity at the airport, which affects the shape of the technology's Pareto frontier. Depending on the assumptions made, the C&Ts either increase the arrival capacity only or they also improve the airport's total capacity and departure capacity.

For the left Pareto frontier from Figure 21, the airport configuration is assumed to be either a single runway or highly dependent runways. The increased arrival capacity is traded off with the departure capacity. If there is only one runway or highly dependent runways, the maximum airport capacity does not increase. It can only handle more arrivals at the expense of departures. This method is more conservative. The right Pareto frontier assumes that the airport has independent arrival and departure runways. So even though the arrival capacity is increased, it does not adversely affect the departure capacity. In fact, the departure capacity and total capacity also receive a slight increase. This method will be referred to as the maintaining departure operations approach. Both these methods will be analyzed further.

For the conservative approach, the area of the Pareto frontier where the flights receive benefits is smaller. The improvement area is highlighted in green below in Figure 22. The green points show the actual arrival/departure demand per 15 minute time period for JFK for the year 2020. There are several periods where the airport is operating in the green region, so it is expected that there will be some improvements in delay with the new technologies.

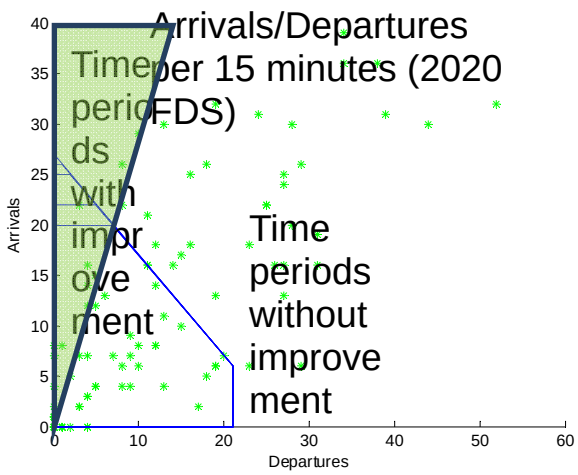


Figure 22: Conservative Pareto Frontier

Whenever the data point is inside the Pareto frontier, the airport can handle that amount of traffic. However, whenever the data point is outside the envelope, the airport cannot handle all the aircraft in that time period. Thus, some aircraft have to be delayed until the next time period. To determine the delay experienced, the actual arrival time is calculated using a queue approach. The airport is treated as a node and the input to the node is the arrival and departure demand. The airport has a service rate described by the Pareto frontier. During the 15 minute time interval, the baseline technology (TMA) can allow a certain amount of aircraft to land. So, for JFK, the TMA C&T allows 20 arrivals per hour. Thus, the 15 minute time period is divided into 20 arrival slots. Any time an aircraft has to land, it finds an available slot that is equal to or greater than its scheduled arrival time. The slot it finds is the flight's actual arrival time. If there are 23 aircraft scheduled to land in the 15 minute time period, then three aircraft will have to be delayed until the next time period. Any flights that are delayed to the next time period are given priority to land before the other flights not yet delayed. For the TMA-TM + CMS C&T, the airport arrival capacity is increased to 25 flights. So, for this C&T, the time period is divided into 25 arrival slots. This means that the airport can handle the 3 additional aircraft and they would not experience any delay.

Furthermore, whenever the data point falls within the green shaded area, there is potential for a decreased arrival delay with C&Ts because of the increase in arrival slots. Since the arrivals can be scheduled closer together, the aircraft has more slots that it can choose from to land. For example, even if there are only five arrivals in the 15 minute time interval, they will still have 20 arrival slots to choose from to land in the baseline case. For the TMA-TM + CMS C&T, they will have 25 arrival slots to choose from, giving the arrivals more opportunity to find a slot closer to their scheduled arrival time. To illustrate this point further, imagine an extreme case with infinite arrival slots in the time period. The arrival delay would be zero since the aircraft's scheduled arrival time would also be its actual arrival time.

Once all the actual arrival times are established, the delay is calculated by subtracting the actual arrival time with the scheduled arrival time.

Looking at the maintaining departure ops method of constructing Pareto frontier, which increases both arrival capacity and departure capacity, there is a larger area of improvement. See Figure 23.

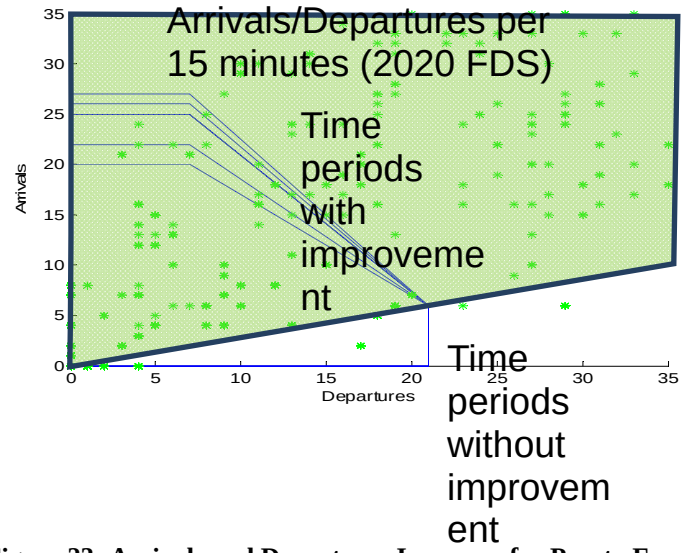


Figure 23: Arrivals and Departures Increases for Pareto Frontier

The increased departure and total capacity means that the airport can handle a larger amount of flights in the same time period. So there will be fewer flights delayed to the next time period compared to the conservative Pareto frontier. The same analysis done for the conservative Pareto frontier is also performed using the maintaining departure ops Pareto frontier.

9.3 JPDO Scenarios

Several input demand sets are used to determine how much benefit the airport experiences with the improvements provided by the C&Ts. The input demand sets to the analysis are JPDO scenarios from 2009 – 2030 in yearly increments and from 2035 – 2060 in five year increments. Even though an airport may have a large increase in arrival throughput, if the arrival demand to that airport is not high enough, there will not be much reduction in delay. This type of analysis allows for a more realistic look at the benefits at an airport by applying an actual demand set to the Pareto frontier. Likewise, if the arrival and departure demand is not within the green shaded area, then there will not be any decrease in delay.

There are eight JPDO scenario days available that represent typical air traffic across the NAS. The traffic count for the baseline year (2009) for each of these days is shown in Table 23.

Table 23: Traffic count for different JPDO scenario days for 2009

Day	Total AC
11-08-2008	33,576
11-20-2008	49,295
01-18-2009	33,390
03-19-2009	48,134
04-12-2009	36,507

06-18-2009	49,359
08-13-2009	51,082
09-28-2009	38,381

September 28, 2009 was chosen as the first day to analyze since it represents a nominal day where the traffic is not at a maximum or minimum value.

9.4 Results

After running the simulations, the following results were obtained. The average arrival delay in seconds, as an example of the delay results, is calculated for both types of Pareto frontiers for JFK, see Table 24 and Table 25.

Table 24: Average arrival delay by decision support tool by years at JFK for conservative Pareto Frontier

YEAR	TMA only	TMA + EDA	TMA-TM + CMS	TMA-TM + CMS + EDA	TMA-TM + FIM	Theoretical Max
2009	69.44	69.10	68.82	68.82	68.81	68.80
2010	67.63	67.28	66.78	66.78	66.78	66.78
2011	71.21	70.83	70.58	70.58	70.58	70.56
2012	74.70	74.10	73.84	73.84	73.83	73.82
2013	86.33	85.61	84.87	84.87	84.86	84.86
2014	95.06	94.37	93.55	93.55	93.55	93.52
2015	110.12	108.40	107.67	107.67	107.67	107.65
2016	124.19	123.29	122.89	122.89	122.89	122.86
2017	151.41	150.27	149.48	149.48	149.47	149.47
2018	190.80	188.88	188.23	188.23	188.22	188.19
2019	230.06	228.54	227.90	227.90	227.88	227.87
2020	318.97	315.41	315.02	315.02	315.01	315.00
2021	512.46	510.20	509.39	509.39	509.38	509.36
2022	669.94	659.08	658.49	658.49	658.49	658.46
2023	965.39	962.16	961.90	961.90	961.90	961.88
2024	1293.34	1288.29	1288.05	1288.05	1288.05	1288.04

Table 25: Average arrival delay by decision support tool by years at JFK for the maintaining departure ops Pareto frontier

YEAR	TMA only	TMA + EDA	TMA-TM + CMS	TMA-TM + CMS + EDA	TMA-TM + FIM	Theoretical Max
2009	69.44	63.93	57.85	57.85	57.54	56.39
2010	67.63	62.76	57.05	57.05	56.50	55.11
2011	71.21	65.02	59.47	59.47	59.12	58.12
2012	74.70	69.88	62.40	62.40	61.93	60.16
2013	86.33	77.67	67.88	67.88	67.46	65.11
2014	95.06	86.51	74.16	74.16	73.00	70.76
2015	110.12	94.77	82.98	82.98	80.99	77.12
2016	124.19	106.94	91.29	91.29	87.76	85.34
2017	151.41	124.29	103.69	103.69	97.15	93.79

2018	190.80	144.60	112.57	112.57	107.69	104.40
2019	230.06	172.95	131.42	131.42	125.15	119.11
2020	318.97	226.57	164.48	164.48	158.19	144.31
2021	512.46	341.98	221.28	221.28	210.13	193.77
2022	669.94	426.75	282.94	282.94	254.27	230.34
2023	965.39	651.95	384.00	384.00	346.83	312.62
2024	1293.34	907.63	536.02	536.02	465.81	418.34
2025	1631.08	1197.17	753.80	753.80	656.66	601.08
2026	1958.64	1476.98	977.24	977.24	867.26	773.61
2027	2593.96	2005.15	1389.14	1389.14	1279.12	1155.59

In Figure 24, the left image shows the conservative Pareto frontier results and the right image shows the delay when the airport capacity is allowed to increase.

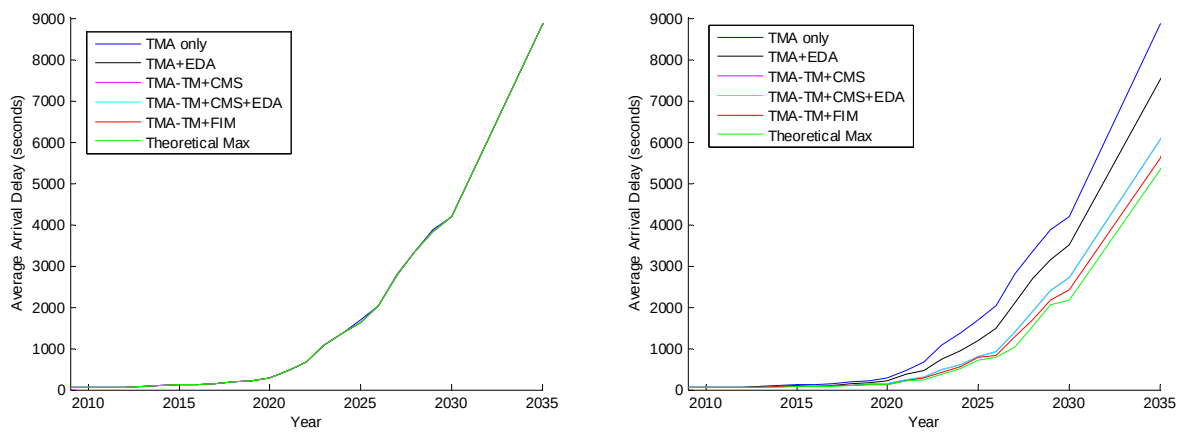


Figure 24: Delay reduction for JFK for 2020 (Conservative vs. Maintaining Dep. Pareto Frontier approach)

The results after the airport experiences greater than 900 seconds (15 minutes) of average arrival delay should be ignored. During these periods of high congestion, flights may be grounded in real world operations to absorb some of this delay. This analysis does not take into account these situations.

With the conservative approach, the average delay decreases slightly with the different technologies during the earlier years. As the demand increases, the delay decreases as well. However, the improvements are rather small. The traffic at JFK is fairly balanced so there are few periods when the increase in arrival capacity has an impact on the arrival delay. The improvements are more substantial with the maintain departure ops Pareto frontier approach. As shown in Figure 24, the Pareto frontier shows more delay reduction as different C&Ts are applied to the demand set. This result is expected since JFK's traffic is fairly balanced between arrivals and departures for most time periods. There are only a few time periods where it experiences an influx of arrivals. Figure 25 shows a heat map of the traffic JFK experiences from 2009 to 2065. The dark red parts show a high density of aircraft and the dark blue show a low density of aircraft. So, the conservative Pareto frontier would not benefit JFK much while the other Pareto frontier would have more benefits.

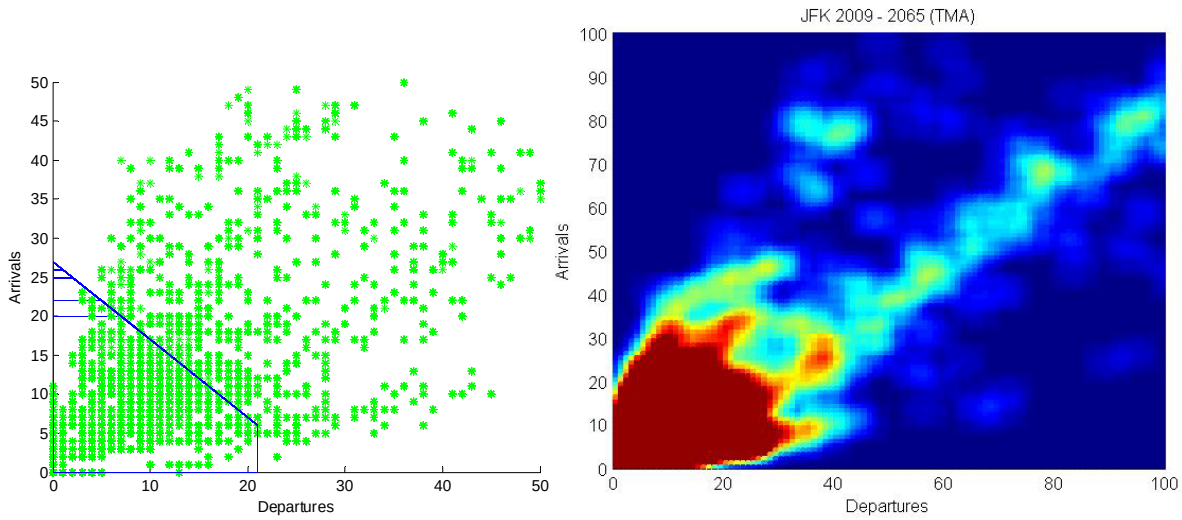


Figure 25: JFK Arrival/Departure in 15 minute time bins for 2009 – 2065

This same analysis was applied to the other airports to assess the delay saving benefits at each one. There are some interesting results.

By comparing the delay numbers for a specific year for each of the different airports, a general trend can be ascertained. The year 2017 is looked at further for the conservative Pareto frontier approach.

Table 26: Arrival Delay at 2017 for Different Airports (Conservative Pareto Frontier)

APT	TMA only	TMA + EDA	TMA-TM + CMS	TMA-TM + CMS + EDA	TMA-TM + FIM	Theoretical Max
ATL	798.80	737.69	703.28	703.28	703.28	686.37
CLT	166.96	163.47	162.90	162.89	162.88	162.86
DEN	60.94	48.00	39.51	39.51	39.51	34.56
DTW	84.16	83.21	82.99	82.99	82.96	82.96
EWR	166.47	165.89	165.49	165.49	165.45	165.45
IAH	44.39	35.65	31.09	31.09	31.09	30.05
JFK	151.41	150.27	149.48	149.48	149.47	149.47
LAX	67.16	67.16	60.28	60.28	60.28	60.28
MCO	27.68	26.55	25.32	25.32	25.32	19.72
MEM	32.08	32.08	32.00	32.00	32.00	32.00
MIA	49.97	48.86	48.08	48.08	48.08	47.69
MKE	24.79	22.73	21.91	21.91	21.91	21.91
ORD	35.75	34.25	34.02	34.02	34.02	33.99
SDF	33.89	33.15	32.43	32.43	32.43	31.41
SEA	41.33	39.81	39.64	39.64	39.64	39.64
STL	39.48	39.45	39.33	39.33	39.33	39.28

JFK was already shown to have little benefit through the conservative approach. However, there are several airports that benefit greatly. ATL and DEN show drastic improvement with C&Ts over the baseline TMA only case. These improvements can be explained by plotting the Pareto frontier and looking at a heat map showing the traffic these airports experience.

In Figure 26 below, the arrival and departure demand is shown for both ATL and DEN. The Pareto frontier is much wider than JFK since the total airport capacity for both ATL and DEN is larger. So the trade-off between the arrivals and departures is less during periods of high arrival traffic. Likewise, there are more periods of higher arrivals for both these airports, unlike JFK which had more balanced levels of arrivals and departures. All these characteristics mean that the conservative approach results in a greater delay reduction than at JFK.

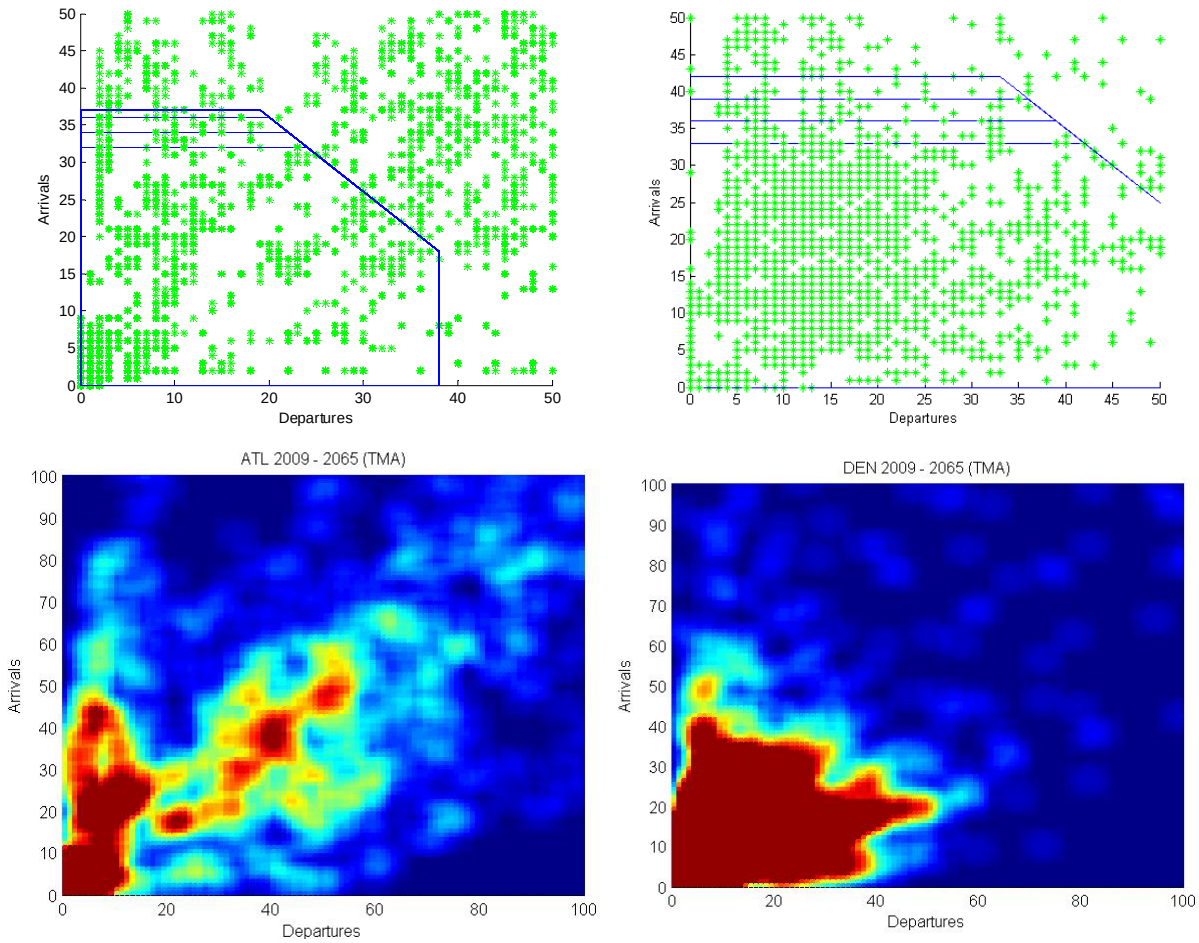


Figure 26: ATL and DEN Arrival/Departure in 15 minute time bins for 2009 – 2065

The arrival delay for the maintaining departure ops Pareto frontier analysis for the year 2017 is shown in Table 27 below.

Table 27: Average Arrival Delay using Maintaining Dep. Ops Pareto frontier

APT	TMA only	TMA + EDA	TMA-TM + CMS	TMA-TM + CMS + EDA	TMA-TM + FIM	Theoretical Max
ATL	798.80	567.68	443.99	443.99	443.99	400.56
CLT	166.96	131.80	109.69	106.79	98.97	94.69
DEN	60.94	47.43	38.57	38.57	38.57	33.22
DTW	84.16	78.49	74.92	74.92	73.83	73.83
EWR	166.47	155.57	144.25	144.25	140.85	140.85

IAH	44.39	35.01	30.83	30.83	30.83	29.69
JFK	151.41	124.29	103.69	103.69	97.15	93.79
LAX	67.16	67.16	60.29	60.29	60.29	60.29
MCO	27.68	26.48	25.35	25.35	25.35	18.65
MEM	32.08	32.08	31.87	31.87	31.87	31.77
MIA	49.97	47.86	46.06	46.06	46.06	45.13
MKE	24.79	22.75	21.63	21.63	21.63	19.78
ORD	35.75	32.58	31.03	31.03	31.03	30.34
SDF	33.89	31.56	30.47	30.47	30.47	30.47
SEA	41.33	37.67	37.20	37.20	37.20	37.20
STL	39.48	35.30	33.18	33.18	33.18	32.92

As expected, almost all airports show significant improvement with this approach. Most airports operate with a balanced number of arrivals and departures, which is the region where the airports will experience benefits with the C&Ts.

However, we still need to determine which method to apply to each airport to accurately represent the improvements at each airport. In order to do so, we analyzed all the airports' most popular runway configuration from the ASPM data. By looking at the runway configuration, we can see the interaction between the arrivals/departures to see their effects on the runway operations. If there are heavy interactions between departure and arrival runways, then the benefits at this airport are best described using the conservative Pareto frontier approach. Conversely, if the departures/arrivals do not affect each other and the runway interactions are independent, then the Maintaining Departure Operations approach is used. For the ASDE-X airports, the methodology for each airport is displayed in Table 28 below.

Table 28: Pareto Methodology Selection

Airport	Arrival |Departure Runway Configuration	Pareto Methodology
ATL	26R,27L,28 | 26L, 27R	Maintaining Departure
CLT	23 | 18C	Conservative
DTW	21L,22R | 21R, 22L	Maintaining Departure
EWR	22L | 22R	Maintaining Departure
IAH	26L,26R,27 | 15L, 15R	Maintaining Departure
JFK	31L,31R | 31L	Conservative
LAX	24R,25L | 24L, 25R	Maintaining Departure
MCO	17L,18R | 17R, 18L	Maintaining Departure
MEM	18L,18R | 18C, 18L, 18R	Conservative
MIA	8L,9 | 8R, 12	Conservative
MKE	25L | 19R	Maintaining Departure
ORD	27L, 27R | 22L, 28	Maintaining Departure
SDF	35L,35R |35L, 35R	Conservative
SEA	16C, 16R | 16C	Conservative
STL	12L, 12R | 12L, 12R	Conservative

10 Nationalization and Annualization

Section 9 described obtaining the average per aircraft delay savings for each project year for the 16 ASDE-X airports. In order to determine the national benefits, these results are extrapolated to other TMA airports. Also, the simulations to determine the per aircraft delay savings were done for one day, and the single day simulations need to be expanded to provide annual delay savings.

10.1 Nationalization of Results

Several of the major airports are not adapted for TMA, so they are ignored. The remaining TMA-capable airports beyond the 16 airports analyzed in Section 9 are listed in Table 29. We need to calculate the benefits at these places to extrapolate the national benefits.

Table 29: TMA Airports to Analyze

BOS	BWI	CVG	DCA
FLL	IAD	LAS	LGA
MSP	PDX	PHL	PHX

First, each of these airports is analyzed to look for their most common runway configuration based on 2011 ASPM data. The arrival runway configuration at each airport is compared to the ASDE-X airports to find similarities. Depending on the arrival configuration, they may look like one of the airports that were already analyzed. Each of the TMA airports is then mapped to an ASDE-X airport.

Without the necessary track data, the TMA airports listed above are not modeled in detail. Instead, the benefits are taken from the ASDE-X airport and applied to the corresponding TMA airport. The benefits analysis is then performed using these additional airports starting from the Pareto analysis.

It is assumed that at each TMA airport, they will have the same percentage improvement as their mapped airport for each given C&T. So, if DFW is mapped to ATL, then DFW will share the same benefits as we obtained at ATL.

The percentage improvement is applied to each TMA airport's Pareto frontier and the rest of the analysis is completed in the same manner described previously for the ASDE-X airports. This process is completed and the benefits at these airports are representative of the entire NAS.

10.2 Annualization of Results

Initially, only one JPDO scenario was used for the Pareto analysis. In order to annualize the results, somehow these results need to be applied across an entire year. We have eight JPDO scenarios, so each of these scenarios can be used to better represent traffic for a year. As a reminder, the table of JPDO scenarios is shown below.

Table 30: JPDO Scenarios

Day	Total AC	Weight
11-08-2008	33,576	3
11-20-2008	49,295	4

01-18-2009	33,390	3
03-19-2009	48,134	4
04-12-2009	36,507	3
06-18-2009	49,359	4
08-13-2009	51,082	4
09-28-2009	38,381	3

Each JPDO scenario reflects different types of traffic, ranging from low traffic to high traffic. Each day is weighted differently based on the amount of aircraft, with peak days given a weight of 4 and off-peak days given a weight of 3. Thus, the average benefit for each day of the year is calculated by the following formula:

$$\text{Average Benefit Per Day} = \frac{4*(\text{Sum of Peak Days' Benefit}) + 3*(\text{Sum of Off-Peak Days' Benefit})}{28}$$

The benefit for each JPDO scenario is calculated and averaged using the formula to get the average benefit per day.

We then obtain the average delay savings per day for each airport and each technology. The benefits assessment will use these numbers to calculate the total benefits that can be expected from each technology. Then, this result is nationalized by multiplying the number by 365 days.

11 Analysis Methodology for Time Savings Benefits

Two types of benefits are assessed in this report: (1) flight time savings from more efficient trajectories and (2) fuel savings from flying OPDs. Sections 6 through 10 have been explaining the estimation of the time savings benefits. Section 11 describes the completion of the time savings benefits assessment. Section 12 describes the completion of the OPD fuel savings benefit.

The benefit associated with flight time savings includes reduced aircraft operating costs and passenger time savings. The operating cost benefit includes fuel savings from the reduced flight time. The analysis in this report includes this fuel savings as part of estimating reduced operating costs from decreased flight time; fuel saving benefits from flying OPDs is estimated separately.

The benefits are estimated for three concept migration paths listed below:

Migration Path 1

- TMA (baseline)
- TMA + TM + CMS
- TMA + TM + CMS + FIM

Migration Path 2

- TMA (baseline)
- TMA + EDA
- TMA + EDA + TM + FIM

Migration Path 3

- TMA (baseline)
- TMA + EDA
- TMA + EDA + TM + CMS
- TMA + EDA + TM + CMS + FIM

11.1 Approach to Estimate Time Saving Benefits

Previous sections discussed how simulations were conducted to determine delay times at each TMA airport. The simulations were conducted for each set of concepts listed above, and were conducted using a demand set appropriate for each future year. The simulations at each airport were conducted for eight different representative days used by the JPDO. The eight days represent different weather and status conditions of the NAS during a year. Section 10.2 discussed how these delay times from the eight-day delay time simulations for each TMA airport are combined to estimate a representative daily delay savings which if multiplied by 365 to obtain the annual delay savings.

By subtracting the total delay for each set of concepts from the TMA only delay, we can then determine the decrease in flight times for each set of concepts as compared to the base case of TMA only. We also determine the decrease in flight times as each concept is incrementally

added to the previous concept set by subtracting that delay from the previous set of concepts in the migration path. This gives us the incremental time savings benefits of adding each concept.

11.2 Calculating Total Flight Time Savings in each Future Year

For years through 2030, simulations were run for each year so we have the total annual delays for each concept set for these years. After 2030, simulation runs were made at 5-year intervals and the total annual delays for intervening years were determined using linear interpolation.

It is noted that for some airports the average arrival delay calculated by the simulation model exceeds reasonable levels for the projected demand and airport capacity. Airlines would unlikely scheduled flights when average arrival delay reaches unreasonable levels. For this reason, the calculated average delay results were capped in the year before the average arrival delay exceeded 5 minutes. The cap year is different at each airport. This assumption allows no further growth in demand at an airport after the cap year. Since both the flight time savings and OPD savings depend directly on demand, both benefits show no further growth and are assumed to stay at the same level beginning at the cap year.

11.3 Adjustment for Implementation of Ground and Airborne Equipment

After the calculations in Section 11.2, we now have the total annual flight times summed across all TMA airports for each year in the project lifecycle. Furthermore, we have this for each set of concepts listed in at the beginning of Section 11.

An adjustment now needs to be made in each year to account for the implementation schedules of ground and airborne equipment for the concepts. Ground equipment will be needed at each airport for EDA, TM, and CMS; in addition, aircraft equipage, such as ADS-B Out, ADS-B In, and upgrade of aircraft's Flight Management System, will be needed for these concepts and for FIM.

Not all delay reductions determined in the simulations will be obtained in the beginning years until all TMA airports have the equipment needed for each concept set and all aircraft have the equipage needed. Aircraft equipage involves the introduction of new aircraft with needed equipage and retrofitting existing aircraft with needed equipage. Thus, the aircraft equipage usually proceeds over a longer time period than the implementation of ground equipment.

Implementation schedules for ground and airborne equipment were developed as part of the cost estimation effort covered in Sections 14 through 17 for EDA, CMS, TM, and FIM respectively. These implementation schedules were used to adjust the benefits in the beginning years. For example, if 30 percent of airports and 20 percent of aircraft had equipment in one year, the delay savings in that year is reduced to 30 percent to account for airport installations and then to another 20 percent to account for the percent of aircraft equipped.

Since we are estimating the benefits of delay savings for sets of concepts, as listed at the beginning of Section 11, the adjustments for implementation of ground and airborne equipment are more complicated than if doing so for just a single concept. For example in adding a second capability to a set, its implementation schedule for airports and aircraft is compared to the schedule for the first capability. It may be that some or all of the ground and aircraft equipment needed for the second capabilities has already been implemented under the first concept. If there are differences, then the percent of additional flight time savings benefits achieved each year are adjusted to account for the second capability's implementation scheduled.

11.4 Determining the Monetary Present Value of Time Savings Benefits

The calculations described thus far yield the total delay time for each set of concepts listed at the beginning of Section 11 and for each future year. As was stated previously, subtracting the total delay for each set of concepts from the TMA only delay determines the decrease in flight times for each set of concepts as compared to the base case of TMA only. We also determine the decrease in flight times as each concept is incrementally added to the previous concept set by subtracting delay from the previous set of concepts in the migration path.

A dollar value needs to be assigned to the time savings to determine a monetary benefit. The FAA has standard dollar values for operating cost (expressed as costs per hour) for aircraft and standard dollar values of passenger time (also expressed as costs per hour). The FAA also has standard value of number of seats in aircraft and the load factor for these seats (i.e., percent of seats occupied). These values were applied to the time savings calculation to obtain the dollar benefit for each year for each concept set in Fiscal Year 2012 dollars (FY12 $). These standard dollar values are presented in Section 13 when the dollar benefits are shown.

The standard process specified by the Office of Management and Budget (OMB) to determine the present value of dollar benefits for federal programs is to apply a 7 percent discount rate per year to the base year (FY12) dollar benefits. This was done for the future year flight time reduction dollar benefits to obtain the present value of time saving benefits for each concept set. Again, monetary benefits are presented in Section 13.

12 Approach to Estimate Fuel Savings Benefits from Flying OPDs

The benefits from time savings and from flying OPDs are estimated separately since there are differences in the estimation approaches. Several studies have estimated benefits from flying OPDs, but these studies estimated the maximum potential fuel savings benefits possible from OPDs and not benefits related to any concepts that will enable flying OPDs. The concepts examined in this report will enable OPD trajectories but not to the extent to achieve 100 percent compliance of all arrivals to fly OPDs. Thus, we needed to find an approach to estimate the extent to which the different concept sets will enable OPDs. Section 12 describes the approach to do this.

A paper by John E. Robinson III and Maryam Kamgarpour, "Benefits of Continuous Descent Operations in High-Density Terminal Airspace Under Scheduling Constraints," NASA Ames Research Center, Moffett Field, California, 94035, estimated the average potential fuel savings per flight flying an OPD. This represents the maximum potential fuel savings per average flight. The results of the Robinson and Kamgarpour study were adapted to help estimate the fuel saving from OPDs as enabled by the concept sets examined in our study. Our approach used the maximum potential fuel savings per flight estimated by this study for the 14 TMA airports that were examined by the study. A method was designed to extend the results of the Robinson and Kamgarpour study to the remainder of the TMA airports. Then a method was developed to make downward adjustments to the maximum potential per flight fuel savings to account for the extent to which each concept set will enable OPDs.

12.1 Calculating Maximum Potential OPD Fuel Savings at TMA Airports

Estimating maximum potential OPD fuel saving benefits at the TMA airports is explained in this subsection. First the method used in the Robinson and Kamgarpour study will be summarized. This approach used historical data on descent trajectories at a number of airports, including 14 of the TMA airports we examined. The level portions of these descent trajectories were identified using a software program. To represent the trajectories flown under OPDs, the level portions of the descent trajectory were moved to the top of descent. There is less fuel usage if the level portions are flown at a higher altitude. BADA (Base of Aircraft Data), which is a model that determines fuel burn for aircraft flying at various altitudes, was used to calculate fuel use in flying the level portions at the higher altitude (i.e., OPD trajectories) and at the different lower altitudes of the historical trajectories when not flying OPDs. The differences in these fuel burns are the fuel savings from flying OPDs. Thus, the Robinson and Kamgarpour study provides estimates of the maximum per flight fuel savings for flying OPDs at 14 TMA airports. In moving the horizontal segments of arrival trajectories to the top of descent, this study considers only a change in the vertical component of the trajectory and not the lateral component, and thus the OPD is defined within the vertical dimension. Since we use the Robinson and Kamgarpour study as a basis, this definition applies to our study also.

Results for the 14 TMA airports analyzed by the Robinson study were used directly as estimates of the maximum potential OPD fuel savings for these airports. However, we also need estimates of the maximum potential per flight OPD fuel savings for the remaining TMA airports. Three other studies were identified that estimated OPD fuel savings at these other TMA airports:

- Melby, P., Mayer, R., "Benefit Potential of Continuous Climb and Descent Operations," ICAS 2008 Congress including the 8th AIAA 2008 ATIO Conference, September 2008, AIAA 2008-8920.
- FAA Performance Analysis and Strategy Office, "Projected Benefits of CDAs," July 31, 2008 (J. Post)
- FAA Research and Technology Development Office, Air Traffic System Concept Development Group, "4D Advanced Arrivals Metrics/Benefits Analysis Report," December 2009 (D. Howell).

But we would like to use the Robinson and Kamgarpour study results as basis. We did this by: (1) For each of the three studies, found ratio of fuel savings at each airport other than the 14 to fuel savings of each of the 14 airports from Robinson and Kamgarpour study (produces 14 ratios per airport for each study); (2) averaged the 14 ratios across the 3 studies; (3) multiplied the averaged ratios for each additional airport by the Robinson and Kamgarpour values for the 14 airports (produces 14 estimates of savings per airport); (4) took the average of the savings estimates. The results of these calculations yields an estimate of the maximum potential per flight OPD fuel savings for each of the other TMA airports based on the fuel savings estimated for the 14 airports in the Robinson and Kamgarpour study.

From the Robinson and Kamgarpour study, we directly have the maximum potential per flight OPD fuel savings at the 14 TMA airports covered in the Robinson study. For the remaining TMA airports, the above calculation yields the maximum potential per flight OPD fuel savings at the TMA airports not addressed in the Robinson and Kamgarpour study.

12.2 Calculating the Percentage of the Maximum Potential OPD Fuel Savings Enabled by each Set of Concepts

As previously discussed, the Robinson and Kamgarpour study, as well as the other three studies mentioned above, estimated the maximum potential average flight OPD fuel savings rather than evaluating the fuel saving enabled by any particular concept, which would likely be less than this maximum potential fuel savings. We designed an approach to estimate the percent of this maximum potential per flight fuel savings that would be enabled by each set of concepts we are examining.

In our simulations of the time savings benefits covered earlier, curves were generated that show controller intervention rate for a pair of arriving aircraft versus the size of the runway buffer. There is a set of curves for each set TMA airport analyzed and each curve in the set represents a particular set of the concepts being analyzed. A sample of these curves for Denver Airport is shown in Figure 27. The curves are for saturated demand; this is suitable for our analysis since the concepts will provide a benefit at high demand. At low demand levels, the concepts will not be needed to fly OPDs.

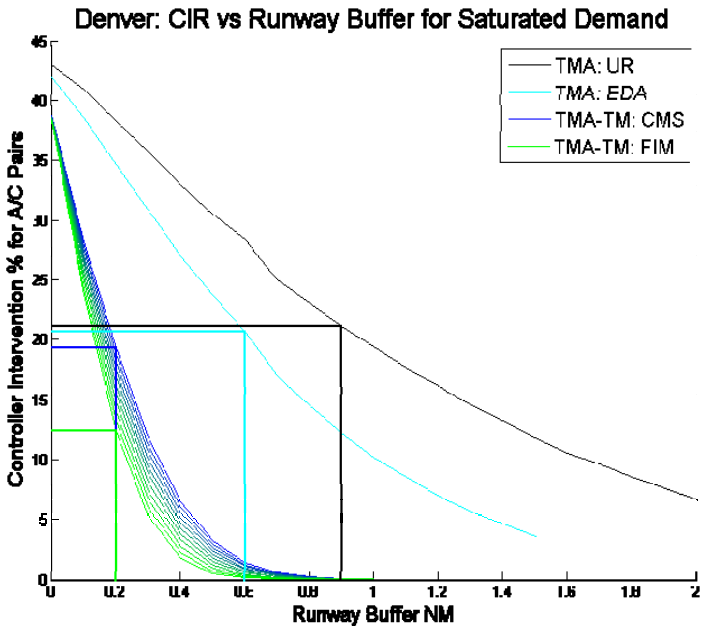


Figure 27: Controller Intervention Rate vs. Runway Buffer at Denver Airport

The controller intervention rate in these curves refers to the percent of arrivals for which there will be a potential loss of separation at a metering point, and thus the controller needs to intervene to provide a conflict resolution to change the trajectory of an arriving aircraft. In our approach, we assume if the controller intervenes with a conflict resolution advisory, then the OPD is not flown by that aircraft and there is no fuel savings benefit for that arrival. This is a worst case assumption in the sense that part of an OPD may have been flown before the controller intervention. However, the fidelity of the estimate does not allow us to estimate where during an arrival trajectory a controller intervention would take place, so we have assumed that the location of the controller intervention would not differ dramatically between the scenarios. Since we are looking at incremental benefits the impact of the location of the intervention should average out.

The runway buffer correlates to the airport throughput rate since a smaller runway buffer allows for an increase in airport throughput and vice versa. Thus, the curves can be viewed as controller intervention rate vs. throughput for each concept set. From these curves, the percent of arrivals with controller intervention for a particular throughput indicates the percent of arrivals with controller intervention and for which our assumption is the percent of arrivals where an OPD is not flown. Thus, [1- controller intervention percentage] is the percent of arrivals that would be flown as OPDs (i.e., no controller intervention and hence the OPD success rate). Figure 28 shows an example of Figure 27 showing controller intervention rate versus runway buffer converted to showing hourly arrival capacity versus controller intervention rate.

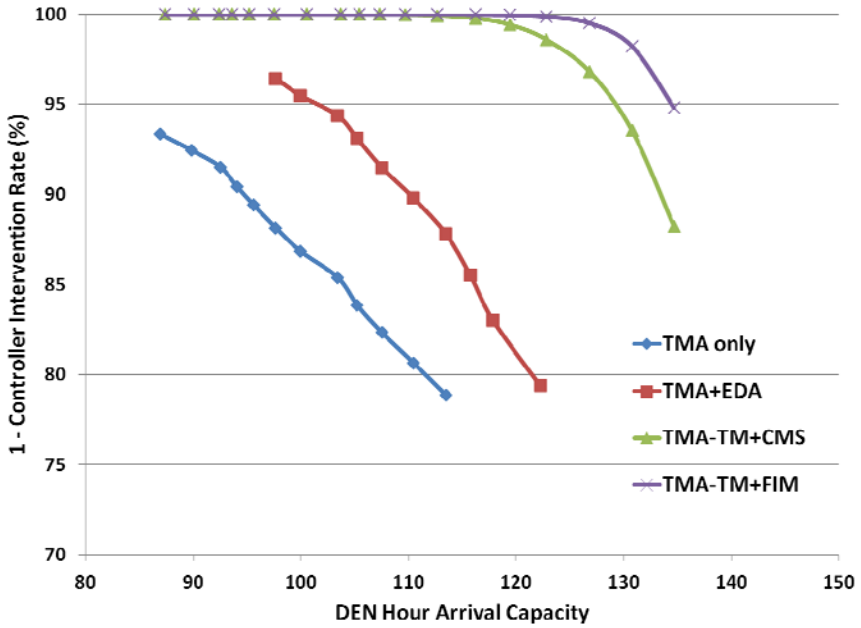


Figure 28 Arrival Capacity vs. 1- Controller Intervention Rate at Denver Airport

12.3 Calculating the OPD Fuel Savings Enabled by each Set of Concepts

The approach in Section 12.1 gives the maximum potential average per flight OPD fuel savings at each TMA airport; the approach in Section 12.2 shows how we determine the percent of this potential that will be obtained for each set of concepts studied. Multiplying these two values together provides the per flight OPD fuel savings for each concept set at each TMA airport.

The flight count for OPD arrivals for each TMA airport by future year for each concept set was obtained from the previous simulations of future arrivals. Multiplying these number of arrivals by the per flight OPD fuel savings and totaling fuel savings across all TMA airports gives the total annual OPD fuel savings for each concept set for each future year.

12.4 Adjustment for Implementation of Ground and Airborne Equipment

After the calculations in Section 12.3, we now have the total annual fuel savings from aircraft flying OPDs to the extent enabled by each set of concepts listed at the beginning of Section 11. As with the time saving benefits calculations presented in Section 11.3, adjustments need to be made in each year to account for the implementation schedules of ground and airborne equipment for the concepts. The same adjustments for the implementation schedule discussed in Section 11.3 are made for the future annual OPD fuel savings.

12.5 Determining the Monetary Present Value of OPD Fuel Savings Benefits

The calculations described so far in Section 12 yield the total annual fuel savings for each set of concepts. The OPD fuel savings benefits for that concept as compared to the base case of TMA only is obtained by subtracting the total TMA fuel savings from the fuel savings for a particular concept set. We also determine the increase in fuel savings as each concept is incrementally added to the previous concept set by subtracting fuel savings for the current set from the previous set of concepts in the migration path.

A dollar value needs to be assigned to the OPD fuel savings to determine a monetary benefit. Standard FAA dollar values for future fuel costs were applied to the fuel savings to obtain the dollar benefit for each year for each concept set in Fiscal Year 2012 dollars (FY12 $). This value is listed in Section 13 where the monetary benefits of OPS fuel savings are presented.

As with the time savings benefits, the standard process specified by the Office of Management and Budget (OMB) to determine the present value of dollar benefits for federal programs is to apply a 7 percent discount rate per year to the base year (FY12) dollar benefits. This was done for the future year OPD fuel savings dollar benefits in Section 13 to obtain the present value of fuel saving benefits for each concept set.

13 Monetary Benefit Analysis Results

The purpose of this section is to present the monetized results of the benefits discussed in previous sections.

In Section 10 the throughput/delay calculations were produced for 6 scenarios, including a baseline and 5 migration paths. The number of additional OPDs was calculated for 4 scenarios (a baseline and 3 test cases). The benefits are always reported incremental to the baseline for each test scenario. Later in Section 18, System Benefit and Cost Analysis Results, we combine the incremental benefits and costs to produce relevant economic metrics for use by decision makers during investment decisions.

13.1 Assumed Implementation Schedules

Each of the modeled scenarios depends on one or more technologies (EDA, TM, CMS, FIM). The benefits depend on the NAS-wide rollout of these technologies to the selected airports. Reasonable implementation schedules for EDA, TM and CMS were obtained from subject matter experts as part of the cost analyses presented in Sections 14 through 17. The FIM implementation schedule is based on recent assumptions used in the May 2012 FAA Surveillance and Broadcast Services (SBS) investment decision.

In the following subsections, we first present the benefits without considering implementation schedules, and then apply the assumed implementation schedules. Showing both these estimates should allow the reader to infer how changing the assumed implementation schedule could impact results.

When applying the implementation schedule, the benefits were assumed to start in the year after implementation because of uncertainty in the application start date and to allow time for a learning curve. None of the implementation assumptions are airport-specific, so benefits accrue at each airport using the percentage rollout across the NAS. This is a conservative assumption because an operational program would most likely implement at the higher benefit airport sites first.

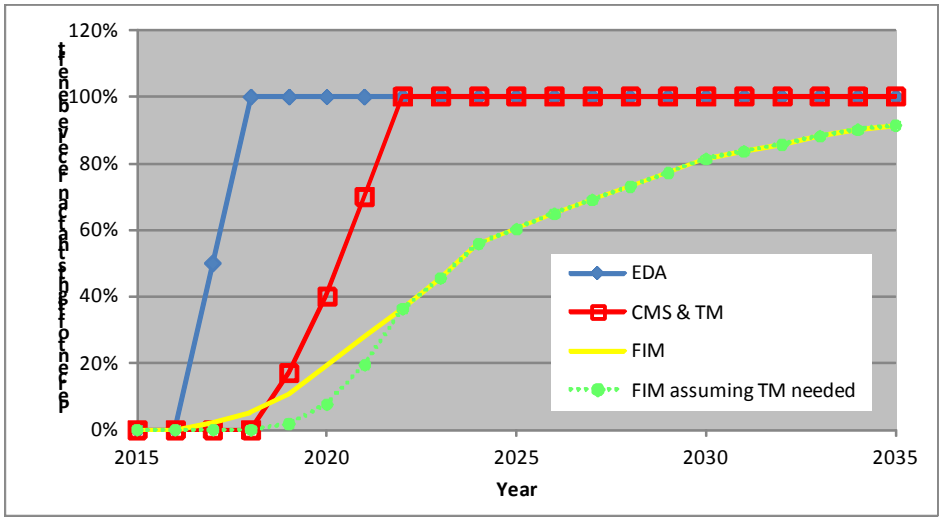


Figure 29: Percent of flights that receive benefit per year for supporting technologies

13.2 Monetary Valuation of Benefits

The delay benefits are derived in hours and monetized in terms of variable Aircraft Direct Operating Costs (ADOC) and Passenger Value of Time (PVT). The OPD benefits are derived in gallons of fuel saved and monetized directly using an assumed fuel cost.

Each year, the FAA Investment Planning and Analysis Office produces guidance on values to use for economic analysis. This analysis uses the April 2012 version of that guidance [1] that lists values in Fiscal Year (FY) 2012 units. For ease of use, average the FAA presents ADOC and PVT for 4 major aircraft categories (Air Carrier, Commuter & Air Taxi, General Aviation, and Military). The categories conform to the categories used for airport operations forecasts produced by the FAA Policy and Plans Office Terminal Area Forecast (TAF) [2].

Table 31 presents the variable ADOC per phase of flight and TAF aircraft category. Variable ADOC includes costs associated with fuel, oil, crew and maintenance. The average fuel price from 2012 to 2032 is $3.00 per gallon in $FY12 and was used to monetize the OPD benefits directly.

Table 31: Variable Aircraft Direct Operating Costs per phase of flight and TAF Aircraft Category [1]

	Variable Aircraft Direct Operating Costs (ADOC) FY12 $		
TAF Aircraft Category	**Per Airborne Hour**	**Per Ground Hour**	**Per Gate Hour**
Air Carrier	$5,064	$2,358	$1,507
Commuter & Air Taxi	$1,363	$633	$403
General Aviation	$780	$362	$230
Military	$8,528	$3,976	$2,550

As seen in Table 31, ADOC varies by phases of flight. The FAA guidance on applying ADOC for generic delay savings is to default to 18 percent Airborne, 41 percent Ground and 41 percent Gate. While the delay savings in this study is most likely related to airborne delay, we decided to apply the generic delay savings to be conservative. Table 32 presents the weighted ADOC used to monetize the delay savings.

Table 32: Weighted Variable Aircraft Direct Operating Costs per TAF Aircraft Category

Weighted Average ADOC per hour (weighted by phase of flight)			
Air Carrier	**Commuter & Air Taxi**	**General Aviation**	**Military**
$2,496	$670	$383	$4,211

PVT is calculated per passenger per hour and is based on Office of Management and Budget guidance. To calculate PVT per aircraft category the number of passenger seats (capacity) and load factor are needed. In December 2011, the OMB released a memo that stated that PVT per passenger would increase by 1.6 percent per year over and beyond inflation; this means the value of PVT increases each year even when calculating benefits in base year (e.g. FY12) dollars. Table 33 presents the passenger capacity and load factor and Table 34 presents the PVT per TAF aircraft category.

Table 33: Passenger Capacity and Load Factor per TAF Aircraft Category [1]

TAF Aircraft Category	Passenger Capacity	Passenger Load Factor
Air Carrier	102.2	83%
Commuter & Air Taxi	35.0	77%
General Aviation	4.0	53%

Table 34: Hourly Passenger Value of Time per passenger and per aircraft type [1]

Year	Average PVT per passenger	Average PVT per aircraft FY12 $			
		Air Carrier	Commuter & Air Taxi	General Aviation	Military
2012	$43.50	$3,685	$1,177	$92	$0
2013	$44.20	$3,745	$1,196	$93	$0
2014	$44.91	$3,805	$1,215	$95	$0
2015	$45.63	$3,866	$1,235	$96	$0
2016	$46.36	$3,928	$1,255	$98	$0
2017	$47.10	$3,990	$1,275	$99	$0
2018	$47.85	$4,054	$1,295	$101	$0
2019	$48.62	$4,119	$1,316	$102	$0
2020	$49.40	$4,185	$1,337	$104	$0
2021	$50.19	$4,252	$1,358	$106	$0
2022	$50.99	$4,320	$1,380	$107	$0
2023	$51.81	$4,389	$1,402	$109	$0
2024	$52.64	$4,460	$1,424	$111	$0
2025	$53.48	$4,531	$1,447	$113	$0
2026	$54.34	$4,604	$1,470	$115	$0
2027	$55.21	$4,677	$1,494	$116	$0
2028	$56.09	$4,752	$1,518	$118	$0
2029	$56.99	$4,828	$1,542	$120	$0
2030	$57.90	$4,905	$1,567	$122	$0
2031	$58.83	$4,984	$1,592	$124	$0
2032	$59.77	$5,064	$1,617	$126	$0
2033	$60.73	$5,145	$1,643	$128	$0
2034	$61.70	$5,227	$1,670	$130	$0
2035	$62.69	$5,311	$1,696	$132	$0
2036	$63.69	$5,396	$1,723	$134	$0
2037	$64.71	$5,482	$1,751	$136	$0
2038	$65.75	$5,570	$1,779	$139	$0
2039	$66.80	$5,659	$1,808	$141	$0
2040	$67.87	$5,750	$1,837	$143	$0
2041	$68.96	$5,842	$1,866	$145	$0
2042	$70.06	$5,935	$1,896	$148	$0
2043	$71.18	$6,030	$1,926	$150	$0
2044	$72.32	$6,127	$1,957	$152	$0
2045	$73.48	$6,225	$1,988	$155	$0
2046	$74.66	$6,325	$2,020	$157	$0
2047	$75.85	$6,426	$2,053	$160	$0
2048	$77.06	$6,528	$2,085	$162	$0
2049	$78.29	$6,633	$2,119	$165	$0
2050	$79.54	$6,739	$2,152	$168	$0
2051	$80.81	$6,846	$2,187	$170	$0
2052	$82.10	$6,955	$2,222	$173	$0
2053	$83.41	$7,066	$2,257	$176	$0
2054	$84.74	$7,179	$2,293	$179	$0
2055	$86.10	$7,294	$2,330	$181	$0
2056	$87.48	$7,411	$2,367	$184	$0
2057	$88.88	$7,530	$2,405	$187	$0
2058	$90.30	$7,650	$2,444	$190	$0
2059	$91.74	$7,772	$2,483	$193	$0
2060	$93.21	$7,897	$2,522	$196	$0

13.3 Monetizing Throughput Benefits

Section 8 presents the simulation methodology and Section 9.2 describes the two Pareto frontier approaches applied in the simulations. For each airport, a Pareto frontier approach was chosen as most reasonable based on airport runway configuration and current operations.

As mentioned in Section 11, the average delay calculated by the simulation model exceeds reasonable levels using the projected demand and airport capacity. Airlines would unlikely scheduled flights when average arrival delay reaches unreasonable levels. For this reason the calculated average delay results were capped in the year before the average arrival delay exceeded 5 minutes per aircraft. While individual flights may have long airborne delays, the average airborne delay in the current system is quite low. The 5 minute cap was used because an analysis of FY11 average airborne delay (defined as actual airborne time minus the estimated time en route) at each of the airports in the study showed a maximum average airborne delay of ~5 minutes (maximum seen at PHL). The cap year is different at each airport. This assumption allows no further growth in demand at an airport after the cap year. Since both the flight time savings and OPD savings depend directly on demand, both benefits show no further growth and are assumed to stay at the same level beginning at the cap year.

Table 35 presents the Pareto frontier approach chosen as most reasonable and the resulting demand capping year for each airport.

Table 35: Pareto curve used and demand capping year per airport

Airport	Pareto Curve Used	Demand capping start year	Airport	Pareto Curve Used	Demand capping start year
ATL	Maintain Departure	2012	LAX	Maintain Departure	2030
BOS	Maintain Departure	N/A	LGA	Conservative	N/A
BWI	Conservative	2051	MCO	Maintain Departure	2045
CLT	Conservative	2022	MDW	Conservative	2026
CVG	Conservative	N/A	MEM	Conservative	2052
DCA	Conservative	N/A	MIA	Conservative	2038
DEN	Conservative	2033	MSP	Conservative	2026
DFW	Conservative	2057	ORD	Maintain Departure	2035
DTW	Maintain Departure	2035	PDX	Conservative	N/A
EWR	Maintain Departure	2021	PHL	Conservative	2027
FLL	Conservative	2046	PHX	Maintain Departure	2041
IAD	Maintain Departure	2030	SEA	Conservative	2050
IAH	Maintain Departure	2035	SFO	Conservative	2026
JFK	Conservative	2019	SLC	Conservative	2037
LAS	Maintain Departure	2018	STL	Conservative	N/A

Figure 30 and Figure 31 present the annual delay savings derived from the simulations for the 5 concept migration scenarios before and after applying the implementation schedule, respectively. The results are incremental to the baseline and reflect the Pareto frontier approach and demand capping displayed in the Table 5. A major result of the simulation is that the delay savings (before implementation) are identical for 3 of the test scenarios: TMA-TM+CMS, TMA-

TM+CMS+EDA, TMA-TM+FIM. This implies that there is overlap and little synergistic impact between the applications when examining throughput.

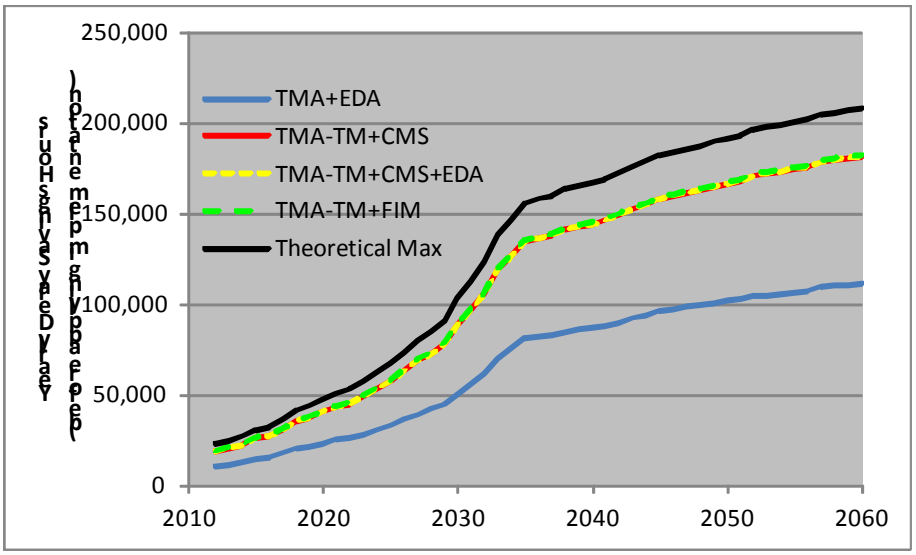


Figure 30: Yearly delay savings in hours before applying implementation

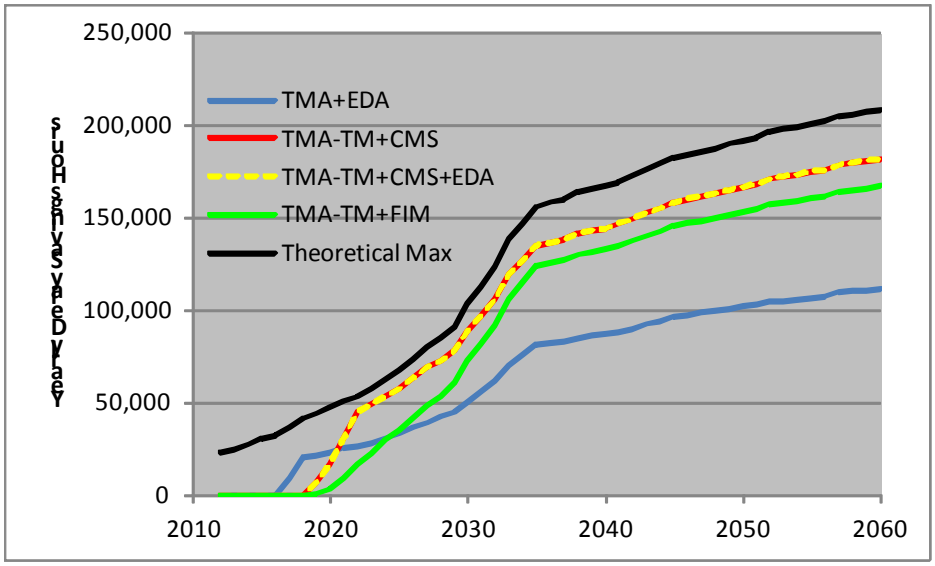


Figure 31: Yearly delay savings in hours

Figure 32 and Figure 33 display the total delay savings from 2012 through 2060 for each airport in the study before and after applying implementation. The benefits are not distributed evenly across the airports in the study. The top 5 airports represent 54 percent of the total benefit and the top 10 correspond to 81 percent of the total.

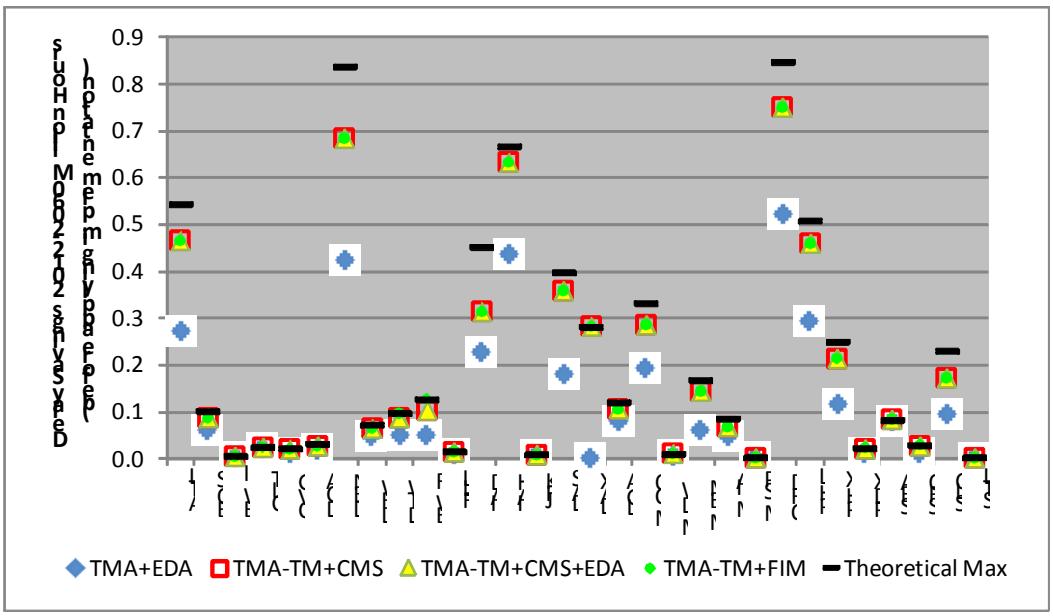


Figure 32: Delay savings 2012-2060 by airport before applying implementation

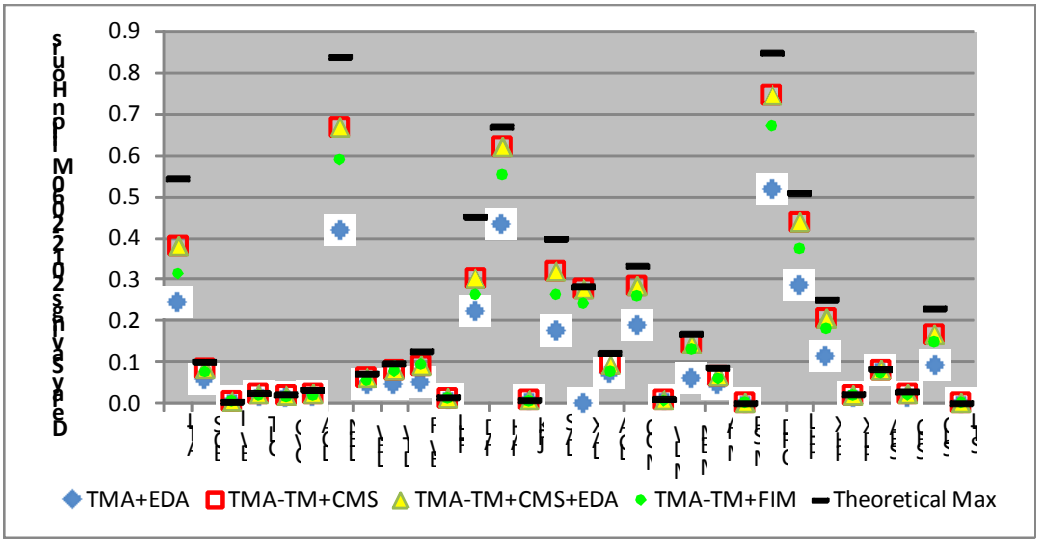


Figure 33: Delay savings 2012-2060 by airport

To monetize the delay savings benefits presented above using the economic values displayed in Table 32 and Table 34, we first need to determine the percent of each TAF aircraft type at each airport for each year. The FAA APO website projects the number of each aircraft type at each airport through 2040. We assumed the ratio of aircraft types stayed constant after 2040. Figure 34 and Figure 35 present the resulting yearly delay savings in FY12 millions of dollars ($M) before and after applying the implementation schedule.

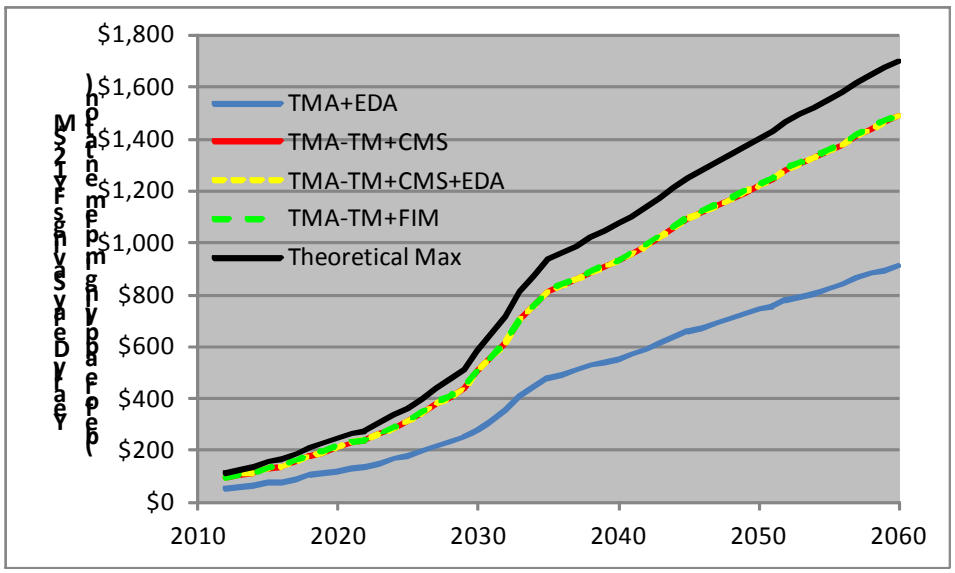


Figure 34: Yearly delay savings in FY12 $M before applying implementation

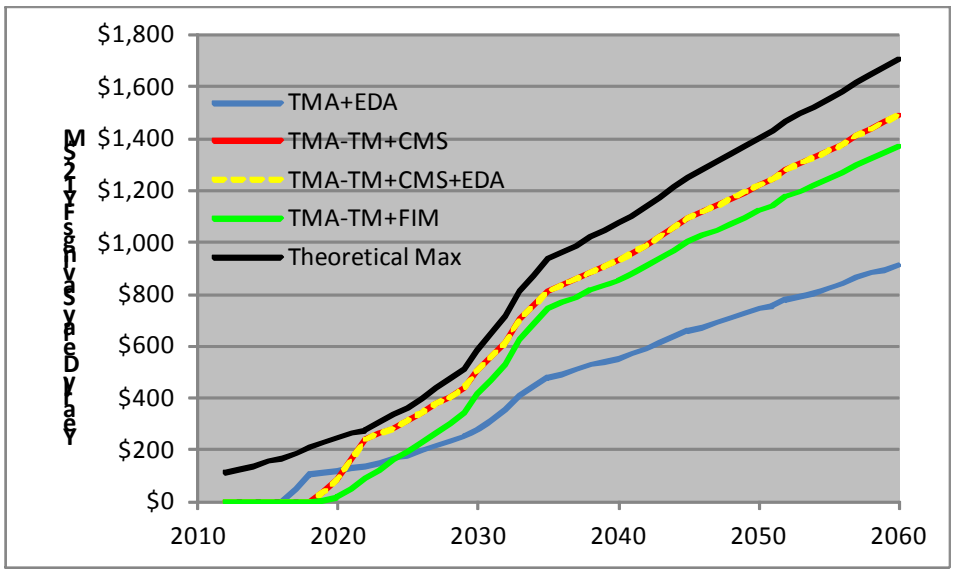


Figure 35: Yearly delay savings in FY12 $M

13.4 Monetizing Fuel Benefit

There are two major steps in estimating the OPD benefits related to the test scenarios. One is determining the average potential fuel savings per OPD; this value differs dramatically by site based on amount of inefficiency in the current route structure. The second step is examining the number of additional OPDs that can be expected by each scenario; this value is related to the amount of controller intervention required to handle different levels of demand. Section 12.1 describes how the average potential fuel savings was determined and Section 12.2 discusses the relationship between controller intervention and demand.

After applying the reasoning presented in Section 12.1, we derived the average OPD potential per aircraft at each airport of interest (see Figure 36.) This per aircraft average OPD potential takes the inefficiencies in the current system and the aircraft mix seen at these airports into account.

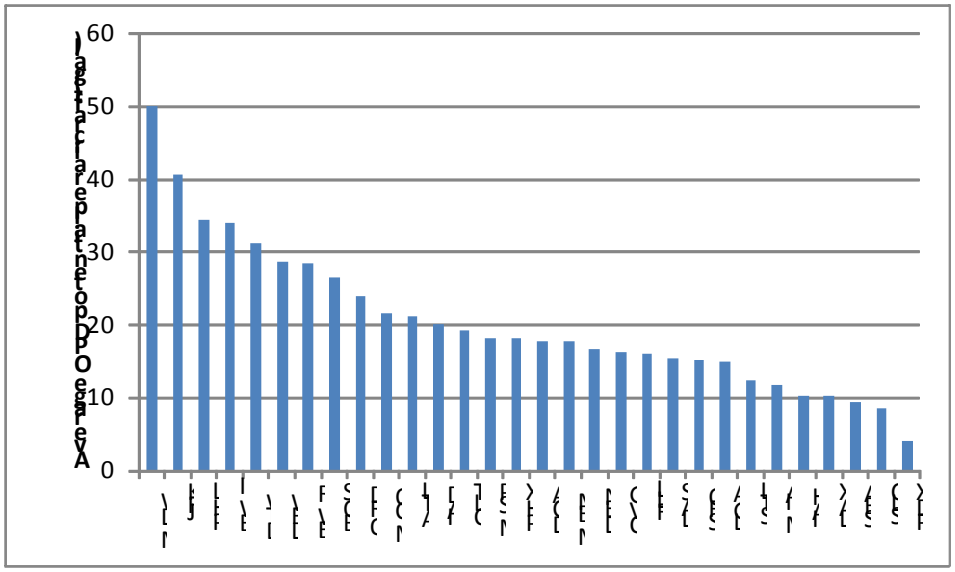


Figure 36: Average OPD potential per aircraft (gallons)

Figure 37 and Figure 38 display the yearly additional OPDs for each of the test scenarios before and after applying the implementation schedule. Unlike the throughout results, there are some differences between the later scenarios when examining the results before implementation. The TMA-TM+CMS and TMA-TM+CMS+EDA scenarios are still identical in Figure 37; however, the TMA-TM+FIM scenario does show some incremental benefit. Figure 38 shows that the incremental TMA-TM+FIM benefit is reduced to below that estimated by TMA-TM+CMS when the implementation schedule is applied.

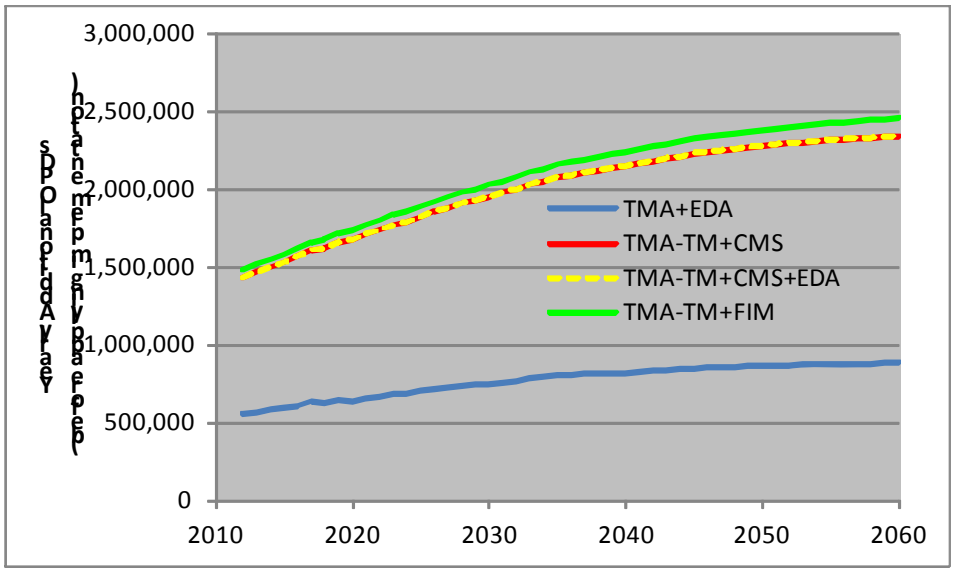


Figure 37: Yearly additional OPDs before applying implementation

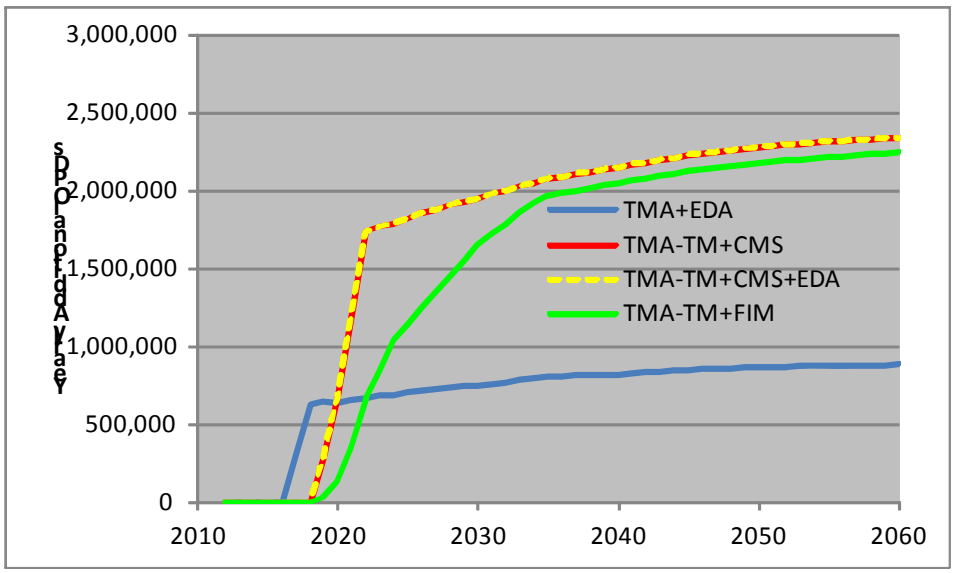


Figure 38: Yearly additional OPDs

Figure 39 and Figure 40 display the additional OPDs from 2012 through 2060 for each airport in the study before and after applying implementation. The benefits are not distributed evenly across the airports in the study; however, they are more evenly distributed than in the throughput case. The top 5 airports represent 29 percent of the total benefit and the top 10 correspond to 51 percent of the total.

Figure 39 also shows that the additional TMA-TM+FIM benefit only applies at a few airports, namely: DFW, LAX, MEM, MIA, MSP, PDX, and PHX.

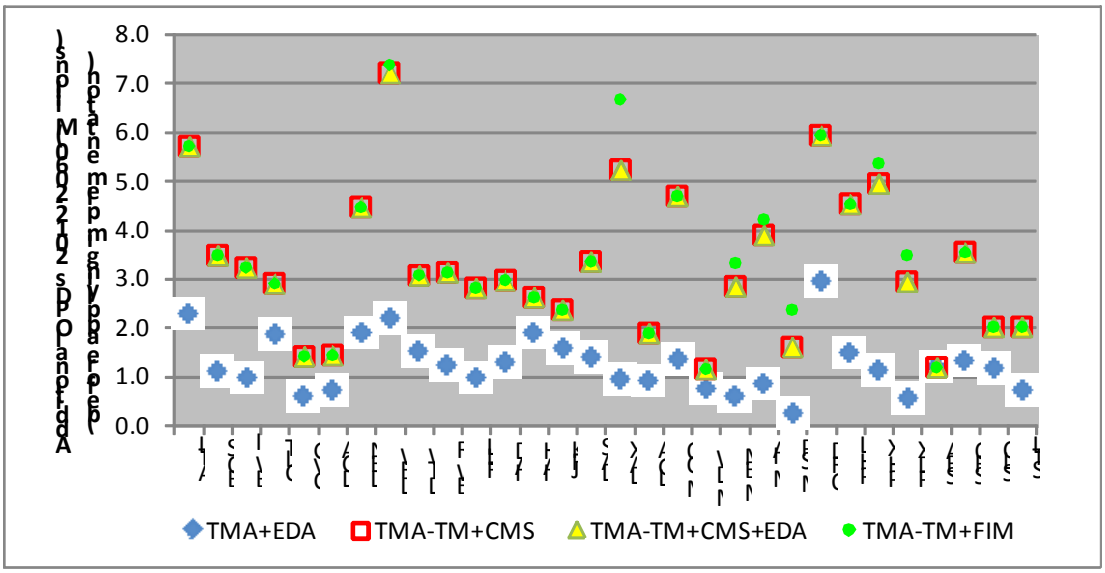


Figure 39: Additional OPDs 2012-2060 by airport before applying implementation

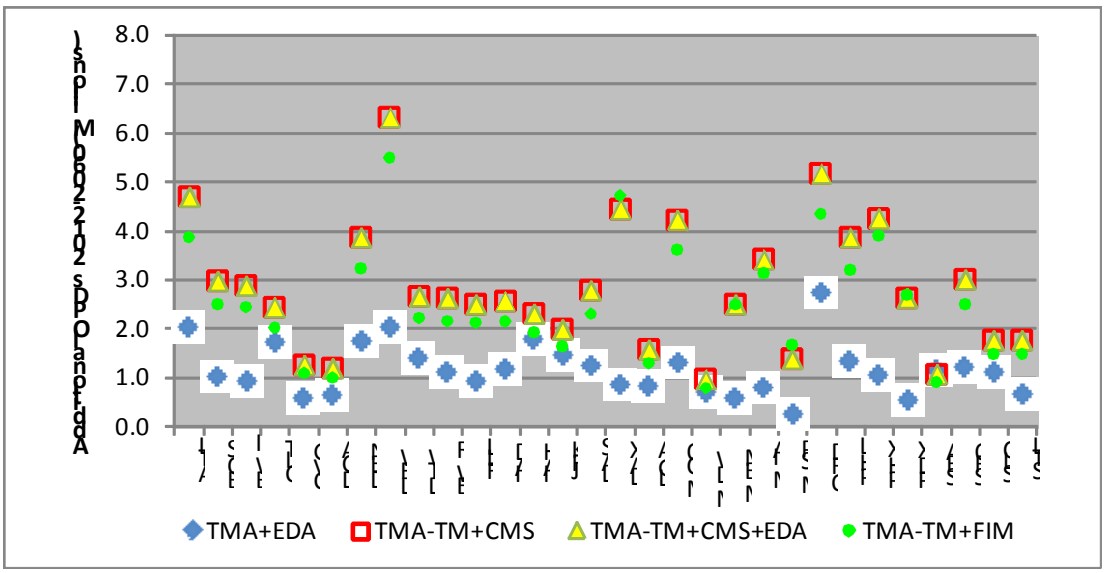


Figure 40: Additional OPDs 2012-2060 by airport

To monetize the OPD benefit, we applied the average OPD potential per aircraft per site (Figure 8) to the additional OPDs in each year (Figure 37 through Figure 40) and used the FAA guidance of $3.00 per gallon in FY12 dollars. Figure 41 and Figure 42 display the yearly OPD savings in FY12 $M before and after applying the implementation schedule. The magnitude of the OPD benefit is quite a bit smaller than the benefit associated with delay savings (Figure 34 and Figure 35) and does not grow as rapidly over time.

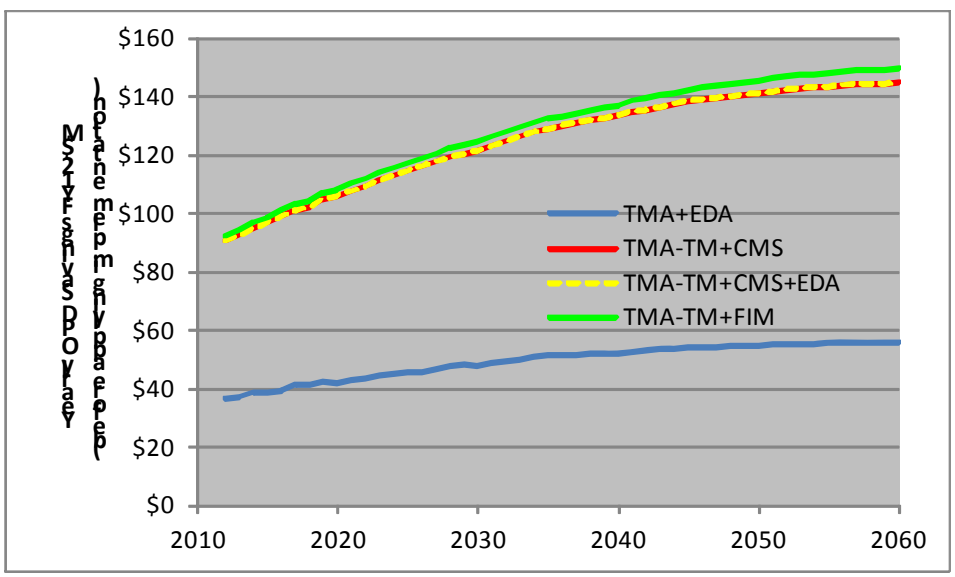


Figure 41: Yearly OPD savings in FY12 $M before applying implementation

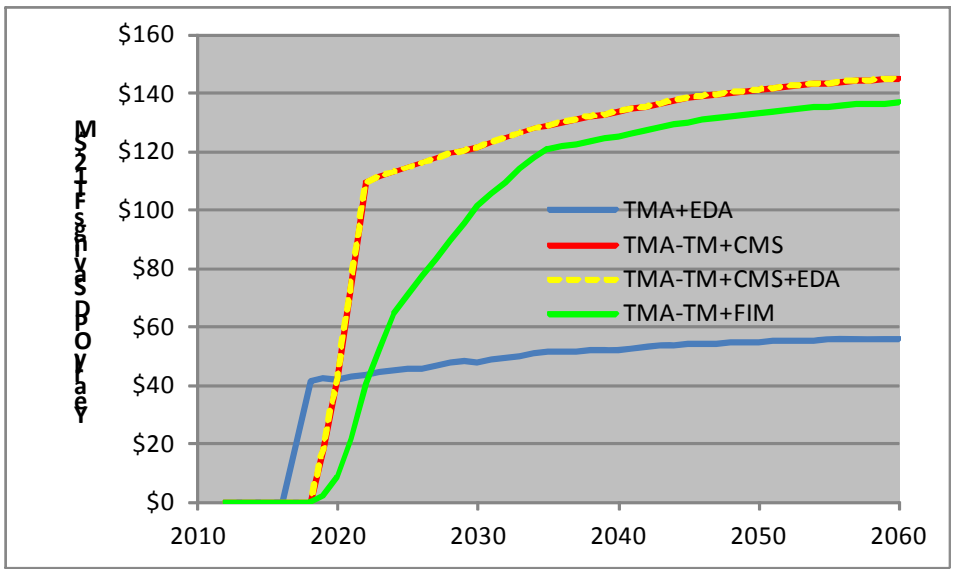


Figure 42: Yearly OPD savings in FY12 $M

13.5 Total Benefit Analysis

Figure 43 and Figure 44 display the yearly combined throughput and OPD savings in FY12 $M for the test scenarios before and after applying the implementation schedule. As indicated previously, the final NAS-wide results are driven by the throughput-related delay savings. A major result of the effort is that the savings (before implementation) is virtually identical for 3 of the test scenarios in the later years: TMA-TM+CMS, TMA-TM+CMS+EDA, TMA-TM+FIM. This implies that there is overlap and little synergistic impact between the applications when examining throughput. When the implementation schedule is applied the TMA-TM+FIM result is lowered because 100 percent FIM equipage was never assumed.

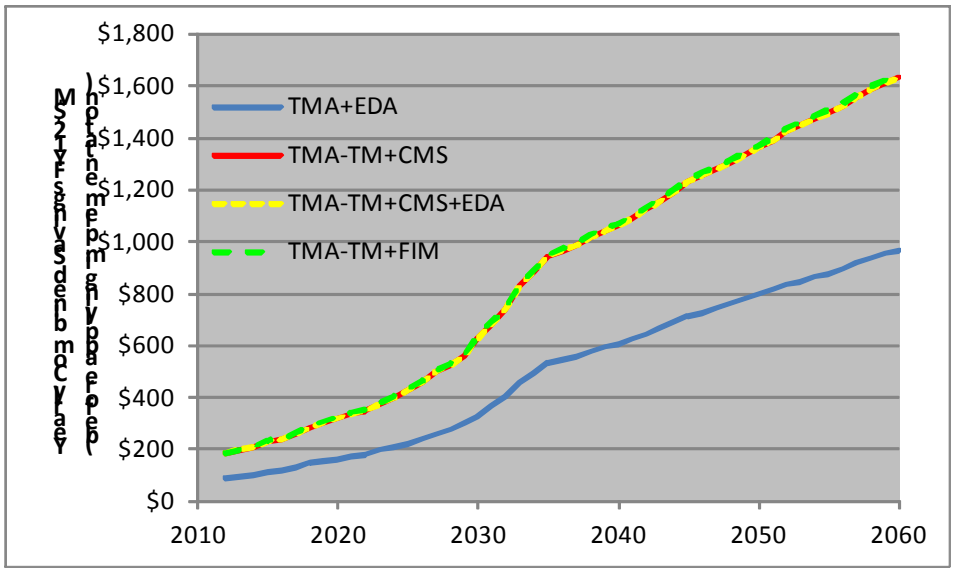


Figure 43: Yearly combined savings in FY12 $M before applying implementation

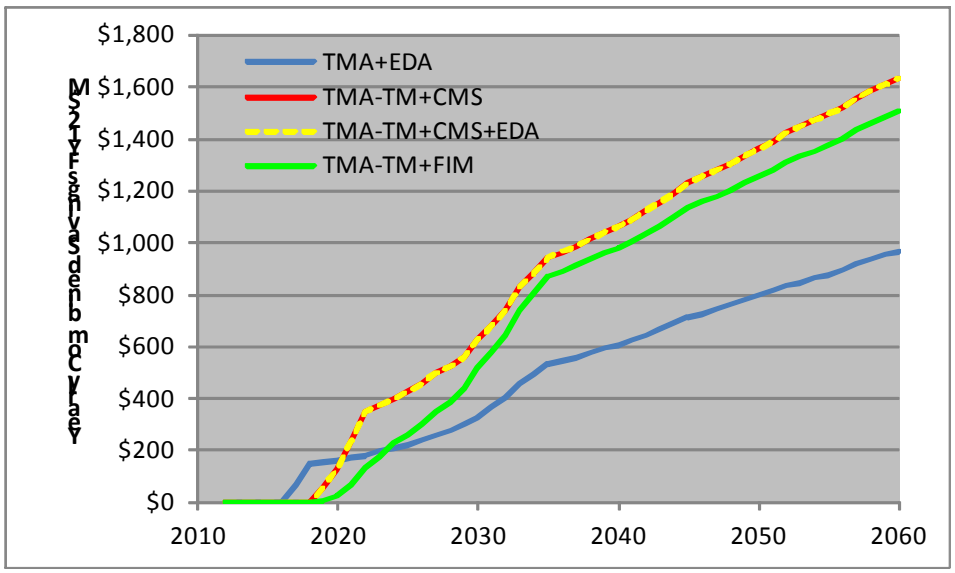


Figure 44: Yearly combined savings in FY12 $M

Figure 45 displays the total benefit (after applying implementation schedule) between 2012 and 2060 at each airport divided into categories of valuation (ADOC, PVT, and OPD). This was done to acknowledge that different stakeholders may consider part of the benefit more applicable to them than the others. Figure 46 displays the percentage of the total benefit at each airport related to each of the categories of valuation (ADOC, PVT, and OPD). This was done to show the relative importance of each benefit at each site.

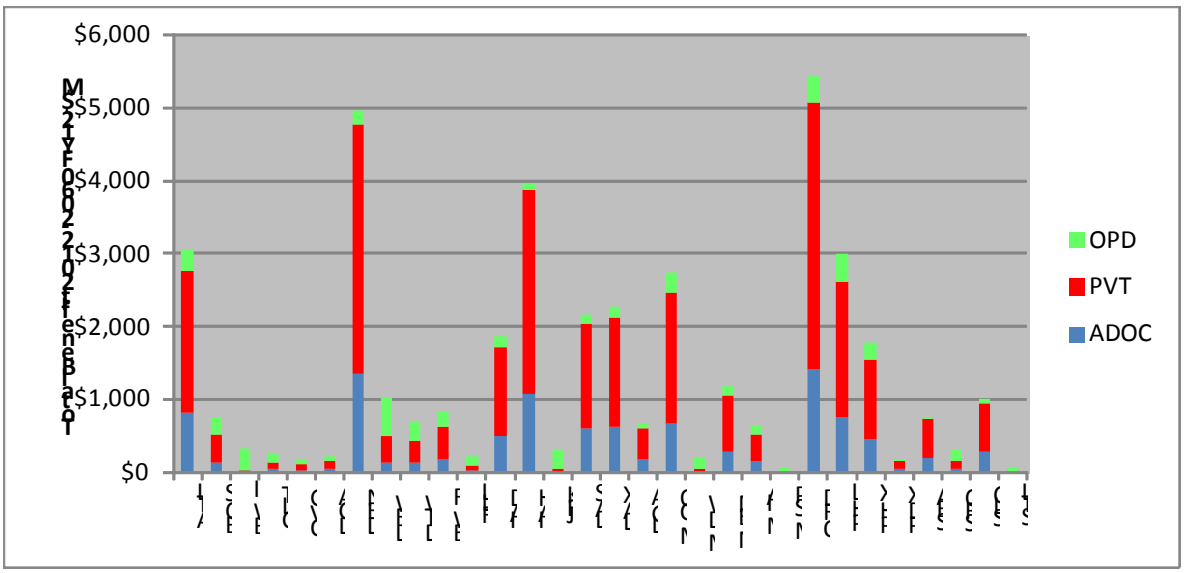


Figure 45: Total benefit 2012-2060 in each category (ADOC, PVT, OPD) per airport

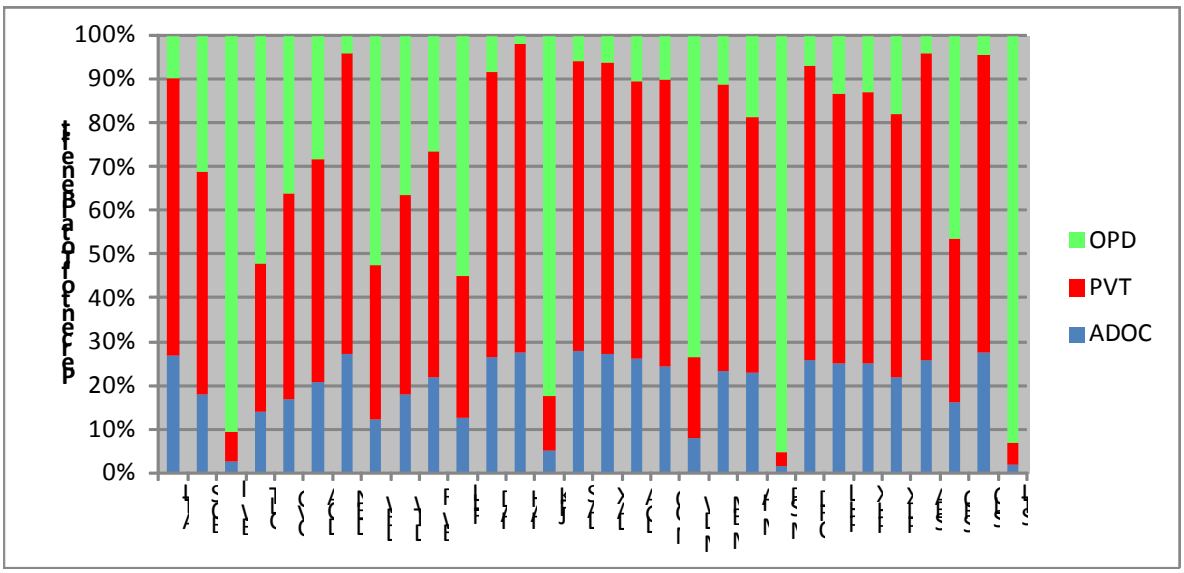


Figure 46: Percentage of total benefit 2012-2060 in each category (ADOC, PVT, OPD) per airport

The benefits presented above can be considered point estimates because no attempt was made to risk-adjustment the results. There are several possible variables that could be used to risk-adjust the model including projected demand, implementation schedule, and system effectiveness. Changes in many of these variables would impact each scenario similarly; however, we expect the significant changes to the original inter-arrival time error assumptions would dramatically impact the results. With the current assumptions there is no real difference in the inter-arrival time error assumptions of CMS and FIM at the runway threshold, therefore the benefits directly overlap.

14 Efficient Descent Advisor Concept Cost Analysis Update

The costs of the EDA concept are presented below along with the objective metrics, rationale, and calculations used to determine them. The Saab Sensis team used a method that complies with the FAA cost analysis standards.

14.1 Assumptions

These assumptions are general in nature, more detailed assumptions are provided in WBS element specific narratives in later sub-sections:

- Costs were estimated using Fiscal Year (FY) 2012 constant dollars
- Then year dollar cost summary tables were derived using appropriate inflation indices. "Then year dollars" refers to dollars appropriate to any particular year. These are typically inflated from a base year constant dollar.
  - Bureau of Economic Analysis, Table 1.1.9. Implicit Price Deflators for Gross Domestic Product: http://bea.gov/iTable/iTable.cfm?ReqID=9&step=1
  - Office of Management and Budget, Budget of the United States Government Fiscal Year 2013, Table 2–1. Economic Assumptions: http://www.whitehouse.gov/sites/default/files/omb/budget/fy2013/assets/spec.pdf
- Present value figures were derived using appropriate discount rate information.
  - Office of Management and Budget, Circular No. A-94 Appendix C: http://www.whitehouse.gov/omb/circulars_a094/a94_appx-c
- The cost model is based upon Version 5.0 of the FAA Work Breakdown Structure (WBS).
  - http://fast.faa.gov/
- The timeframe of the analysis is FY 2012 through FY 2037.
- No decommissioning costs are assumed at the end of analysis.
- Labor rates for contractor labor are divided into three categories: senior, middle, and junior level. The fully loaded annual pay for each of these levels is assumed to be $250K, $225K, and $200K respectively.
- Labor rates for federal government employees are based on the information below:
  - U.S. Office of Personnel Management, 2012 Salary Table including a locality payment of 35.15% for the area of San Jose, San Francisco, and Oakland, California: http://www.opm.gov/oca/12tables/pdf/SF.pdf
  - Office of Management and Budget, Circular No. A-76, Figure C1, Civilian Position Full Fringe Benefit Cost Factor (36.25%): http://www.whitehouse.gov/omb/circulars_a076_a76_incl_tech_correction/

14.2 Work Breakout Structure (WBS)

To provide a structure from which costs and benefits can be compared, the following cost elements from FAA AMS WBS 5.0 were used and contain the principal cost and benefit drivers evaluated.

Table 36: Work breakout structures

Phase 1 MISSION ANALYSIS
1.3.1 Research, Engineering, and Development
Phase 2 INVESTMENT ANALYSIS
2.1 Initial Investment Analysis
2.3 Final Investment Analysis
Phase 3 SOLUTION IMPLEMENTATION
3.1.3 Prime Mission Product Application Software
3.1.5 Prime Mission Product Platform Integration
3.1.6.4 Training
3.2 Program Management
3.3 Systems Engineering
3.5.1 Development Test and Evaluation
3.5.2 Operational Test and Evaluation
3.5.3 Independent Software Verification and Validation
3.6.8 Technical Data
3.7.1 Implementation Planning, Management, and Control
3.7.3 Implementation Engineering
3.7.9 Site Preparation, Installation, Test, and Activation
4 IN-SERVICE MANAGEMENT
4.5 Watch Standing Coverage
4.6.1 Program Planning, Authorization, Management and Control
4.7.8 Technical Data
4.8.3 Software and Hardware Modification and Support

14.3 WBS Element Specific Cost Detail

WBS Element 1.3.1 Research, Engineering, and Development. All activities associated with discovering applications of new technology for the National Airspace System (NAS), exploring new opportunities for service delivery, solving problems with current operations, defining and stabilizing requirements, maturing operational concepts, and mitigating risk. These activities generate information to quantify and characterize capability shortfalls, service needs and requirements, benefit expectations, and design alternatives.

The cost buildup appears in the table below, which depicts the NASA headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 37: Research and development concept to lab R&D staff requirement

Labor Category	Pay	FY12	FY13	FY14
PM	GS14	0.5	0.5	0.5
Senior Scientists	GS14	1	0.5	0.5
Engineers	GS13	1	1	1
SW Engineers	GS13	2	1	1
Testers	GS12	1	1	0
Lab Support	GS12	0.5	0.5	0.5
SMEs (Participants for Testing)	GS12	1	0	0
Subtotal		**7.0**	**4.5**	**3.5**

Table 38: Research and development concept to lab R&D cost per year

EDA Cost Summary: TY $K	FY12	FY13	FY14	Total
1.3.1 Research and Development	1,028.3	675.5	556.6	2,260.4

WBS Element 2.1 Initial Investment Analysis. All activities associated with analyzing alternative solutions to mission need in preparation for an initial investment decision. Specific activities include:

- Form and prepare investment analysis team members, verify entry criteria are satisfied, hold kickoff meeting, and refine the investment analysis plan, if needed, particularly the roles and responsibilities of team members and the timeline for conduct of investment analysis.
- Define the business case including assumptions and constraints, the legacy reference case, strategic performance measures, and design to cost goals.
- Analyze market capability including definition of a functional/performance specification, development and evaluation of a screening request for information, conduct of an industry day to meet with organizations with potential solutions, operational capability demonstrations, and analysis and evaluation of results.
- Analyze alternatives including adding or modifying alternatives as a result of the market survey; the comparative assessment of performance, benefits, cost, risk safety, and schedule; economic analysis; evaluation of human factors, environmental safety and health impacts, radio frequency spectrum availability, supportability, regulatory or procedural impact, test readiness/maturity level; operational suitability, operational effectiveness, ability to upgrade, and interdependencies with existing or proposed programs; and recording results in the preliminary business case.
- Conduct of operational capability demonstrations and tests to evaluate candidate solution to the service need.
- Assess budget impact.
- Prepare the initial implementation strategy and planning document for each alternative.
- Update requirements in the program requirements document.
- Verify and validate key work products.
- Plan for final investment analysis including all coordination necessary for approval.

The cost buildup appears in the table below, which depicts the FAA headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 39: Initial investment stage staff requirement

Labor Category	Pay	FY12
Program Manager	GS14	1
Assistant PM	GS13	1
Senior Engineers	GS13	1
Engineers	GS12	2
Contracting Officer (COTR)	GS12	0.5
Logistics Analyst	GS12	0.5
Configuration Management	GS12	0.25
Subtotal		**6.3**

Table 40: Initial investment stage staff cost by year

EDA Cost Summary: TY $K	FY12	Total
2.1 Initial Investment Analysis	884.7	884.7

WBS Element 2.3 Final Investment Analysis. All activities associated with detailed planning for the alternative selected for implementation, soliciting offers from potential suppliers, and development of required program documentation. Specific activities include:

- Identify all tasks, actions, and events needed to deliver and support the solution over its lifecycle.
- Reduce risk and finalize requirements including a detailed risk assessment; risk-reduction modeling, simulations, and prototyping; competitive fly-offs among offerors.
- Finalize the strategy for implementation and lifecycle support including risk management, program segmentation, procurement strategy, benefits realization strategy, in-service operations strategy, logistics and support strategy, test and evaluation strategy, and detailed costs and schedules for the entire segment or phase for which approval is sought.
- Solicit offers for prime contract(s) including development of the performance/functional specification, completion of evaluation criteria and weights, conduct of an industry day meeting, development and issuance of the screening information request, and communications with potential bidders.
- Evaluate vendor offers including evaluation and scoring of proposals, comparison with government estimates, and adjustment of baselines and planning as needed.
- Develop detailed program planning including a complete program work breakdown structure, detailed tasks, schedules, and resource estimates; development of an earned value management strategy and framework, completion of the final economic analysis, and finalization of the business case.
- Finalize the acquisition program baseline, program requirements document, business case analysis report, and implementation strategy and planning document, and Exhibit 300 for

designated programs. This includes independent scoring the Exhibit 300 and all activity necessary to improve the document to as high a score as possible.
- Verify and validate the key work products of final investment analysis.
- Prepare for the final investment decision including completion of the JRC readiness checklist, update of enterprise architecture products and amendments, verification that final investment analysis exit criteria are satisfied, coordination with stakeholders, conduct of final budget and financial reviews, approval to move forward by the JRC subordinate review board

The cost buildup appears in the table below, which depicts the FAA headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 41: Final investment stage staff requirement

Labor Category	Pay	FY13
Program Manager	GS14	1
Assistant PM	GS13	1
Senior Engineers	GS13	1
Engineers	GS12	3
Contracting Officer (COTR)	GS12	0.5
Logistics Analyst	GS12	0.5
Configuration Management	GS12	0.25
Subtotal		**7.3**

Table 42: Final investment stage staff cost by year

EDA Cost Summary: TY $K	FY13	Total
2.3 Final Investment Analysis	1,027.2	1,027.2

WBS Element 3.1.3 Prime Mission Product Application Software. This PMP contractor activity associated with software specifically produced for the functional use of a prime mission product.

The cost buildup appears in the table below, which depicts source lines of code (SLOC) required at ARTCCs , phased by year. The cost per line of code is based on analogy to the FAA's NNEW program, where Lincoln Labs estimated a cost of $115 per SLOC to modify R&D code to NAS specifications. The extended costs are summarized in the second table below.

Table 43: Software SLOC by category

Software SLOC by Category	$K/SLOC	FY13	FY14	FY15
ARTCCs	$0.115	25,000	50,000	25,000
Subtotal		**25,000**	**50,000**	**25,000**

Table 44: Prime mission product application software development cost by year

EDA Cost Summary: TY $K	FY13	FY14	FY15	Total
3.1.3 Prime Mission Product Application Software	2,922.4	5,939.5	3,024.6	11,886.5

WBS Element 3.1.5 Prime Mission Product Platform Integration. This PMP contractor activity associated with technical and engineering services to the platform manufacture or integrator during installation and integration of the prime mission product into a larger host system or operational environment.
The implementation schedule that drives this cost element's software integration appears in the table below.

Table 45: Product platform integration airport implementation schedule

Implementation Schedule	FY16	FY17	Total
20 Centers (ARTCCs)	10	10	**20**

It is estimated that 4 man months of software integration will be required at each ARTCC, the extended total man months of required software integration phased by year appears below.

Table 46: Product platform integration airport implementation man months requirement

SW Adaptation (Man Months)	FY16	FY17	Total
ARTCCs	40	40	**80**

The extended costs appear in the table below, based on the man months schedule above and contractor software engineers estimated at a $250K fully loaded annual salary.

Table 47: Product platform integration airport implementation cost

EDA Cost Summary: TY $K	FY16	FY17	Total
3.1.5 Prime Mission Product Platform Integration	892.6	908.5	1,801.1

WBS Element 3.1.6.4 Training. All PMP contractor activity associated with planning, developing, and establishing training for operators and maintainers; provisioners, item managers, and deport repair technicians; maintenance of common and peculiar support equipment and test and measurement equipment; second-level engineering support; computer resources support; and packaging, handling, storage, and transportation of training materials.

It is estimated that 1 senior engineer ($250K per year) and 1 mid-level engineer ($225K per year) will be needed in each year from FY15 through FY17 to prepare and conduct training. The extended costs are summarized in the second table below.

Table 48: Training staff requirement by year

Labor Category	Pay	FY15	FY16	FY17
Senior Engineer	SrContr	1	1	1
Engineer	MdContr	1	1	1
Subtotal		**2.0**	**2.0**	**2.0**

Table 49: Training staff cost by year

EDA Cost Summary: TY $K	FY15	FY16	FY17	Total
3.1.6.4 Training	499.7	508.8	517.8	1,526.3

WBS Element 3.2 Program Management. All government activity associated with business and administrative planning, organizing, directing, coordinating, controlling, and approval actions to accomplish overall program objectives. This includes all program management support contracts.

The cost buildup appears in the table below, which depicts the FAA headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 50: Program management staff requirement by year

Labor Category	Pay	FY14	FY15
Program Manager	GS14	1	1
Assistant PM	GS13	1	1
Senior Engineers	GS13	1	1
Engineers	GS12	1	1
Contracting Officer (COTR)	GS12	0.5	0.5
Logistics Analyst	GS12	0.5	0.5
Configuration Management	GS12	0.25	0.25
Subtotal		**5.3**	**5.3**

Table 51: Program management staff cost by year

EDA Cost Summary: TY $K	FY14	FY15	Total
3.2 Program Management	783.9	798.4	1,582.4

WBS Element 3.3 Systems Engineering . All government technical and engineering activities associated with planning, directing, and controlling a totally integrated engineering effort for a solution. Specific activities include: requirements definition and allocation; analysis, design, and integration; supportability, maintainability, and reliability engineering; quality assurance; interface management; human factors engineering; security engineering; safety engineering; technical risk management; and specialty engineering.

The cost buildup appears in the table below, which depicts the FAA headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 52: System engineering staff requirement by year

Labor Category	Pay	FY14	FY15
Senior Engineers	GS13	1	1
Engineers	GS12	1	1
Subtotal		**2.0**	**2.0**

Table 53: System engineering staff cost by year

EDA Cost Summary: TY $K	FY14	FY15	Total
3.3 Systems Engineering	284.4	289.7	574.1

WBS Element 3.5.1 Development Test and Evaluation. All government activities associated with testing during product development to determine whether engineering design and development activities are complete; whether the product will meet specifications, security certification, and authorization criteria; and whether it is operating properly so as to achieve government acceptance. This includes all government activities associated with hardware and software validation and verification, factory acceptance testing, and site acceptance testing. It includes all government test support activities (e.g., technical assistance, maintenance, labor, material, support elements and testing spares, etc.), as well as all government activities associated with development and construction of special test facilities, test tools, and models required for performance of developmental tests.

The cost buildup appears in the table below, which depicts the FAA headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 54: Development test and evaluation staff requirement

Labor Category	Pay	FY13
Senior Engineers	GS14	1
Engineers	GS13	1
Subtotal		**2.0**

Table 55: Development test and evaluation staff cost

EDA Cost Summary: TY $K	FY13	Total
3.5.1 Development Test and Evaluation	331.7	331.7

WBS Element 3.5.2 Operational Test and Evaluation. All government activities associated with tests and evaluations conducted to assess product utility, operational effectiveness, operational suitability, and logistics supportability (including compatibility, interoperability,

reliability, maintainability, logistics requirements, safety requirements, security administration, etc.). This includes all test support activities (e.g., technical assistance, maintenance, labor, material, support elements, and testing spares) as well as all activities associated with development and construction of special test facilities, test tools, and models required for performance of operational tests. Operational testing also includes site operational testing (covered in WBS element 3.7.8) and support by test and evaluation personnel during field familiarization.

The cost buildup appears in the table below, which depicts the FAA headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 56: Operational test and evaluation staff requirement

Labor Category	Pay	FY14
Senior Engineers	GS14	1
Engineers	GS13	1
Subtotal		**2.0**

Table 57: Operational test and evaluation staff cost

EDA Cost Summary: TY $K	FY14	Total
3.5.2 Operational Test and Evaluation	337.1	337.1

WBS Element 3.5.3 Independent Software Verification and Validation. All activities performed by organizations other than the developer to determine the degree to which software fulfills the specifications. Verification is a rigorous mathematical demonstration to ensure the source code conforms to its requirements. Validation evaluates a software product throughout the development process to determine compliance with product requirements.
The cost buildup appears in the table below, which depicts the FAA and contractor headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 58: Independent software verification and validation staff requirement

Labor Category	Pay	FY15
Senior Engineers	GS14	1
Engineers	GS13	1
Senior Engineers	SrContr	1
Engineers	MdContr	2
Subtotal		**5.0**

Table 59: Independent software verification and validation staff cost by year

EDA Cost Summary: TY $K	FY15	Total

3.5.3 Independent Software Verification and Validation	1,079.7	1,079.7

WBS Element 3.6.8 Technical Data. All government activities associated with planning and reviewing program and contractor technical data. Technical data includes items such as engineering drawings, notebooks, maintenance handbooks, operator manuals, maintenance manuals, installation drawings, and all contract data deliverables. This includes delivery and maintenance of documentation in place by contractors with government access, as well as activity related to treatment of intellectual property rights and third-party retention of data and documentation.
The cost buildup appears in the table below, which depicts the FAA headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 60: Technical data planning and review staff requirement by year

Labor Category	Pay	FY14	FY15	FY16	FY17
Senior Engineer	GS14	0.5	0.5	0.5	0.5
Engineer	GS13	0.5	0.5	0.5	0.5
Subtotal		**1.0**	**1.0**	**1.0**	**1.0**

Table 61: Technical data planning and review staff cost by year

EDA Cost Summary: TY $K	FY14	FY15	FY16	FY17	Total
3.6.8 Technical Data	168.5	171.7	174.8	177.9	692.9

WBS Element 3.7.1 Implementation Planning, Management, and Control. All government activities associated with implementation planning, control, contract management, and business management. Specific activities include:

- Planning, organizing, directing, coordinating, estimating, scheduling, controlling, and approving actions to accomplish program implementation, including project-specific input to agency-level planning documents such as the call for estimates, blue sheets, white sheets, the capital investment plan, and the enterprise architecture.
- Development and dissemination of deployment planning information to regional and site personnel.
- Tailoring the in-service review (ISR) checklist, conducting ISR checklist status reviews, developing action plans and briefing package to obtain the in-service decision, conducting stakeholder meetings, obtaining the in-service decision, tracking ISD action plans, and updating the implementation strategy and planning document.
- All activities associated with awarding and managing program-related contracts, including technical support contracts.

The cost buildup appears in the table below, which depicts the FAA headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 62: Implementation planning, management and control staff requirement by year

Labor Category	Pay	FY16	FY17
Program Manager	GS14	1	1
Assistant PM	GS13	1	1
Senior Engineers	GS13	1	1
Engineers	GS12	1	1
Contracting Officer (COTR)	GS12	0.5	0.5
Logistics Analyst	GS12	0.5	0.5
Configuration Management	GS12	0.25	0.25
Subtotal		**5.3**	**5.3**

Table 63: Implementation planning, management and control staff cost by year

EDA Cost Summary: TY $K	FY16	FY17	Total
3.7.1 Implementation Planning, Management, and Control	812.9	827.4	1,640.3

WBS Element 3.7.3 Implementation Engineering. All government engineering activity associated with site surveys, design, analysis, and studies. Specific activities include:

- Civil, electrical, mechanical, architectural, industrial, and other "non-electronic" engineering positions.
- Drafting and developing site plans and specifications.
- All electronic engineering activities associated with the study, analysis, and design of electronic installation.
- Spectrum analysis and engineering.
- Coordination with organizations associated with site engineering.
- Development of installation drawings.
- Physical integration associated with site modification requirements to ensure the solution integrates into the NAS.
- Assessment of site conditions, physical requirements of the solution, and transition requirements.
- Transition and operational requirements for physical security.

The cost buildup appears in the table below, which depicts the FAA headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 64: Implementation engineering staff requirement by year

Labor Category	Pay	FY16	FY17
Senior Engineer	GS14	1	1
Engineer	GS13	1	1
Subtotal		**2.0**	**2.0**

Table 65: Implementation engineering staff cost by year

EDA Cost Summary: TY $K	FY16	FY17	Total
3.7.3 Implementation Engineering	349.5	335.8	705.3

WBS Element 3.7.9 Site Preparation, Installation, Test, and Activation. All activity associated with site preparation, installation, acceptance testing, operations testing, and checkout of hardware, software, and equipment to achieve operational status. This includes coordination with all applicable organizations, unions, and the public during installation and transition. Specific activities include:

- Preparation and Installation: All activities associated with site preparation, equipment installation, acceptance testing, and checkout of hardware and software to achieve operational status. This includes coordination with all applicable organizations, unions, and the public during installation and transition.
- Test and Evaluation: All government test and evaluation activities (from WBS 3.5) to verify and validate operational readiness at each site. This includes test support activities (e.g., technical assistance, maintenance, labor, material, support elements, and testing spares) as well as all activities associated with development and construction of special test facilities, test tools, and models required for performance of operational tests; Support of T&E personnel during field familiarization. Field familiarization is the conduct of activities that allow the facility to gain confidence in the asset and attain a higher level of hands-on familiarization.
- Joint Acceptance Inspection and Commissioning: All activities associated with preparing for and achieving declaration of operational readiness, initial operational capability, full operational capability, joint acceptance inspection, service availability, and commissioning. Specific activities include: Development or modification of operational procedures; Issuance of Notice to Airmen; field familiarization activities; preliminary and final commissioning; flight inspections and other applicable testing; Initial certification activities, initial standards testing and evaluation, and initial publication of certification standards.
- Decommissioning and removal of replaced assets: All activities associated with the termination and removal of a decommissioned system or equipment. This includes planning and engineering; environmental assessments, cleanup, abatement, and disposal of hazardous materials as stipulated by laws and regulations engineering; dismantling demolishing, and removing decommissioned systems or equipment; restoring a site to acceptable condition; and all actions to revert real estate to the owner and close the project.

The cost buildup appears in the table below, which depicts the FAA headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 66: Site preparation, installation, test and activation staff requirement by year

Labor Category	Pay	FY16	FY17

Senior Engineer	GS14	1	1
Engineer	GS13	1	1
Subtotal		**2.0**	**2.0**

Table 67: Site preparation, installation, test and activation staff requirement by year

EDA Cost Summary: TY $K	FY16	FY17	Total
3.7.9 Site Preparation, Installation, Test, and Activation	349.5	355.8	705.3

WBS Element 4.5 Watch Standing Coverage. All activities associated with watch-standing coverage beyond stated staffing requirements.
It is assumed there are 245 controllers per ARTCC that will require training. When multiplying these students by the implementation schedule shown in WBS Element 3.1.5 Prime Mission Product Platform Integration, the total students requiring training by year is determined.

Table 68: Watch standing coverage student training requirement by year

Students requiring training	Average per facility	FY16	FY17	Total
ARTCCs	245	2,450	2,450	**4,900**

Assuming a 20 hour course and 1,776 productive work hours in a year, the full time equivalent backfill watch standers presented in the table below will be required. The associated costs are summarized in the second table below.

Table 69: Watch standing coverage controller requirement by year

FTE Backfill Watch Standers Required	Pay	FY16	FY17
Controller: ARTCCs	GS12	27.59	27.59
Subtotal		**27.59**	**27.59**

Table 70: Associated costs for watch standing coverage by year

EDA Cost Summary: TY $K	FY16	FY17	Total
4.5 Watch Standing Coverage	3,717.3	3,783.5	7,500.8

WBS Element 4.6.1 Program Planning, Authorization, Management and Control. All activities associated with planning, authorizing, and managing actions that must be accomplished for operation and maintenance. Specific activities include:

- Preparing project-specific input to agency-level planning documents such as the call for estimates and the enterprise architecture.
- Security control.
- Activities to ensure cost, schedule, operational performance, and benefit objectives are met.

The cost buildup appears in the table below, which depicts the FAA and contractor headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 71: Program planning, authorization, management and control staff requirement

Labor Category	Pay	FY18	FY19	FY20	FY21	FY22	Each year FY23 –FY37
Senior Engineer	GS14	1	1	1	1	1	1
Engineer	GS13	1	1	1	1	1	1
Senior Engineer	SrContr	1	1	1	1	1	1
Engineer	MdContr	2	2	2	2	2	2
Subtotal		**5.0**	**5.0**	**5.0**	**5.0**	**5.0**	**5.0**

Table 72: Program planning, authorization, management and control staff cost by year

EDA Cost Summary: TY $K	FY18	FY19	FY20	FY21	FY22	FY23-FY37	Total
4.6.1 Program Planning, Authorization, Management and Control	1,138.5	1,159.0	1,180.3	1,201.7	1,223.1	21,184.5	27,087.1

WBS Element 4.7.8 Technical Data. All activities associated with product-specific documentation including engineering drawings, operator manuals, maintenance manuals, repair and test procedures, provisioning data, logistics management information, and other technical data used by or directly associated with operations, maintenance, and support of operational systems, facilities, and equipment.
The cost buildup appears in the table below, which depicts the FAA and contractor headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 73: Technical data staff requirement by year

Labor Category	Pay	FY18	FY19	FY20	FY21	FY22	Each year FY23 –FY37
Engineer	GS13	0.25	0.25	0.25	0.25	0.25	0.25
Engineer	MdContr	0.50	0.50	0.50	0.50	0.50	0.50
Subtotal		**0.75**	**0.75**	**0.75**	**0.75**	**0.75**	**0.75**

Table 74: Technical data staff cost by year

EDA Cost Summary: TY $K	FY18	FY19	FY20	FY21	FY22	FY23-FY37	Total
4.7.8 Technical Data	166.3	169.3	172.4	175.5	178.6	3,094.0	3,956.0

WBS Element 4.8.3 Software and Hardware Modification and Support. All activities associated with the analysis, design, test, and implementation of computer resources modifications, operational and support elements, and sustainment of the NAS including site adaptation.

The cost buildup appears in the table below, which depicts the FAA and contractor headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 75: Software and hardware modification and support staff requirement by year

Labor Category	Pay	FY18	FY19	FY20	FY21	FY22	Each year FY23 –FY37
Senior Engineer	GS14	1.00	1.00	1.00	1.00	1.00	1.00
Engineer	GS13	2.00	2.00	2.00	2.00	2.00	2.00
Senior Engineer	SrContr	1.00	1.00	1.00	1.00	1.00	1.00
Engineer	MdContr	2.00	2.00	2.00	2.00	2.00	2.00
Subtotal		**6.00**	**6.00**	**6.00**	**6.00**	**6.00**	**6.00**

Table 76: Software and hardware modification and support staff cost by year

EDA Cost Summary: TY $K	FY18	FY19	FY20	FY21	FY22	FY23-FY37	Total
4.8.3 Software and Hardware Modification and Support	1,304.4	1,327.9	1,352.3	1,376.8	1,401.3	24,272.0	31,034.7

Table 77: Base Year 2012 Life Cycle Cost Table Phased By Year, $K

EDA Cost Summary: BY12 $K	FY12	FY13	FY14	FY15	FY16	FY17	FY18	FY19	FY20	FY21-FY37	Total
Phase 1 MISSION ANALYSIS	**1,028.3**	**664.6**	**538.8**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**2,231.7**
1.3.1 Research, Engineering, and Development	1,028.3	664.6	538.8	-	-	-	-	-	-	-	2,231.7
Phase 2 INVESTMENT ANALYSIS	**884.7**	**1,010.5**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**1,895.2**
2.1 Initial Investment Analysis	884.7	-	-	-	-	-	-	-	-	-	884.7
2.3 Final Investment Analysis	-	1,010.5	-	-	-	-	-	-	-	-	1,010.5
Phase 3 SOLUTION IMPLEMENTATION	**-**	**3,201.3**	**7,273.8**	**5,573.8**	**2,883.1**	**2,883.1**	**-**	**-**	**-**	**-**	**21,815.1**
3.1.3 Prime Mission Product Application Software	-	2,875.0	5,750.0	2,875.0	-	-	-	-	-	-	11,500.0
3.1.5 Prime Mission Product Platform Integration	-	-	-	-	833.3	833.3	-	-	-	-	1,666.7
3.1.6.4 Training	-	-	-	475.0	475.0	475.0	-	-	-	-	1,425.0
3.2 Program Management	-	-	758.9	758.9	-	-	-	-	-	-	1,517.9
3.3 Systems Engineering	-	-	275.4	275.4	-	-	-	-	-	-	550.7
3.5.1 Development Test and Evaluation	-	326.3	-	-	-	-	-	-	-	-	326.3
3.5.2 Operational Test and Evaluation	-	-	326.3	-	-	-	-	-	-	-	326.3
3.5.3 Independent Software Verification and Validation	-	-	-	1,026.3	-	-	-	-	-	-	1,026.3
3.6.8 Technical Data	-	-	163.2	163.2	163.2	163.2	-	-	-	-	652.7
3.7.1 Implementation Planning, Management, and Control	-	-	-	-	758.9	758.9	-	-	-	-	1,517.9
3.7.3 Implementation Engineering	-	-	-	-	326.3	326.3	-	-	-	-	652.7
3.7.9 Site Preparation, Installation, Test, and Activation	-	-	-	-	326.3	326.3	-	-	-	-	652.7
Phase 4 IN-SERVICE MANAGEMENT	**-**	**-**	**-**	**-**	**3,470.5**	**3,470.5**	**2,352.1**	**2,352.1**	**2,352.1**	**39,986.4**	**53,983.8**
4.5 Watch Standing Coverage	-	-	-	-	3,470.5	3,470.5	-	-	-	-	6,941.0
4.6.1 Program Planning, Authorization, Management and Control	-	-	-	-	-	-	1,026.3	1,026.3	1,026.3	17,447.7	20,526.7
4.7.8 Technical Data	-	-	-	-	-	-	149.9	149.9	149.9	2,548.2	2,997.9
4.8.3 Software and Hardware Modification and Support	-	-	-	-	-	-	1,175.9	1,175.9	1,175.9	19,990.5	23,518.2
Total	**$1,913.06**	**$4,876.43**	**$7,812.60**	**$5,573.80**	**$6,353.59**	**$6,353.59**	**$2,352.14**	**$2,352.14**	**$2,352.14**	**$39,986.38**	**$79,925.87**

Table 78: Then Year Life Cycle Cost Table Phased By Year, $K

EDA Cost Summary: TY $K	FY12	FY13	FY14	FY15	FY16	FY17	FY18	FY19	FY20	FY21-FY37	Total
Phase 1 MISSION ANALYSIS	**1,028.3**	**675.5**	**556.6**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**2,260.4**
1.3.1 Research, Engineering, and Development	1,028.3	675.5	556.6	-	-	-	-	-	-	-	2,260.4
Phase 2 INVESTMENT ANALYSIS	**884.7**	**1,027.2**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**1,911.9**
2.1 Initial Investment Analysis	884.7	-	-	-	-	-	-	-	-	-	884.7
2.3 Final Investment Analysis	-	1,027.2	-	-	-	-	-	-	-	-	1,027.2
Phase 3 SOLUTION IMPLEMENTATION	**-**	**3,254.1**	**7,513.5**	**5,863.8**	**3,088.1**	**3,143.2**	**-**	**-**	**-**	**3,143.2**	**22,862.8**
3.1.3 Prime Mission Product Application Software	-	2,922.4	5,939.5	3,024.6	-	-	-	-	-	-	11,886.5
3.1.5 Prime Mission Product Platform Integration	-	-	-	-	892.6	908.5	-	-	-	908.5	1,801.1
3.1.6.4 Training	-	-	-	499.7	508.8	517.8	-	-	-	517.8	1,526.3
3.2 Program Management	-	-	783.9	798.4	-	-	-	-	-	-	1,582.4
3.3 Systems Engineering	-	-	284.4	289.7	-	-	-	-	-	-	574.1
3.5.1 Development Test and Evaluation	-	331.7	-	-	-	-	-	-	-	-	331.7
3.5.2 Operational Test and Evaluation	-	-	337.1	-	-	-	-	-	-	-	337.1
3.5.3 Independent Software Verification and Validation	-	-	-	1,079.7	-	-	-	-	-	-	1,079.7
3.6.8 Technical Data	-	-	168.5	171.7	174.8	177.9	-	-	-	177.9	692.9
3.7.1 Implementation Planning, Management, and Control	-	-	-	-	812.9	827.4	-	-	-	827.4	1,640.3
3.7.3 Implementation Engineering	-	-	-	-	349.5	355.8	-	-	-	355.8	705.3
3.7.9 Site Preparation, Installation, Test, and Activation	-	-	-	-	349.5	355.8	-	-	-	355.8	705.3
Phase 4 IN-SERVICE MANAGEMENT	**-**	**-**	**-**	**-**	**3,717.3**	**3,783.5**	**2,609.2**	**2,656.1**	**2,705.1**	**65,861.4**	**69,578.7**
4.5 Watch Standing Coverage	-	-	-	-	3,717.3	3,783.5	-	-	-	3,783.5	7,500.8
4.6.1 Program Planning, Authorization, Management and Control	-	-	-	-	-	-	1,138.5	1,159.0	1,180.3	27,087.1	27,087.1
4.7.8 Technical Data	-	-	-	-	-	-	166.3	169.3	172.4	3,956.0	3,956.0
4.8.3 Software and Hardware Modification and Support	-	-	-	-	-	-	1,304.4	1,327.9	1,352.3	31,034.7	31,034.7
Total	**$1,913.06**	**$4,956.79**	**$8,070.09**	**$5,863.85**	**$6,805.45**	**$6,926.68**	**$2,609.18**	**$2,656.10**	**$ 2,705.06**	**$ 69,004.51**	**$ 96,613.74**

15 Terminal Metering and Controller Managed Spacing Concept Cost Analysis

15.1 Introduction

The costs of integrated TM & CMS implementation are presented below along with the objective metrics, rationale and calculations used to determine them. Costs of TM standalone are covered in Section 17. The Sensis team used a method that complies with the FAA cost analysis standards.

15.2 Assumptions

These assumptions are general in nature, more detailed assumptions are provided in WBS element specific narratives:

- Costs were estimated using Fiscal Year (FY) 2012 constant dollars
- Then year summary tables were derived using appropriate inflation indices.
  - Bureau of Economic Analysis, Table 1.1.9. Implicit Price Deflators for Gross Domestic Product: http://bea.gov/iTable/iTable.cfm?ReqID=9&step=1
  - Office of Management and Budget, Budget of the United States Government Fiscal Year 2013, Table 2–1. Economic Assumptions: http://www.whitehouse.gov/sites/default/files/omb/budget/fy2013/assets/spec.pdf
- Present value figures were derived using appropriate discount rate information.
  - Office of Management and Budget, Circular No. A-94 Appendix C: http://www.whitehouse.gov/omb/circulars_a094/a94_appx-c
- The cost model is based upon Version 5.0 of the FAA Work Breakdown Structure (WBS).
  - http://fast.faa.gov/
- The timeframe of the analysis is FY 2012 through FY 2041.
- No decommissioning is assumed at the end of analysis.
- Labor rates for contractor labor are divided into three categories: senior, middle, and junior level. The fully loaded annual pay for each of these levels is assumed to be $250K, $225K, and $200K respectively.
- Labor rates for federal government employees are based on the information below:
  - U.S. Office of Personnel Management, 2012 Salary Table including a locality payment of 35.15% for the area of San Jose, San Francisco, and Oakland, California: http://www.opm.gov/oca/12tables/pdf/SF.pdf
  - Office of Management and Budget, Circular No. A-76, Figure C1, Civilian Position Full Fringe Benefit Cost Factor (36.25%): http://www.whitehouse.gov/omb/circulars_a076_a76_incl_tech_correction/

15.3 Work Breakout Structure (WBS)

To provide a structure from which costs and benefits can be compared, the following cost elements from FAA AMS WBS 5.0 were used and contain the principal cost and benefit drivers evaluated.

Table 79: Work breakout structures

Phase 1 MISSION ANALYSIS
1.3.1.1 Research, Engineering, and Development (Concept to Lab R&D)
1.3.1.2 Research, Engineering, and Development (Field Research)
Phase 2 INVESTMENT ANALYSIS
2.1 Initial Investment Analysis
2.3 Final Investment Analysis
Phase 3 SOLUTION IMPLEMENTATION
3.1.3 Prime Mission Product Application Software
3.1.5 Prime Mission Product Platform Integration
3.1.6.4 Training
3.2 Program Management
3.3 Systems Engineering
3.5.1 Development Test and Evaluation
3.5.2 Operational Test and Evaluation
3.5.3 Independent Software Verification and Validation
3.6.8 Technical Data
3.7.1 Implementation Planning, Management, and Control
3.7.3 Implementation Engineering
3.7.9 Site Preparation, Installation, Test, and Activation
4 IN-SERVICE MANAGEMENT
4.5 Watch Standing Coverage
4.6.1 Program Planning, Authorization, Management and Control
4.7.8 Technical Data
4.8.3 Software and Hardware Modification and Support

15.4 WBS Element Specific Cost Detail

WBS Element 1.3.1 Research, Engineering, and Development. All activities associated with discovering applications of new technology for the National Airspace System (NAS), exploring new opportunities for service delivery, solving problems with current operations, defining and stabilizing requirements, maturing operational concepts, and mitigating risk. These activities generate information to quantify and characterize capability shortfalls, service needs and requirements, benefit expectations, and design alternatives.

This cost element was split into two subsections WBS Element 1.3.1.1, which covers concept to lab research and development, and WBS Element 1.3.1.2, which accounts for field research.

WBS Element 1.3.1.1 Research and Development (Concept to Lab R&D). The cost buildup appears in the table below, which depicts the NASA headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 80: Research and development concept to lab R&D staff requirement

Labor Category	Pay	FY12	FY13
PM	GS14	0.5	0.5
Senior Scientists	GS14	1	0.5
Engineers	GS13	2	1
SW Engineers	GS13	3	2
Testers	GS12	0	0
Lab Support	GS12	0.5	0.5
SMEs (Participants for Testing)	GS12	2	2
Subtotal		**9.0**	**6.5**

Table 81: Research and development concept to lab R&D cost per year

TM & CMS Cost Summary: TY $K	FY12	FY13	Total
1.3.1.1 Research and Development (Concept to Lab R&D)	1,327.5	955.4	2,282.9

WBS Element 1.3.1.2 Research and Development (Field Research). The cost buildup appears in the table below, which depicts the NASA headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 82: Research and development field research staff requirement

Labor Category	Pay	FY13	FY14	FY15	FY16
PM	GS14	0.75	1.25	1.25	1.25
Senior Scientists	GS14	0.5	1	1	1
Engineers	GS13	2	3	3	3
SW Engineers	GS13	4	6	6	6
Testers	GS12	1	1	3	3

Field Support	GS12	1	2	2	2
SMEs (Participants for Testing)	GS12	1	3	3	3
Analyst	GS12			1	1
Subtotal		**10.3**	**17.3**	**20.3**	**20.3**

Table 83: Research and development field research staff cost by year

TM & CMS Cost Summary: TY $K	FY13	FY14	FY15	FY16	Total
1.3.1.2 Research and Development (Field Research)	1,520.4	2,581.0	3,025.6	3,080.5	10,207.6

WBS Element 2.1 Initial Investment Analysis. All activities associated with analyzing alternative solutions to mission need in preparation for an initial investment decision. Specific activities include:

- Form and prepare investment analysis team members, verify entry criteria are satisfied, hold kickoff meeting, and refine the investment analysis plan, if needed, particularly the roles and responsibilities of team members and the timeline for conduct of investment analysis.
- Define the business case including assumptions and constraints, the legacy reference case, strategic performance measures, and design to cost goals.
- Analyze market capability including definition of a functional/performance specification, development and evaluation of a screening request for information, conduct of an industry day to meet with organizations with potential solutions, operational capability demonstrations, and analysis and evaluation of results.
- Analyze alternatives including adding or modifying alternatives as a result of the market survey; the comparative assessment of performance, benefits, cost, risk safety, and schedule; economic analysis; evaluation of human factors, environmental safety and health impacts, radio frequency spectrum availability, supportability, regulatory or procedural impact, test readiness/maturity level; operational suitability, operational effectiveness, ability to upgrade, and interdependencies with existing or proposed programs; and recording results in the preliminary business case.
- Conduct of operational capability demonstrations and tests to evaluate candidate solution to the service need.
- Assess budget impact.
- Prepare the initial implementation strategy and planning document for each alternative.
- Update requirements in the program requirements document.
- Verify and validate key work products.
- Plan for final investment analysis including all coordination necessary for approval.

The cost buildup appears in the table below, which depicts the FAA headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 84: Initial investment stage staff requirement

Labor Category	Pay	FY13

Program Manager	GS14	1
Assistant PM	GS13	1
Senior Engineers	GS13	1
Engineers	GS12	2
Contracting Officer (COTR)	GS12	0.5
Logistics Analyst	GS12	0.5
Configuration Management	GS12	0.25
Subtotal		**6.3**

Table 85: Initial investment stage staff cost by year

TM & CMS Cost Summary: TY $K	FY13	Total
2.1 Initial Investment Analysis	899.3	899.3

WBS Element 2.3 Final Investment Analysis. All activities associated with detailed planning for the alternative selected for implementation, soliciting offers from potential suppliers, and development of required program documentation. Specific activities include:

- Identify all tasks, actions, and events needed to deliver and support the solution over its lifecycle.
- Reduce risk and finalize requirements including a detailed risk assessment; risk-reduction modeling, simulations, and prototyping; competitive fly-offs among offerors.
- Finalize the strategy for implementation and lifecycle support including risk management, program segmentation, procurement strategy, benefits realization strategy, in-service operations strategy, logistics and support strategy, test and evaluation strategy, and detailed costs and schedules for the entire segment or phase for which approval is sought.
- Solicit offers for prime contract(s) including development of the performance/functional specification, completion of evaluation criteria and weights, conduct of an industry day meeting, development and issuance of the screening information request, and communications with potential bidders.
- Evaluate vendor offers including evaluation and scoring of proposals, comparison with government estimates, and adjustment of baselines and planning as needed.
- Develop detailed program planning including a complete program work breakdown structure, detailed tasks, schedules, and resource estimates; development of an earned value management strategy and framework, completion of the final economic analysis, and finalization of the business case.
- Finalize the acquisition program baseline, program requirements document, business case analysis report, and implementation strategy and planning document, and Exhibit 300 for designated programs. This includes independent scoring the Exhibit 300 and all activity necessary to improve the document to as high a score as possible.
- Verify and validate the key work products of final investment analysis.
- Prepare for the final investment decision including completion of the JRC readiness checklist, update of enterprise architecture products and amendments, verification that final investment analysis exit criteria are satisfied, coordination with stakeholders, conduct of final budget and financial reviews, approval to move forward by the JRC subordinate review board

The cost buildup appears in the table below, which depicts the FAA headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 86: Final investment stage staff requirement

Labor Category	Pay	FY14
Program Manager	GS14	1
Assistant PM	GS13	1
Senior Engineers	GS13	1
Engineers	GS12	3
Contracting Officer (COTR)	GS12	0.5
Logistics Analyst	GS12	0.5
Configuration Management	GS12	0.25
Subtotal		**7.3**

Table 87: Final investment stage staff cost by year

TM & CMS Cost Summary: TY $K	FY14	Total
2.3 Final Investment Analysis	1,043.8	1,043.8

WBS Element 3.1.3 Prime Mission Product Application Software. This PMP contractor activity associated with software specifically produced for the functional use of a prime mission product.

The cost buildup appears in the table below, which depicts source lines of code (SLOC) required at ARTCCs and TRACONs, phased by year. The cost per line of code is based on FAA historical costs incurred during ERAM implementation, which averaged $1,624 per SLOC. The extended costs are summarized in the second table below.

Table 88: Software SLOC by category

Software SLOC by Category	$K/SLOC	FY15	FY16
ARTCCs	$1.62	1,500	1,500
TRACONs (those with TMA Adapted Airports)	$1.62	7,500	7,500
Subtotal		**9,000.0**	**9,000.0**

Table 89: Prime mission product application software development cost by year

TM & CMS Cost Summary: TY $K	FY15	FY16	Total
3.1.3 Prime Mission Product Application Software	15,373.0	15,651.8	31,024.8

WBS Element 3.1.5 Prime Mission Product Platform Integration. This PMP contractor activity associated with technical and engineering services to the platform manufacture or integrator during installation and integration of the prime mission product into a larger host system or operational environment.

The implementation schedule that drives this cost element's software integration appears in the table below.

Table 90: Product platform integration airport implementation schedule

Implementation Schedule	FY18	FY19	FY20	FY21	Total
20 Centers (ARTCCs)	3	5	6	6	**20**
30 TRACONS (those with TMA Adapted Airports)	5	7	9	9	**30**

It is estimated that 4 man months of software integration will be required at each ARTCC, and 2 man months at each TRACON. The extended total man months of required software integration phased by year appears below.

Table 91: Product platform integration airport implementation man months requirement

SW Adaptation (Man Months)	FY18	FY19	FY20	FY21	Total
ARTCCs	12	20	24	24	**80**
TRACONs (those with TMA Adapted Airports)	10	14	18	18	**60**

The extended costs appear in the table below, based on the man months schedule above and contractor software engineers estimated at a $250K fully loaded annual salary.

Table 92: Product platform integration airport implementation cost

TM & CMS Cost Summary: TY $K	FY18	FY19	FY20	FY21	Total
3.1.5 Prime Mission Product Platform Integration	508.4	799.9	1,006.3	1,024.5	3,339.1

WBS Element 3.1.6.4 Training. All PMP contractor activity associated with planning, developing, and establishing training for operators and maintainers; provisioners, item managers, and deport repair technicians; maintenance of common and peculiar support equipment and test and measurement equipment; second-level engineering support; computer resources support; and packaging, handling, storage, and transportation of training materials.

It is estimated that 1 senior engineer ($250K per year) and 1 mid-level engineer ($225K per year) will be needed in each year from FY17 through FY21 to prepare and conduct training. The extended costs are summarized in the second table below.

Table 93: Training staff requirement by year

Labor Category	Pay	FY17	FY18	FY19	FY20	FY21

Senior Engineer	SrContr	1	1	1	1	1
Engineer	MdContr	1	1	1	1	1
Subtotal		**2.0**	**2.0**	**2.0**	**2.0**	**2.0**

Table 94: Training staff cost by year

TM & CMS Cost Summary: TY $K	FY17	FY18	FY19	FY20	FY21	Total
3.1.6.4 Training	517.8	526.9	536.4	546.3	556.2	2,683.6

WBS Element 3.2 Program Management. All government activity associated with business and administrative planning, organizing, directing, coordinating, controlling, and approval actions to accomplish overall program objectives. This includes all program management support contracts.

The cost buildup appears in the table below, which depicts the FAA headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 95: Program management staff requirement by year

Labor Category	Pay	FY15	FY16	FY17
Program Manager	GS14	1	1	1
Assistant PM	GS13	1	1	1
Senior Engineers	GS13	1	1	1
Engineers	GS12	1	1	1
Contracting Officer (COTR)	GS12	0.5	0.5	0.5
Logistics Analyst	GS12	0.5	0.5	0.5
Configuration Management	GS12	0.25	0.25	0.25
Subtotal		**5.3**	**5.3**	**5.3**

Table 96: Program management staff cost by year

TM & CMS Cost Summary: TY $K	FY15	FY16	FY17	Total
3.2 Program Management	798.4	812.9	827.4	2,438.7

WBS Element 3.3 Systems Engineering . All government technical and engineering activities associated with planning, directing, and controlling a totally integrated engineering effort for a solution. Specific activities include: requirements definition and allocation; analysis, design, and integration; supportability, maintainability, and reliability engineering; quality assurance; interface management; human factors engineering; security engineering; safety engineering; technical risk management; and specialty engineering.

The cost buildup appears in the table below, which depicts the FAA headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 97: System engineering staff requirement by year

Labor Category	Pay	FY15	FY16	FY17
Senior Engineers	GS13	1	1	1
Engineers	GS12	1	1	1
Subtotal		**2.0**	**2.0**	**2.0**

Table 98: System engineering staff cost by year

TM & CMS Cost Summary: TY $K	FY15	FY16	FY17	Total
3.3 Systems Engineering	289.7	294.9	300.2	884.8

WBS Element 3.5.1 Development Test and Evaluation. All government activities associated with testing during product development to determine whether engineering design and development activities are complete; whether the product will meet specifications, security certification, and authorization criteria; and whether it is operating properly so as to achieve government acceptance. This includes all government activities associated with hardware and software validation and verification, factory acceptance testing, and site acceptance testing. It includes all government test support activities (e.g., technical assistance, maintenance, labor, material, support elements and testing spares, etc.), as well as all government activities associated with development and construction of special test facilities, test tools, and models required for performance of developmental tests.

The cost buildup appears in the table below, which depicts the FAA headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 99: Development test and evaluation staff requirement

Labor Category	Pay	FY15
Senior Engineers	GS14	1
Engineers	GS13	1
Subtotal		**2.0**

Table 100: Development test and evaluation staff cost

TM & CMS Cost Summary: TY $K	FY15	Total
3.5.1 Development Test and Evaluation	343.3	343.3

WBS Element 3.5.2 Operational Test and Evaluation. All government activities associated with tests and evaluations conducted to assess product utility, operational effectiveness, operational suitability, and logistics supportability (including compatibility, interoperability, reliability, maintainability, logistics requirements, safety requirements, security administration, etc.). This includes all test support activities (e.g., technical assistance, maintenance, labor,

material, support elements, and testing spares) as well as all activities associated with development and construction of special test facilities, test tools, and models required for performance of operational tests. Operational testing also includes site operational testing (covered in WBS element 3.7.8) and support by test and evaluation personnel during field familiarization.

The cost buildup appears in the table below, which depicts the FAA headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 101: Operational test and evaluation staff requirement

Labor Category	Pay	FY16
Senior Engineers	GS14	1
Engineers	GS13	1
Subtotal		**2.0**

Table 102: Operational test and evaluation staff cost

TM & CMS Cost Summary: TY $K	FY16	Total
3.5.2 Operational Test and Evaluation	349.5	349.5

WBS Element 3.5.3 Independent Software Verification and Validation. All activities performed by organizations other than the developer to determine the degree to which software fulfills the specifications. Verification is a rigorous mathematical demonstration to ensure the source code conforms to its requirements. Validation evaluates a software product throughout the development process to determine compliance with product requirements.

The cost buildup appears in the table below, which depicts the FAA and contractor headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 103: Independent software verification and validation staff requirement

Labor Category	Pay	FY17
Senior Engineers	GS14	1
Engineers	GS13	1
Senior Engineers	SrContr	1
Engineers	MdContr	1
Subtotal		**4.0**

Table 104: Independent software verification and validation staff cost by year

TM & CMS Cost Summary: TY $K	FY17	Total
3.5.3 Independent Software Verification and	873.6	873.6

Validation		

WBS Element 3.6.8 Technical Data. All government activities associated with planning and reviewing program and contractor technical data. Technical data includes items such as engineering drawings, notebooks, maintenance handbooks, operator manuals, maintenance manuals, installation drawings, and all contract data deliverables. This includes delivery and maintenance of documentation in place by contractors with government access, as well as activity related to treatment of intellectual property rights and third-party retention of data and documentation.

The cost buildup appears in the table below, which depicts the FAA headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 105: Technical data planning and review staff requirement by year

Labor Category	Pay	FY16	FY17	FY18	FY19	FY20	FY21
Senior Engineer	GS14	0.5	0.5	0.5	0.5	0.5	0.5
Engineer	GS13	0.5	0.5	0.5	0.5	0.5	0.5
Subtotal		**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**

Table 106: Technical data planning and review staff cost by year

TM & CMS Cost Summary: TY $K	FY16	FY17	FY18	FY19	FY20	FY21	Total
3.6.8 Technical Data	174.8	177.9	181.0	184.3	187.6	191.0	1,096.6

WBS Element 3.7.1 Implementation Planning, Management, and Control. All government activities associated with implementation planning, control, contract management, and business management. Specific activities include:

- Planning, organizing, directing, coordinating, estimating, scheduling, controlling, and approving actions to accomplish program implementation, including project-specific input to agency-level planning documents such as the call for estimates, blue sheets, white sheets, the capital investment plan, and the enterprise architecture.
- Development and dissemination of deployment planning information to regional and site personnel.
- Tailoring the in-service review (ISR) checklist, conducting ISR checklist status reviews, developing action plans and briefing package to obtain the in-service decision, conducting stakeholder meetings, obtaining the in-service decision, tracking ISD action plans, and updating the implementation strategy and planning document.
- All activities associated with awarding and managing program-related contracts, including technical support contracts.

The cost buildup appears in the table below, which depicts the FAA headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 107: Implementation planning, management and control staff requirement by year

Labor Category	Pay	FY18	FY19	FY20	FY21
Program Manager	GS14	1	1	1	1
Assistant PM	GS13	1	1	1	1
Senior Engineers	GS13	1	1	1	1
Engineers	GS12	1	1	1	1
Contracting Officer (COTR)	GS12	0.5	0.5	0.5	0.5
Logistics Analyst	GS12	0.5	0.5	0.5	0.5
Configuration Management	GS12	0.25	0.25	0.25	0.25
Subtotal		**5.3**	**5.3**	**5.3**	**5.3**

Table 108: Implementation planning, management and control staff cost by year

TM & CMS Cost Summary: TY $K	FY18	FY19	FY20	FY21	Total
3.7.1 Implementation Planning, Management, and Control	841.9	857.0	872.8	888.6	3,460.3

WBS Element 3.7.3 Implementation Engineering. All government engineering activity associated with site surveys, design, analysis, and studies. Specific activities include:

- Civil, electrical, mechanical, architectural, industrial, and other "non-electronic" engineering positions.
- Drafting and developing site plans and specifications.
- All electronic engineering activities associated with the study, analysis, and design of electronic installation.
- Spectrum analysis and engineering.
- Coordination with organizations associated with site engineering.
- Development of installation drawings.
- Physical integration associated with site modification requirements to ensure the solution integrates into the NAS.
- Assessment of site conditions, physical requirements of the solution, and transition requirements.
- Transition and operational requirements for physical security.

The cost buildup appears in the table below, which depicts the FAA headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 109: Implementation engineering staff requirement by year

Labor Category	Pay	FY18	FY19	FY20	FY21
Senior Engineer	GS14	1	1	1	1
Engineer	GS13	1	1	1	1

Subtotal		**2.0**	**2.0**	**2.0**	**2.0**

Table 110: Implementation engineering staff cost by year

TM & CMS Cost Summary: TY $K	FY18	FY19	FY20	FY21	Total
3.7.3 Implementation Engineering	362.0	368.5	375.3	382.1	1,487.9

WBS Element 3.7.9 Site Preparation, Installation, Test, and Activation. All activity associated with site preparation, installation, acceptance testing, operations testing, and checkout of hardware, software, and equipment to achieve operational status. This includes coordination with all applicable organizations, unions, and the public during installation and transition. Specific activities include:

- Preparation and Installation: All activities associated with site preparation, equipment installation, acceptance testing, and checkout of hardware and software to achieve operational status. This includes coordination with all applicable organizations, unions, and the public during installation and transition.
- Test and Evaluation: All government test and evaluation activities (from WBS 3.5) to verify and validate operational readiness at each site. This includes test support activities (e.g., technical assistance, maintenance, labor, material, support elements, and testing spares) as well as all activities associated with development and construction of special test facilities, test tools, and models required for performance of operational tests; Support of T&E personnel during field familiarization. Field familiarization is the conduct of activities that allow the facility to gain confidence in the asset and attain a higher level of hands-on familiarization.
- Joint Acceptance Inspection and Commissioning: All activities associated with preparing for and achieving declaration of operational readiness, initial operational capability, full operational capability, joint acceptance inspection, service availability, and commissioning. Specific activities include: Development or modification of operational procedures; Issuance of Notice to Airmen; field familiarization activities; preliminary and final commissioning; flight inspections and other applicable testing; Initial certification activities, initial standards testing and evaluation, and initial publication of certification standards.
- Decommissioning and removal of replaced assets: All activities associated with the termination and removal of a decommissioned system or equipment. This includes planning and engineering; environmental assessments, cleanup, abatement, and disposal of hazardous materials as stipulated by laws and regulations engineering; dismantling demolishing, and removing decommissioned systems or equipment; restoring a site to acceptable condition; and all actions to revert real estate to the owner and close the project.

The cost buildup appears in the table below, which depicts the FAA headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 111: Site preparation, installation, test and activation staff requirement by year

Labor Category	Pay	FY18	FY19	FY20	FY21
Senior Engineer	GS14	1	1	1	1
Engineer	GS13	1	1	1	1
Subtotal		**2.0**	**2.0**	**2.0**	**2.0**

Table 112: Site preparation, installation, test and activation staff requirement by year

TM & CMS Cost Summary: TY $K	FY18	FY19	FY20	FY21	Total
3.7.9 Site Preparation, Installation, Test, and Activation	362.0	368.5	375.3	382.1	1,487.9

WBS Element 4.5 Watch Standing Coverage. All activities associated with watch-standing coverage beyond stated staffing requirements.

It is assumed there are 245 controllers per ARTCC and 30 per TRACON that will require training. When multiplying these students by the implementation schedule shown in WBS Element 3.1.5 Prime Mission Product Platform Integration, the total students requiring training by year is determined.

Table 113: Watch standing coverage student training requirement by year

Students requiring training	Average per facility	FY18	FY19	FY20	FY21	Total
ARTCCs	245	735	1,225	1,470	1,470	**4,900**
TRACONs (those with TMA Adapted Airports)	30	150	210	270	270	**900**

Assuming a 20 hour course and 1,776 productive work hours in a year, the full time equivalent backfill watch standers presented in the table below will be required. The associated costs are summarized in the second table below.

Table 114: Watch standing coverage controller requirement by year

FTE Backfill Watch Standers Required	Pay	FY18	FY19	FY20	FY21
Contoller: ARTCCs	GS12	8.28	13.80	16.55	16.55
Controller: TRACONs (those with TMA Adapted Airports)	GS12	1.69	2.36	3.04	3.04
Subtotal		**10.0**	**16.2**	**19.6**	**19.6**

Table 115: Associated costs for watch standing coverage by year

TM & CMS Cost Summary: TY $K	FY18	FY19	FY20	FY21	Total
4.5 Watch Standing Coverage	1,390.6	2,295.4	2,834.6	2,885.9	9,406.5

WBS Element 4.6.1 Program Planning, Authorization, Management and Control. All activities associated with planning, authorizing, and managing actions that must be accomplished for operation and maintenance. Specific activities include:

- Preparing project-specific input to agency-level planning documents such as the call for estimates and the enterprise architecture.
- Security control.
- Activities to ensure cost, schedule, operational performance, and benefit objectives are met.

The cost buildup appears in the table below, which depicts the FAA and contractor headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 116: Program planning, authorization, management and control staff requirement

Labor Category	Pay	FY22	FY23	FY24	FY25	FY26	Each year FY27 –FY41
Senior Engineer	GS14	1	1	1	1	1	1
Engineer	GS13	1	1	1	1	1	1
Senior Engineer	SrContr	1	1	1	1	1	1
Engineer	MdContr	2	2	2	2	2	2
Subtotal		**5.0**	**5.0**	**5.0**	**5.0**	**5.0**	**5.0**

Table 117: Program planning, authorization, management and control staff cost by year

TM & CMS Cost Summary: TY $K	FY22	FY23	FY24	FY25	FY26	FY27-FY41	Total
4.6.1 Program Planning, Authorization, Management and Control	1,223.1	1,244.8	1,266.9	1,289.5	1,312.4	22,731.6	29,068.2

WBS Element 4.7.8 Technical Data. All activities associated with product-specific documentation including engineering drawings, operator manuals, maintenance manuals, repair and test procedures, provisioning data, logistics management information, and other technical data used by or directly associated with operations, maintenance, and support of operational systems, facilities, and equipment.

The cost buildup appears in the table below, which depicts the FAA and contractor headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 118: Technical data staff requirement by year

Labor Category	Pay	FY22	FY23	FY24	FY25	FY26	Each year FY27 –FY41
Engineer	GS13	0.25	0.25	0.25	0.25	0.25	0.25
Engineer	MdContr	0.50	0.50	0.50	0.50	0.50	0.50
Subtotal		**0.75**	**0.75**	**0.75**	**0.75**	**0.75**	**0.75**

Table 119: Technical data staff cost by year

TM & CMS Cost Summary: TY $K	FY22	FY23	FY24	FY25	FY26	FY27-FY41	Total
4.7.8 Technical Data	178.6	181.8	185.0	188.3	191.7	3,319.9	4,245.4

WBS Element 4.8.3 Software and Hardware Modification and Support. All activities associated with the analysis, design, test, and implementation of computer resources modifications, operational and support elements, and sustainment of the NAS including site adaptation.

The cost buildup appears in the table below, which depicts the FAA and contractor headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 120: Software and hardware modification and support staff requirement by year

Labor Category	Pay	FY22	FY23	FY24	FY25	FY26	Each year FY27 –FY41
Senior Engineer	GS14	0.50	0.50	0.50	0.50	0.50	0.50
Engineer	GS13	1.00	1.00	1.00	1.00	1.00	1.00
Senior Engineer	SrContr	1.00	1.00	1.00	1.00	1.00	1.00
Engineer	MdContr	1.00	1.00	1.00	1.00	1.00	1.00
Subtotal		**3.50**	**3.50**	**3.50**	**3.50**	**3.50**	**3.50**

Table 121: Software and hardware modification and support staff cost by year

TM & CMS Cost Summary: TY $K	FY22	FY23	FY24	FY25	FY26	FY27-FY41	Total
4.8.3 Software and Hardware Modification and Support	849.6	864.7	880.1	895.7	911.7	15,790.8	20,192.6

Table 122: Base Year 2012 Life Cycle Cost Table Phased By Year, $K

TM + CMS Cost Summary: BY12 $K	FY12	FY13	FY14	FY15	FY16	FY17	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25-FY41	Total
Phase 1 MISSION ANALYSIS	**1,327.5**	**2,435.7**	**2,498.6**	**2,876.0**	**2,876.0**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**12,013.8**
1.3.1.1 Research and Development (Concept to Lab R&D)	1,327.5	940.0	-	-	-	-	-	-	-	-	-	-	-	-	2,267.5
1.3.1.2 Research and Development (Field Research)	-	1,495.8	2,498.6	2,876.0	2,876.0	-	-	-	-	-	-	-	-	-	9,746.4
Phase 2 INVESTMENT ANALYSIS	**-**	**884.7**	**1,010.5**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**1,895.2**
2.1 Initial Investment Analysis	-	884.7	-	-	-	-	-	-	-	-	-	-	-	-	884.7
2.3 Final Investment Analysis	-	-	1,010.5	-	-	-	-	-	-	-	-	-	-	-	1,010.5
Phase 3 SOLUTION IMPLEMENTATION	**-**	**-**	**-**	**15,973.2**	**16,136.4**	**2,473.8**	**2,508.1**	**2,758.1**	**2,924.8**	**2,924.8**	**-**	**-**	**-**	**-**	**45,699.1**
3.1.3 Prime Mission Product Application Software	-	-	-	14,612.6	14,612.6	-	-	-	-	-	-	-	-	-	29,225.1
3.1.5 Prime Mission Product Platform Integration	-	-	-	-	-	-	458.3	708.3	875.0	875.0	-	-	-	-	2,916.7
3.1.6.4 Training	-	-	-	-	-	475.0	475.0	475.0	475.0	475.0	-	-	-	-	2,375.0
3.2 Program Management	-	-	-	758.9	758.9	758.9	-	-	-	-	-	-	-	-	2,276.8
3.3 Systems Engineering	-	-	-	275.4	275.4	275.4	-	-	-	-	-	-	-	-	826.1
3.5.1 Development Test and Evaluation	-	-	-	326.3	-	-	-	-	-	-	-	-	-	-	326.3
3.5.2 Operational Test and Evaluation	-	-	-	-	326.3	-	-	-	-	-	-	-	-	-	326.3
3.5.3 Independent Software Verification and Validation	-	-	-	-	-	801.3	-	-	-	-	-	-	-	-	801.3
3.6.8 Technical Data	-	-	-	-	163.2	163.2	163.2	163.2	163.2	163.2	-	-	-	-	979.0
3.7.1 Implementation Planning, Management, and Control	-	-	-	-	-	-	758.9	758.9	758.9	758.9	-	-	-	-	3,035.7
3.7.3 Implementation Engineering	-	-	-	-	-	-	326.3	326.3	326.3	326.3	-	-	-	-	1,305.3
3.7.9 Site Preparation, Installation, Test, and Activation	-	-	-	-	-	-	326.3	326.3	326.3	326.3	-	-	-	-	1,305.3
Phase 4 IN-SERVICE MANAGEMENT	**-**	**-**	**-**	**-**	**-**	**-**	**1,253.6**	**2,032.7**	**2,464.8**	**2,464.8**	**1,889.2**	**1,889.2**	**1,889.2**	**32,116.1**	**45,999.5**
4.5 Watch Standing Coverage	-	-	-	-	-	-	1,253.6	2,032.7	2,464.8	2,464.8	-	-	-	-	8,215.8
4.6.1 Program Planning, Authorization, Management and Control	-	-	-	-	-	-	-	-	-	-	1,026.3	1,026.3	1,026.3	17,447.7	20,526.7
4.7.8 Technical Data	-	-	-	-	-	-	-	-	-	-	149.9	149.9	149.9	2,548.2	2,997.9
4.8.3 Software and Hardware Modification and Support	-	-	-	-	-	-	-	-	-	-	713.0	713.0	713.0	12,120.2	14,259.1
Total	**1,327.5**	**3,320.5**	**3,509.1**	**18,849.2**	**19,012.4**	**2,473.8**	**3,761.7**	**4,790.8**	**5,389.5**	**5,389.5**	**1,889.2**	**1,889.2**	**1,889.2**	**32,116.1**	**105,607.7**

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Table 123: Then Year Life Cycle Cost Table Phased By Year, $K

TM + CMS Cost Summary: TY $K	FY12	FY13	FY14	FY15	FY16	FY17	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25-FY41	Total
Phase 1 MISSION ANALYSIS	**1,327.5**	**2,475.9**	**2,581.0**	**3,025.6**	**3,080.5**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**12,490.5**
1.3.1.1 Research and Development (Concept to Lab R&D)	1,327.5	955.4	-	-	-	-	-	-	-	-	-	-	-	-	2,282.9
1.3.1.2 Research and Development (Field Research)	-	1,520.4	2,581.0	3,025.6	3,080.5	-	-	-	-	-	-	-	-	-	10,207.6
Phase 2 INVESTMENT ANALYSIS	**-**	**899.3**	**1,043.8**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**1,943.1**
2.1 Initial Investment Analysis	-	899.3	-	-	-	-	-	-	-	-	-	-	-	-	899.3
2.3 Final Investment Analysis	-	-	1,043.8	-	-	-	-	-	-	-	-	-	-	-	1,043.8
Phase 3 SOLUTION IMPLEMENTATION	**-**	**-**	**-**	**16,804.4**	**17,284.0**	**#####**	**2,782.2**	**3,114.5**	**3,363.6**	**3,424.5**	**-**	**-**	**-**	**-**	**49,470.1**
3.1.3 Prime Mission Product Application Software	-	-	-	15,373.0	15,651.8	-	-	-	-	-	-	-	-	-	31,024.8
3.1.5 Prime Mission Product Platform Integration	-	-	-	-	-	-	508.4	799.9	1,006.3	1,024.5	-	-	-	-	3,339.1
3.1.6.4 Training	-	-	-	-	-	517.8	526.9	536.4	546.3	556.2	-	-	-	-	2,683.6
3.2 Program Management	-	-	-	798.4	812.9	827.4	-	-	-	-	-	-	-	-	2,438.7
3.3 Systems Engineering	-	-	-	289.7	294.9	300.2	-	-	-	-	-	-	-	-	884.8
3.5.1 Development Test and Evaluation	-	-	-	343.3	-	-	-	-	-	-	-	-	-	-	343.3
3.5.2 Operational Test and Evaluation	-	-	-	-	349.5	-	-	-	-	-	-	-	-	-	349.5
3.5.3 Independent Software Verification and Validation	-	-	-	-	-	873.6	-	-	-	-	-	-	-	-	873.6
3.6.8 Technical Data	-	-	-	-	174.8	177.9	181.0	184.3	187.6	191.0	-	-	-	-	1,096.6
3.7.1 Implementation Planning, Management, and Control	-	-	-	-	-	-	841.9	857.0	872.8	888.6	-	-	-	-	3,460.3
3.7.3 Implementation Engineering	-	-	-	-	-	-	362.0	368.5	375.3	382.1	-	-	-	-	1,487.9
3.7.9 Site Preparation, Installation, Test, and Activation	-	-	-	-	-	-	362.0	368.5	375.3	382.1	-	-	-	-	1,487.9
Phase 4 IN-SERVICE MANAGEMENT	**-**	**-**	**-**	**-**	**-**	**-**	**1,390.6**	**2,295.4**	**2,834.6**	**2,885.9**	**2,251.3**	**2,291.3**	**2,332.0**	**46,631.6**	**62,912.7**
4.5 Watch Standing Coverage	-	-	-	-	-	-	1,390.6	2,295.4	2,834.6	2,885.9	-	-	-	-	9,406.5
4.6.1 Program Planning, Authorization, Management and Control	-	-	-	-	-	-	-	-	-	-	1,223.1	1,244.8	1,266.9	25,333.5	29,068.2
4.7.8 Technical Data	-	-	-	-	-	-	-	-	-	-	178.6	181.8	185.0	3,699.9	4,245.4
4.8.3 Software and Hardware Modification and Support	-	-	-	-	-	-	-	-	-	-	849.6	864.7	880.1	17,598.2	20,192.6
Total	**1,327.5**	**3,375.2**	**3,624.8**	**19,830.1**	**20,364.5**	**#####**	**4,172.8**	**5,409.9**	**6,198.2**	**6,310.4**	**2,251.3**	**2,291.3**	**2,332.0**	**46,631.6**	**126,816.5**

16 Terminal Metering Concept Cost Analysis

16.1 Introduction

The costs of the standalone TM concept are presented below along with the objective metrics, rationale and calculations used to determine them. Costs for integrated TM and CMS were presented in Section 16. The Saab Sensis team used a method that complies with the FAA cost analysis standards.

16.2 Assumptions

These assumptions are general in nature, more detailed assumptions are provided in WBS element specific narratives:

- Costs were estimated using Fiscal Year (FY) 2012 constant dollars
- Then year summary tables were derived using appropriate inflation indices.
  - Bureau of Economic Analysis, Table 1.1.9. Implicit Price Deflators for Gross Domestic Product: http://bea.gov/iTable/iTable.cfm?ReqID=9&step=1
  - Office of Management and Budget, Budget of the United States Government Fiscal Year 2013, Table 2–1. Economic Assumptions: http://www.whitehouse.gov/sites/default/files/omb/budget/fy2013/assets/spec.pdf
- Present value figures were derived using appropriate discount rate information.
  - Office of Management and Budget, Circular No. A-94 Appendix C: http://www.whitehouse.gov/omb/circulars_a094/a94_appx-c
- The cost model is based upon Version 5.0 of the FAA Work Breakdown Structure (WBS).
  - http://fast.faa.gov/
- The timeframe of the analysis is FY 2012 through FY 2041.
- No decommissioning is assumed at the end of analysis.
- Labor rates for contractor labor are divided into three categories: senior, middle, and junior level. The fully loaded annual pay for each of these levels is assumed to be $250K, $225K, and $200K respectively.
- Labor rates for federal government employees are based on the information below:
  - U.S. Office of Personnel Management, 2012 Salary Table including a locality payment of 35.15% for the area of San Jose, San Francisco, and Oakland, California: http://www.opm.gov/oca/12tables/pdf/SF.pdf
  - Office of Management and Budget, Circular No. A-76, Figure C1, Civilian Position Full Fringe Benefit Cost Factor (36.25%): http://www.whitehouse.gov/omb/circulars_a076_a76_incl_tech_correction/

16.3 Work Breakout Structure (WBS)

To provide a structure from which costs and benefits can be compared, the following cost elements from FAA AMS WBS 5.0 were used and contain the principal cost and benefit drivers evaluated.

Table 124: breakout structures

Phase 1 MISSION ANALYSIS
1.3.1.1 Research, Engineering, and Development (Concept to Lab R&D)
1.3.1.2 Research, Engineering, and Development (Field Research)
Phase 2 INVESTMENT ANALYSIS
2.1 Initial Investment Analysis
2.3 Final Investment Analysis
Phase 3 SOLUTION IMPLEMENTATION
3.1.3 Prime Mission Product Application Software
3.1.5 Prime Mission Product Platform Integration
3.1.6.4 Training
3.2 Program Management
3.3 Systems Engineering
3.5.1 Development Test and Evaluation
3.5.2 Operational Test and Evaluation
3.5.3 Independent Software Verification and Validation
3.6.8 Technical Data
3.7.1 Implementation Planning, Management, and Control
3.7.3 Implementation Engineering
3.7.9 Site Preparation, Installation, Test, and Activation
4 IN-SERVICE MANAGEMENT
4.5 Watch Standing Coverage
4.6.1 Program Planning, Authorization, Management and Control
4.7.8 Technical Data
4.8.3 Software and Hardware Modification and Support

16.4 WBS Element Specific Cost Detail

WBS Element 1.3.1 Research, Engineering, and Development. All activities associated with discovering applications of new technology for the National Airspace System (NAS), exploring new opportunities for service delivery, solving problems with current operations, defining and stabilizing requirements, maturing operational concepts, and mitigating risk. These activities generate information to quantify and characterize capability shortfalls, service needs and requirements, benefit expectations, and design alternatives.

This cost element was split into two subsections WBS Element 1.3.1.1, which covers concept to lab research and development, and WBS Element 1.3.1.2, which accounts for field research.

WBS Element 1.3.1.1 Research and Development (Concept to Lab R&D). The cost buildup appears in the table below, which depicts the NASA headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 125: Research and development concept to lab R&D staff requirement

Labor Category	Pay	FY12	FY13
PM	GS14	0.5	0.5
Senior Scientists	GS14	1	0.5
Engineers	GS13	2	1
SW Engineers	GS13	3	2
Testers	GS12	0	0
Lab Support	GS12	0.5	0.5
SMEs (Participants for Testing)	GS12	2	2
Subtotal		**9.0**	**6.5**

Table 126: Research and development concept to lab R&D cost per year

TM Cost Summary: TY $K	FY12	FY13	Total
1.3.1.1 Research and Development (Concept to Lab R&D)	1,327.5	955.4	2,282.9

WBS Element 1.3.1.2 Research and Development (Field Research). The cost buildup appears in the table below, which depicts the NASA headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 127: Research and development field research staff requirement

Labor Category	Pay	FY13	FY14	FY15	FY16
PM	GS14	0.75	1.25	1.25	1.25
Senior Scientists	GS14	0.5	1	1	1
Engineers	GS13	2	3	3	3
SW Engineers	GS13	4	6	6	6
Testers	GS12	1	1	3	3
Field Support	GS12	1	2	2	2
SMEs (Participants for Testing)	GS12	1	3	3	3
Analyst	GS12			1	1
Subtotal		**10.3**	**17.3**	**20.3**	**20.3**

Table 128: Research and development field research staff cost by year

TM Cost Summary: TY $K	FY13	FY14	FY15	FY16	Total

1.3.1.2 Research and Development (Field Research)	1,520.4	2,581.0	3,025.6	3,080.5	10,207.6

WBS Element 2.1 Initial Investment Analysis. All activities associated with analyzing alternative solutions to mission need in preparation for an initial investment decision. Specific activities include:

- Form and prepare investment analysis team members, verify entry criteria are satisfied, hold kickoff meeting, and refine the investment analysis plan, if needed, particularly the roles and responsibilities of team members and the timeline for conduct of investment analysis.
- Define the business case including assumptions and constraints, the legacy reference case, strategic performance measures, and design to cost goals.
- Analyze market capability including definition of a functional/performance specification, development and evaluation of a screening request for information, conduct of an industry day to meet with organizations with potential solutions, operational capability demonstrations, and analysis and evaluation of results.
- Analyze alternatives including adding or modifying alternatives as a result of the market survey; the comparative assessment of performance, benefits, cost, risk safety, and schedule; economic analysis; evaluation of human factors, environmental safety and health impacts, radio frequency spectrum availability, supportability, regulatory or procedural impact, test readiness/maturity level; operational suitability, operational effectiveness, ability to upgrade, and interdependencies with existing or proposed programs; and recording results in the preliminary business case.
- Conduct of operational capability demonstrations and tests to evaluate candidate solution to the service need.
- Assess budget impact.
- Prepare the initial implementation strategy and planning document for each alternative.
- Update requirements in the program requirements document.
- Verify and validate key work products.
- Plan for final investment analysis including all coordination necessary for approval.

The cost buildup appears in the table below, which depicts the FAA headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 129: Initial investment stage staff requirement

Labor Category	Pay	FY13
Program Manager	GS14	1
Assistant PM	GS13	1
Senior Engineers	GS13	1
Engineers	GS12	2
Contracting Officer (COTR)	GS12	0.5
Logistics Analyst	GS12	0.5
Configuration Management	GS12	0.25

Subtotal		**6.3**

Table 130: Initial investment stage staff cost by year

TM Cost Summary: TY $K	FY13	Total
2.1 Initial Investment Analysis	899.3	899.3

WBS Element 2.3 Final Investment Analysis. All activities associated with detailed planning for the alternative selected for implementation, soliciting offers from potential suppliers, and development of required program documentation. Specific activities include:

- Identify all tasks, actions, and events needed to deliver and support the solution over its lifecycle.
- Reduce risk and finalize requirements including a detailed risk assessment; risk-reduction modeling, simulations, and prototyping; competitive fly-offs among offerors.
- Finalize the strategy for implementation and lifecycle support including risk management, program segmentation, procurement strategy, benefits realization strategy, in-service operations strategy, logistics and support strategy, test and evaluation strategy, and detailed costs and schedules for the entire segment or phase for which approval is sought.
- Solicit offers for prime contract(s) including development of the performance/functional specification, completion of evaluation criteria and weights, conduct of an industry day meeting, development and issuance of the screening information request, and communications with potential bidders.
- Evaluate vendor offers including evaluation and scoring of proposals, comparison with government estimates, and adjustment of baselines and planning as needed.
- Develop detailed program planning including a complete program work breakdown structure, detailed tasks, schedules, and resource estimates; development of an earned value management strategy and framework, completion of the final economic analysis, and finalization of the business case.
- Finalize the acquisition program baseline, program requirements document, business case analysis report, and implementation strategy and planning document, and Exhibit 300 for designated programs. This includes independent scoring the Exhibit 300 and all activity necessary to improve the document to as high a score as possible.
- Verify and validate the key work products of final investment analysis.
- Prepare for the final investment decision including completion of the JRC readiness checklist, update of enterprise architecture products and amendments, verification that final investment analysis exit criteria are satisfied, coordination with stakeholders, conduct of final budget and financial reviews, approval to move forward by the JRC subordinate review board

The cost buildup appears in the table below, which depicts the FAA headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 131: Final investment stage staff requirement

Labor Category	Pay	FY14

Program Manager	GS14	1
Assistant PM	GS13	1
Senior Engineers	GS13	1
Engineers	GS12	3
Contracting Officer (COTR)	GS12	0.5
Logistics Analyst	GS12	0.5
Configuration Management	GS12	0.25
Subtotal		**7.3**

Table 132: Final investment stage staff cost by year

TM Cost Summary: TY $K	FY14	Total
2.3 Final Investment Analysis	1,043.8	1,043.8

WBS Element 3.1.3 Prime Mission Product Application Software. This PMP contractor activity associated with software specifically produced for the functional use of a prime mission product.

The cost buildup appears in the table below, which depicts source lines of code (SLOC) required at ARTCCs and TRACONs, phased by year. The cost per line of code is based on FAA historical costs incurred during ERAM implementation, which averaged $1,624 per SLOC. The extended costs are summarized in the second table below.

Table 133: Software SLOC by category

Software SLOC by Category	$K/SLOC	FY15	FY16
ARTCCs	$1.62	1,500	1,500
TRACONs (those with TMA Adapted Airports)	$1.62	225	225
Subtotal		**1,725.0**	**1,725.0**

Table 134: Prime mission product application software development cost by year

TM Cost Summary: TY $K	FY15	FY16	Total
3.1.3 Prime Mission Product Application Software	2,946.5	2,999.9	5,946.4

WBS Element 3.1.5 Prime Mission Product Platform Integration. This PMP contractor activity associated with technical and engineering services to the platform manufacture or integrator during installation and integration of the prime mission product into a larger host system or operational environment.

The implementation schedule that drives this cost element's software integration appears in the table below.

Table 135: Product platform integration airport implementation schedule

Implementation Schedule	FY18	FY19	FY20	FY21	Total
20 Centers (ARTCCs)	3	5	6	6	**20**
30 TRACONS (those with TMA Adapted Airports)	5	7	9	9	**30**

It is estimated that 4 man months of software integration will be required at each ARTCC, and 2 man months at each TRACON. The extended total man months of required software integration phased by year appears below.

Table 136: Product platform integration airport implementation man months requirement

SW Adaptation (Man Months)	FY18	FY19	FY20	FY21	Total
ARTCCs	12	20	24	24	**80**
TRACONs (those with TMA Adapted Airports)	10	14	18	18	**60**

The extended costs appear in the table below, based on the man months schedule above and contractor software engineers estimated at a $250K fully loaded annual salary.

Table 137: Product platform integration airport implementation cost

TM Cost Summary: TY $K	FY18	FY19	FY20	FY21	Total
3.1.5 Prime Mission Product Platform Integration	508.4	799.9	1,006.3	1,024.5	3,339.1

WBS Element 3.1.6.4 Training. All PMP contractor activity associated with planning, developing, and establishing training for operators and maintainers; provisioners, item managers, and deport repair technicians; maintenance of common and peculiar support equipment and test and measurement equipment; second-level engineering support; computer resources support; and packaging, handling, storage, and transportation of training materials.

It is estimated that 1 senior engineer ($250K per year) and 1 mid-level engineer ($225K per year) will be needed in each year from FY17 through FY21 to prepare and conduct training. The extended costs are summarized in the second table below.

Table 138: Training staff requirement by year

Labor Category	Pay	FY17	FY18	FY19	FY20	FY21
Senior Engineer	SrContr	1	1	1	1	1
Engineer	MdContr	1	1	1	1	1
Subtotal		**2.0**	**2.0**	**2.0**	**2.0**	**2.0**

Table 139: Training staff cost by year

TM Cost Summary: TY $K	FY17	FY18	FY19	FY20	FY21	Total
3.1.6.4 Training	517.8	526.9	536.4	546.3	556.2	2,683.6

WBS Element 3.2 Program Management. All government activity associated with business and administrative planning, organizing, directing, coordinating, controlling, and approval actions to accomplish overall program objectives. This includes all program management support contracts.

The cost buildup appears in the table below, which depicts the FAA headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 140: Program management staff requirement by year

Labor Category	Pay	FY15	FY16	FY17
Program Manager	GS14	1	1	1
Assistant PM	GS13	1	1	1
Senior Engineers	GS13	1	1	1
Engineers	GS12	1	1	1
Contracting Officer (COTR)	GS12	0.5	0.5	0.5
Logistics Analyst	GS12	0.5	0.5	0.5
Configuration Management	GS12	0.25	0.25	0.25
Subtotal		**5.3**	**5.3**	**5.3**

Table 141: Program management staff cost by year

TM Cost Summary: TY $K	FY15	FY16	FY17	Total
3.2 Program Management	798.4	812.9	827.4	2,438.7

WBS Element 3.3 Systems Engineering . All government technical and engineering activities associated with planning, directing, and controlling a totally integrated engineering effort for a solution. Specific activities include: requirements definition and allocation; analysis, design, and integration; supportability, maintainability, and reliability engineering; quality assurance; interface management; human factors engineering; security engineering; safety engineering; technical risk management; and specialty engineering.
The cost buildup appears in the table below, which depicts the FAA headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 142: System engineering staff requirement by year

Labor Category	Pay	FY15	FY16	FY17
Senior Engineers	GS13	1	1	1
Engineers	GS12	1	1	1
Subtotal		**2.0**	**2.0**	**2.0**

Table 143: System engineering staff cost by year

TM Cost Summary: TY $K	FY15	FY16	FY17	Total

3.3 Systems Engineering	289.7	294.9	300.2	884.8

WBS Element 3.5.1 Development Test and Evaluation. All government activities associated with testing during product development to determine whether engineering design and development activities are complete; whether the product will meet specifications, security certification, and authorization criteria; and whether it is operating properly so as to achieve government acceptance. This includes all government activities associated with hardware and software validation and verification, factory acceptance testing, and site acceptance testing. It includes all government test support activities (e.g., technical assistance, maintenance, labor, material, support elements and testing spares, etc.), as well as all government activities associated with development and construction of special test facilities, test tools, and models required for performance of developmental tests.

The cost buildup appears in the table below, which depicts the FAA headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 144: Development test and evaluation staff requirement

Labor Category	Pay	FY15
Senior Engineers	GS14	1
Engineers	GS13	1
Subtotal		**2.0**

Table 145: Development test and evaluation staff cost

TM Cost Summary: TY $K	FY15	Total
3.5.1 Development Test and Evaluation	343.3	343.3

WBS Element 3.5.2 Operational Test and Evaluation. All government activities associated with tests and evaluations conducted to assess product utility, operational effectiveness, operational suitability, and logistics supportability (including compatibility, interoperability, reliability, maintainability, logistics requirements, safety requirements, security administration, etc.). This includes all test support activities (e.g., technical assistance, maintenance, labor, material, support elements, and testing spares) as well as all activities associated with development and construction of special test facilities, test tools, and models required for performance of operational tests. Operational testing also includes site operational testing (covered in WBS element 3.7.8) and support by test and evaluation personnel during field familiarization.

The cost buildup appears in the table below, which depicts the FAA headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 146: Operational test and evaluation staff requirement

Labor Category	Pay	FY16
Senior Engineers	GS14	1
Engineers	GS13	1
Subtotal		**2.0**

Table 147: Operational test and evaluation staff cost

TM Cost Summary: TY $K	FY16	Total
3.5.2 Operational Test and Evaluation	349.5	349.5

WBS Element 3.5.3 Independent Software Verification and Validation. All activities performed by organizations other than the developer to determine the degree to which software fulfills the specifications. Verification is a rigorous mathematical demonstration to ensure the source code conforms to its requirements. Validation evaluates a software product throughout the development process to determine compliance with product requirements.

The cost buildup appears in the table below, which depicts the FAA and contractor headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 148: Independent software verification and validation staff requirement

Labor Category	Pay	FY17
Senior Engineers	GS14	1
Engineers	GS13	1
Senior Engineers	SrContr	1
Engineers	MdContr	1
Subtotal		**4.0**

Table 149: Independent software verification and validation staff cost by year

TM Cost Summary: TY $K	FY17	Total
3.5.3 Independent Software Verification and Validation	873.6	873.6

WBS Element 3.6.8 Technical Data. All government activities associated with planning and reviewing program and contractor technical data. Technical data includes items such as engineering drawings, notebooks, maintenance handbooks, operator manuals, maintenance manuals, installation drawings, and all contract data deliverables. This includes delivery and maintenance of documentation in place by contractors with government access, as well as activity related to treatment of intellectual property rights and third-party retention of data and documentation.

The cost buildup appears in the table below, which depicts the FAA headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 150: Technical data planning and review staff requirement by year

Labor Category	Pay	FY16	FY17	FY18	FY19	FY20	FY21
Senior Engineer	GS14	0.5	0.5	0.5	0.5	0.5	0.5
Engineer	GS13	0.5	0.5	0.5	0.5	0.5	0.5
Subtotal		**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**

Table 151: Technical data planning and review staff cost by year

TM Cost Summary: TY $K	FY16	FY17	FY18	FY19	FY20	FY21	Total
3.6.8 Technical Data	174.8	177.9	181.0	184.3	187.6	191.0	1,096.6

WBS Element 3.7.1 Implementation Planning, Management, and Control. All government activities associated with implementation planning, control, contract management, and business management. Specific activities include:

- Planning, organizing, directing, coordinating, estimating, scheduling, controlling, and approving actions to accomplish program implementation, including project-specific input to agency-level planning documents such as the call for estimates, blue sheets, white sheets, the capital investment plan, and the enterprise architecture.
- Development and dissemination of deployment planning information to regional and site personnel.
- Tailoring the in-service review (ISR) checklist, conducting ISR checklist status reviews, developing action plans and briefing package to obtain the in-service decision, conducting stakeholder meetings, obtaining the in-service decision, tracking ISD action plans, and updating the implementation strategy and planning document.
- All activities associated with awarding and managing program-related contracts, including technical support contracts.

The cost buildup appears in the table below, which depicts the FAA headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 152: Implementation planning, management and control staff requirement by year

Labor Category	Pay	FY18	FY19	FY20	FY21
Program Manager	GS14	1	1	1	1
Assistant PM	GS13	1	1	1	1
Senior Engineers	GS13	1	1	1	1
Engineers	GS12	1	1	1	1
Contracting Officer (COTR)	GS12	0.5	0.5	0.5	0.5
Logistics Analyst	GS12	0.5	0.5	0.5	0.5

Configuration Management	GS12	0.25	0.25	0.25	0.25
Subtotal		**5.3**	**5.3**	**5.3**	**5.3**

Table 153: Implementation planning, management and control staff cost by year

TM Cost Summary: TY $K	FY18	FY19	FY20	FY21	Total
3.7.1 Implementation Planning, Management, and Control	841.9	857.0	872.8	888.6	3,460.3

WBS Element 3.7.3 Implementation Engineering. All government engineering activity associated with site surveys, design, analysis, and studies. Specific activities include:

- Civil, electrical, mechanical, architectural, industrial, and other "non-electronic" engineering positions.
- Drafting and developing site plans and specifications.
- All electronic engineering activities associated with the study, analysis, and design of electronic installation.
- Spectrum analysis and engineering.
- Coordination with organizations associated with site engineering.
- Development of installation drawings.
- Physical integration associated with site modification requirements to ensure the solution integrates into the NAS.
- Assessment of site conditions, physical requirements of the solution, and transition requirements.
- Transition and operational requirements for physical security.

The cost buildup appears in the table below, which depicts the FAA headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 154: Implementation engineering staff requirement by year

Labor Category	Pay	FY18	FY19	FY20	FY21
Senior Engineer	GS14	1	1	1	1
Engineer	GS13	1	1	1	1
Subtotal		**2.0**	**2.0**	**2.0**	**2.0**

Table 155: Implementation engineering staff cost by year

TM Cost Summary: TY $K	FY18	FY19	FY20	FY21	Total
3.7.3 Implementation Engineering	362.0	368.5	375.3	382.1	1,487.9

WBS Element 3.7.9 Site Preparation, Installation, Test, and Activation. All activity associated with site preparation, installation, acceptance testing, operations testing, and checkout of hardware, software, and equipment to achieve operational status. This includes coordination

with all applicable organizations, unions, and the public during installation and transition. Specific activities include:

- Preparation and Installation: All activities associated with site preparation, equipment installation, acceptance testing, and checkout of hardware and software to achieve operational status. This includes coordination with all applicable organizations, unions, and the public during installation and transition.
- Test and Evaluation: All government test and evaluation activities (from WBS 3.5) to verify and validate operational readiness at each site. This includes test support activities (e.g., technical assistance, maintenance, labor, material, support elements, and testing spares) as well as all activities associated with development and construction of special test facilities, test tools, and models required for performance of operational tests; Support of T&E personnel during field familiarization. Field familiarization is the conduct of activities that allow the facility to gain confidence in the asset and attain a higher level of hands-on familiarization.
- Joint Acceptance Inspection and Commissioning: All activities associated with preparing for and achieving declaration of operational readiness, initial operational capability, full operational capability, joint acceptance inspection, service availability, and commissioning. Specific activities include: Development or modification of operational procedures; Issuance of Notice to Airmen; field familiarization activities; preliminary and final commissioning; flight inspections and other applicable testing; Initial certification activities, initial standards testing and evaluation, and initial publication of certification standards.
- Decommissioning and removal of replaced assets: All activities associated with the termination and removal of a decommissioned system or equipment. This includes planning and engineering; environmental assessments, cleanup, abatement, and disposal of hazardous materials as stipulated by laws and regulations engineering; dismantling demolishing, and removing decommissioned systems or equipment; restoring a site to acceptable condition; and all actions to revert real estate to the owner and close the project.

The cost buildup appears in the table below, which depicts the FAA headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 156: Site preparation, installation, test and activation staff requirement by year

Labor Category	Pay	FY18	FY19	FY20	FY21
Senior Engineer	GS14	1	1	1	1
Engineer	GS13	1	1	1	1
Subtotal		**2.0**	**2.0**	**2.0**	**2.0**

Table 157: Site preparation, installation, test and activation staff requirement by year

TM Cost Summary: TY $K	FY18	FY19	FY20	FY21	Total
3.7.9 Site Preparation, Installation, Test, and	362.0	368.5	375.3	382.1	1,487.9

Activation					

WBS Element 4.5 Watch Standing Coverage. All activities associated with watch-standing coverage beyond stated staffing requirements.

It is assumed there are 245 controllers per ARTCC and 30 per TRACON that will require training. When multiplying these students by the implementation schedule shown in WBS Element 3.1.5 Prime Mission Product Platform Integration, the total students requiring training by year is determined.

Table 158: Watch standing coverage student training requirement by year

Students requiring training	Average per facility	FY18	FY19	FY20	FY21	Total
ARTCCs	245	735	1,225	1,470	1,470	**4,900**
TRACONs (those with TMA Adapted Airports)	30	150	210	270	270	**900**

Assuming a 20 hour course and 1,776 productive work hours in a year, the full time equivalent backfill watch standers presented in the table below will be required. The associated costs are summarized in the second table below.

Table 159: Watch standing coverage controller requirement by year

FTE Backfill Watch Standers Required	Pay	FY18	FY19	FY20	FY21
Contoller: ARTCCs	GS12	8.28	13.80	16.55	16.55
Controller: TRACONs (those with TMA Adapted Airports)	GS12	1.69	2.36	3.04	3.04
Subtotal		**10.0**	**16.2**	**19.6**	**19.6**

Table 160: Associated costs for watch standing coverage by year

TM Cost Summary: TY $K	FY18	FY19	FY20	FY21	Total
4.5 Watch Standing Coverage	1,390.6	2,295.4	2,834.6	2,885.9	9,406.5

WBS Element 4.6.1 Program Planning, Authorization, Management and Control. All activities associated with planning, authorizing, and managing actions that must be accomplished for operation and maintenance. Specific activities include:

- Preparing project-specific input to agency-level planning documents such as the call for estimates and the enterprise architecture.
- Security control.

- Activities to ensure cost, schedule, operational performance, and benefit objectives are met.

The cost buildup appears in the table below, which depicts the FAA and contractor headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 161: Program planning, authorization, management and control staff requirement

Labor Category	Pay	FY22	FY23	FY24	FY25	FY26	Each year FY27 –FY41
Senior Engineer	GS14	1	1	1	1	1	1
Engineer	GS13	1	1	1	1	1	1
Senior Engineer	SrContr	1	1	1	1	1	1
Engineer	MdContr	2	2	2	2	2	2
Subtotal		**5.0**	**5.0**	**5.0**	**5.0**	**5.0**	**5.0**

Table 162: Program planning, authorization, management and control staff cost by year

TM Cost Summary: TY $K	FY22	FY23	FY24	FY25	FY26	FY27-FY41	Total
4.6.1 Program Planning, Authorization, Management and Control	1,223.1	1,244.8	1,266.9	1,289.5	1,312.4	22,731.6	29,068.2

WBS Element 4.7.8 Technical Data. All activities associated with product-specific documentation including engineering drawings, operator manuals, maintenance manuals, repair and test procedures, provisioning data, logistics management information, and other technical data used by or directly associated with operations, maintenance, and support of operational systems, facilities, and equipment.

The cost buildup appears in the table below, which depicts the FAA and contractor headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 163: Technical data staff requirement by year

Labor Category	Pay	FY22	FY23	FY24	FY25	FY26	Each year FY27 –FY41
Engineer	GS13	0.25	0.25	0.25	0.25	0.25	0.25
Engineer	MdContr	0.50	0.50	0.50	0.50	0.50	0.50
Subtotal		**0.75**	**0.75**	**0.75**	**0.75**	**0.75**	**0.75**

Table 164: Technical data staff cost by year

TM Cost Summary: TY $K	FY22	FY23	FY24	FY25	FY26	FY27-FY41	Total
4.7.8 Technical Data	178.6	181.8	185.0	188.3	191.7	3,319.9	4,245.4

WBS Element 4.8.3 Software and Hardware Modification and Support. All activities associated with the analysis, design, test, and implementation of computer resources modifications, operational and support elements, and sustainment of the NAS including site adaptation.

The cost buildup appears in the table below, which depicts the FAA and contractor headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 165: Software and hardware modification and support staff requirement by year

Labor Category	Pay	FY22	FY23	FY24	FY25	FY26	Each year FY27 –FY41
Senior Engineer	GS14	0.50	0.50	0.50	0.50	0.50	0.50
Engineer	GS13	1.00	1.00	1.00	1.00	1.00	1.00
Senior Engineer	SrContr	1.00	1.00	1.00	1.00	1.00	1.00
Engineer	MdContr	1.00	1.00	1.00	1.00	1.00	1.00
Subtotal		**3.50**	**3.50**	**3.50**	**3.50**	**3.50**	**3.50**

Table 166: Software and hardware modification and support staff cost by year

TM Cost Summary: TY $K	FY22	FY23	FY24	FY25	FY26	FY27-FY41	Total
4.8.3 Software and Hardware Modification and Support	849.6	864.7	880.1	895.7	911.7	15,790.8	20,192.6

Table 167: Base Year 2012 Life Cycle Cost Table Phased By Year, $K

TM Cost Summary: BY12 $K	FY12	FY13	FY14	FY15	FY16	FY17	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25-FY41	Total
Phase 1 MISSION ANALYSIS	**1,327.5**	**2,435.7**	**2,498.6**	**2,876.0**	**2,876.0**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**12,013.8**
1.3.1.1 Research and Development (Concept to Lab R&D)	1,327.5	940.0	-	-	-	-	-	-	-	-	-	-	-	-	2,267.5
1.3.1.2 Research and Development (Field Research)	-	1,495.8	2,498.6	2,876.0	2,876.0	-	-	-	-	-	-	-	-	-	9,746.4
Phase 2 INVESTMENT ANALYSIS	**-**	**884.7**	**1,010.5**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**1,895.2**
2.1 Initial Investment Analysis	-	884.7	-	-	-	-	-	-	-	-	-	-	-	-	884.7
2.3 Final Investment Analysis	-	-	1,010.5	-	-	-	-	-	-	-	-	-	-	-	1,010.5
Phase 3 SOLUTION IMPLEMENTATION	**-**	**-**	**-**	**4,161.4**	**4,324.5**	**2,473.8**	**2,508.1**	**2,758.1**	**2,924.8**	**2,924.8**	**-**	**-**	**-**	**-**	**22,075.5**
3.1.3 Prime Mission Product Application Software	-	-	-	2,800.7	2,800.7	-	-	-	-	-	-	-	-	-	5,601.5
3.1.5 Prime Mission Product Platform Integration	-	-	-	-	-	-	458.3	708.3	875.0	875.0	-	-	-	-	2,916.7
3.1.6.4 Training	-	-	-	-	-	475.0	475.0	475.0	475.0	475.0	-	-	-	-	2,375.0
3.2 Program Management	-	-	-	758.9	758.9	758.9	-	-	-	-	-	-	-	-	2,276.8
3.3 Systems Engineering	-	-	-	275.4	275.4	275.4	-	-	-	-	-	-	-	-	826.1
3.5.1 Development Test and Evaluation	-	-	-	326.3	-	-	-	-	-	-	-	-	-	-	326.3
3.5.2 Operational Test and Evaluation	-	-	-	-	326.3	-	-	-	-	-	-	-	-	-	326.3
3.5.3 Independent Software Verification and Validation	-	-	-	-	-	801.3	-	-	-	-	-	-	-	-	801.3
3.6.8 Technical Data	-	-	-	-	163.2	163.2	163.2	163.2	163.2	163.2	-	-	-	-	979.0
3.7.1 Implementation Planning, Management, and Control	-	-	-	-	-	-	758.9	758.9	758.9	758.9	-	-	-	-	3,035.7
3.7.3 Implementation Engineering	-	-	-	-	-	-	326.3	326.3	326.3	326.3	-	-	-	-	1,305.3
3.7.9 Site Preparation, Installation, Test, and Activation	-	-	-	-	-	-	326.3	326.3	326.3	326.3	-	-	-	-	1,305.3
Phase 4 IN-SERVICE MANAGEMENT	**-**	**-**	**-**	**-**	**-**	**-**	**1,253.6**	**2,032.7**	**2,464.8**	**2,464.8**	**1,889.2**	**1,889.2**	**1,889.2**	**32,116.1**	**45,999.5**
4.5 Watch Standing Coverage	-	-	-	-	-	-	1,253.6	2,032.7	2,464.8	2,464.8	-	-	-	-	8,215.8
4.6.1 Program Planning, Authorization, Management and Control	-	-	-	-	-	-	-	-	-	-	1,026.3	1,026.3	1,026.3	17,447.7	20,526.7
4.7.8 Technical Data	-	-	-	-	-	-	-	-	-	-	149.9	149.9	149.9	2,548.2	2,997.9
4.8.3 Software and Hardware Modification and Support	-	-	-	-	-	-	-	-	-	-	713.0	713.0	713.0	12,120.2	14,259.1
Total	**1,327.5**	**3,320.5**	**3,509.1**	**7,037.4**	**7,200.5**	**2,473.8**	**3,761.7**	**4,790.8**	**5,389.5**	**5,389.5**	**1,889.2**	**1,889.2**	**1,889.2**	**32,116.1**	**81,984.0**

Table 168: Then Year Life Cycle Cost Table Phased By Year, $K

TM Cost Summary: TY $K	FY12	FY13	FY14	FY15	FY16	FY17	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25-FY41	Total
Phase 1 MISSION ANALYSIS	**1,327.5**	**2,475.9**	**2,581.0**	**3,025.6**	**3,080.5**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**12,490.5**
1.3.1.1 Research and Development (Concept to Lab R&D)	1,327.5	955.4	-	-	-	-	-	-	-	-	-	-	-	-	2,282.9
1.3.1.2 Research and Development (Field Research)	-	1,520.4	2,581.0	3,025.6	3,080.5	-	-	-	-	-	-	-	-	-	10,207.6
Phase 2 INVESTMENT ANALYSIS	**-**	**899.3**	**1,043.8**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**1,943.1**
2.1 Initial Investment Analysis	-	899.3	-	-	-	-	-	-	-	-	-	-	-	-	899.3
2.3 Final Investment Analysis	-	-	1,043.8	-	-	-	-	-	-	-	-	-	-	-	1,043.8
Phase 3 SOLUTION IMPLEMENTATION	**-**	**-**	**-**	**4,377.9**	**4,632.1**	**2,696.9**	**2,782.2**	**3,114.5**	**3,363.6**	**3,424.5**	**-**	**-**	**-**	**-**	**24,391.8**
3.1.3 Prime Mission Product Application Software	-	-	-	2,946.5	2,999.9	-	-	-	-	-	-	-	-	-	5,946.4
3.1.5 Prime Mission Product Platform Integration	-	-	-	-	-	-	508.4	799.9	1,006.3	1,024.5	-	-	-	-	3,339.1
3.1.6.4 Training	-	-	-	-	-	517.8	526.9	536.4	546.3	556.2	-	-	-	-	2,683.6
3.2 Program Management	-	-	-	798.4	812.9	827.4	-	-	-	-	-	-	-	-	2,438.7
3.3 Systems Engineering	-	-	-	289.7	294.9	300.2	-	-	-	-	-	-	-	-	884.8
3.5.1 Development Test and Evaluation	-	-	-	343.3	-	-	-	-	-	-	-	-	-	-	343.3
3.5.2 Operational Test and Evaluation	-	-	-	-	349.5	-	-	-	-	-	-	-	-	-	349.5
3.5.3 Independent Software Verification and Validation	-	-	-	-	-	873.6	-	-	-	-	-	-	-	-	873.6
3.6.8 Technical Data	-	-	-	-	174.8	177.9	181.0	184.3	187.6	191.0	-	-	-	-	1,096.6
3.7.1 Implementation Planning, Management, and Control	-	-	-	-	-	-	841.9	857.0	872.8	888.6	-	-	-	-	3,460.3
3.7.3 Implementation Engineering	-	-	-	-	-	-	362.0	368.5	375.3	382.1	-	-	-	-	1,487.9
3.7.9 Site Preparation, Installation, Test, and Activation	-	-	-	-	-	-	362.0	368.5	375.3	382.1	-	-	-	-	1,487.9
Phase 4 IN-SERVICE MANAGEMENT	**-**	**-**	**-**	**-**	**-**	**-**	**1,390.6**	**2,295.4**	**2,834.6**	**2,885.9**	**2,251.3**	**2,291.3**	**2,332.0**	**46,631.6**	**62,912.7**
4.5 Watch Standing Coverage	-	-	-	-	-	-	1,390.6	2,295.4	2,834.6	2,885.9	-	-	-	-	9,406.5
4.6.1 Program Planning, Authorization, Management and Control	-	-	-	-	-	-	-	-	-	-	1,223.1	1,244.8	1,266.9	25,333.5	29,068.2
4.7.8 Technical Data	-	-	-	-	-	-	-	-	-	-	178.6	181.8	185.0	3,699.9	4,245.4
4.8.3 Software and Hardware Modification and Support	-	-	-	-	-	-	-	-	-	-	849.6	864.7	880.1	17,598.2	20,192.6
Total	**1,327.5**	**3,375.2**	**3,624.8**	**7,403.6**	**7,712.6**	**2,696.9**	**4,172.8**	**5,409.9**	**6,198.2**	**6,310.4**	**2,251.3**	**2,291.3**	**2,332.0**	**46,631.6**	**101,738.1**

17 Flight-deck Interval Management Concept Cost Analysis

17.1 Introduction

The costs of the FIM concept are presented below along with the objective metrics, rationale and calculations used to determine them. The Saab Sensis team used a method that complies with the FAA cost analysis standards.

17.2 Assumptions

These assumptions are general in nature, more detailed assumptions are provided in WBS element specific narratives:

- Costs were estimated using Fiscal Year (FY) 2012 constant dollars
- Then year summary tables were derived using appropriate inflation indices.
  - Bureau of Economic Analysis, Table 1.1.9. Implicit Price Deflators for Gross Domestic Product: http://bea.gov/iTable/iTable.cfm?ReqID=9&step=1
  - Office of Management and Budget, Budget of the United States Government Fiscal Year 2013, Table 2–1. Economic Assumptions: http://www.whitehouse.gov/sites/default/files/omb/budget/fy2013/assets/spec.pdf
- Present value figures were derived using appropriate discount rate information.
  - Office of Management and Budget, Circular No. A-94 Appendix C: http://www.whitehouse.gov/omb/circulars_a094/a94_appx-c
- The cost model is based upon Version 5.0 of the FAA Work Breakdown Structure (WBS).
  - http://fast.faa.gov/
- The timeframe of the analysis is FY 2012 through FY 2043.
- No decommissioning is assumed at the end of analysis.
- Labor rates for contractor labor are divided into three categories: senior, middle, and junior level. The fully loaded annual pay for each of these levels is assumed to be $250K, $225K, and $200K respectively.
- Labor rates for federal government employees are based on the information below:
  - U.S. Office of Personnel Management, 2012 Salary Table including a locality payment of 35.15% for the area of San Jose, San Francisco, and Oakland, California: http://www.opm.gov/oca/12tables/pdf/SF.pdf
  - Office of Management and Budget, Circular No. A-76, Figure C1, Civilian Position Full Fringe Benefit Cost Factor (36.25%): http://www.whitehouse.gov/omb/circulars_a076_a76_incl_tech_correction/

17.3 Work Breakout Structure (WBS)

To provide a structure from which costs and benefits can be compared, the following cost elements from FAA AMS WBS 5.0 were used and contain the principal cost and benefit drivers evaluated.

Table 169: Work breakout structures

Phase 1 MISSION ANALYSIS
1.3.1 Research, Engineering, and Development
Phase 2 INVESTMENT ANALYSIS
2.1 Initial Investment Analysis
2.3 Final Investment Analysis
Phase 3 SOLUTION IMPLEMENTATION
3.1.3 Prime Mission Product Application Software
3.1.5 Prime Mission Product Platform Integration
3.1.6.4 Training
3.2 Program Management
3.3 Systems Engineering
3.5.1 Development Test and Evaluation
3.5.2 Operational Test and Evaluation
3.5.3 Independent Software Verification and Validation
3.6.8 Technical Data
3.7.1 Implementation Planning, Management, and Control
3.7.3 Implementation Engineering
3.7.9 Site Preparation, Installation, Test, and Activation
4 IN-SERVICE MANAGEMENT
4.5 Watch Standing Coverage
4.6.1 Program Planning, Authorization, Management and Control
4.7.8 Technical Data
4.8.3 Software and Hardware Modification and Support

17.4 WBS Element Specific Cost Detail

WBS Element 1.3.1 Research, Engineering, and Development. All activities associated with discovering applications of new technology for the National Airspace System (NAS), exploring new opportunities for service delivery, solving problems with current operations, defining and stabilizing requirements, maturing operational concepts, and mitigating risk. These activities generate information to quantify and characterize capability shortfalls, service needs and requirements, benefit expectations, and design alternatives.

The cost buildup appears in the table below, which depicts the NASA headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 170: Research and development concept to lab R&D staff requirement

Labor Category	Pay	FY12	FY13	FY14	FY15	FY16
PM	GS14	1	1	1	0.5	0.5
Senior Scientists	GS14	1	1	1	0.5	0.5
Engineers	GS13	1	1	1	0.5	0.5
SW Engineers	GS13	2	2	2	0.5	0.5
Testers	GS12	0.5	0.5	0.5	0	0
Lab Support	GS12	0.5	0.5	0.5	0	0
SMEs (Participants for Testing)	GS12	0	0	0	0	0
Subtotal		**6.0**	**6.0**	**6.0**	**2.0**	**2.0**

Table 171: Research and development concept to lab R&D cost per year

FIM Cost Summary: TY $K	FY12	FY13	FY14	FY15	FY16	Total
1.3.1 Research and Development	928.0	943.3	958.6	343.3	349.5	3,522.8

WBS Element 2.1 Initial Investment Analysis. All activities associated with analyzing alternative solutions to mission need in preparation for an initial investment decision. Specific activities include:

- Form and prepare investment analysis team members, verify entry criteria are satisfied, hold kickoff meeting, and refine the investment analysis plan, if needed, particularly the roles and responsibilities of team members and the timeline for conduct of investment analysis.
- Define the business case including assumptions and constraints, the legacy reference case, strategic performance measures, and design to cost goals.
- Analyze market capability including definition of a functional/performance specification, development and evaluation of a screening request for information, conduct of an industry day to meet with organizations with potential solutions, operational capability demonstrations, and analysis and evaluation of results.
- Analyze alternatives including adding or modifying alternatives as a result of the market survey; the comparative assessment of performance, benefits, cost, risk safety, and schedule; economic analysis; evaluation of human factors, environmental safety and health impacts, radio frequency spectrum availability, supportability, regulatory or procedural impact, test readiness/maturity level; operational suitability, operational effectiveness, ability to upgrade, and interdependencies with existing or proposed programs; and recording results in the preliminary business case.
- Conduct of operational capability demonstrations and tests to evaluate candidate solution to the service need.
- Assess budget impact.

- Prepare the initial implementation strategy and planning document for each alternative.
- Update requirements in the program requirements document.
- Verify and validate key work products.
- Plan for final investment analysis including all coordination necessary for approval.

The cost buildup appears in the table below, which depicts the FAA headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 172: Research and development field research staff requirement

Labor Category	Pay	FY12
Program Manager	GS14	1
Assistant PM	GS13	1
Senior Engineers	GS13	1
Engineers	GS12	2
Contracting Officer (COTR)	GS12	0.5
Logistics Analyst	GS12	0.5
Configuration Management	GS12	0.25
Subtotal		**6.3**

Table 173: Research and development field research staff cost by year

FIM Cost Summary: TY $K	FY12	Total
2.1 Initial Investment Analysis	884.7	884.7

WBS Element 2.3 Final Investment Analysis. All activities associated with detailed planning for the alternative selected for implementation, soliciting offers from potential suppliers, and development of required program documentation. Specific activities include:

- Identify all tasks, actions, and events needed to deliver and support the solution over its lifecycle.
- Reduce risk and finalize requirements including a detailed risk assessment; risk-reduction modeling, simulations, and prototyping; competitive fly-offs among offerors.
- Finalize the strategy for implementation and lifecycle support including risk management, program segmentation, procurement strategy, benefits realization strategy, in-service operations strategy, logistics and support strategy, test and evaluation strategy, and detailed costs and schedules for the entire segment or phase for which approval is sought.
- Solicit offers for prime contract(s) including development of the performance/functional specification, completion of evaluation criteria and weights, conduct of an industry day meeting, development and issuance of the screening information request, and communications with potential bidders.
- Evaluate vendor offers including evaluation and scoring of proposals, comparison with government estimates, and adjustment of baselines and planning as needed.
- Develop detailed program planning including a complete program work breakdown structure, detailed tasks, schedules, and resource estimates; development of an earned

value management strategy and framework, completion of the final economic analysis, and finalization of the business case.

- Finalize the acquisition program baseline, program requirements document, business case analysis report, and implementation strategy and planning document, and Exhibit 300 for designated programs. This includes independent scoring the Exhibit 300 and all activity necessary to improve the document to as high a score as possible.
- Verify and validate the key work products of final investment analysis.
- Prepare for the final investment decision including completion of the JRC readiness checklist, update of enterprise architecture products and amendments, verification that final investment analysis exit criteria are satisfied, coordination with stakeholders, conduct of final budget and financial reviews, approval to move forward by the JRC subordinate review board

The cost buildup appears in the table below, which depicts the FAA headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 174: Initial investment stage staff requirement

Labor Category	Pay	FY13
Program Manager	GS14	1
Assistant PM	GS13	1
Senior Engineers	GS13	1
Engineers	GS12	3
Contracting Officer (COTR)	GS12	0.5
Logistics Analyst	GS12	0.5
Configuration Management	GS12	0.25
Subtotal		**7.3**

Table 175: Initial investment stage staff cost by year

FIM Cost Summary: TY $K	FY13	Total
2.3 Final Investment Analysis	1,027.2	1,027.2

WBS Element 3.1.3 Prime Mission Product Application Software. This PMP contractor activity associated with software specifically produced for the functional use of a prime mission product.

For the FIM Concept, it is assumed a third party vendor will develop the software that will subsequently be integrated into the avionics of air carrier/transport aircraft. In querying a vendor that develops airborne application software for avionics, and has been involved in developing the FAA business case for the In Trail Procedures Program, the development and certification costs for the FIM Concept are likely to be in the $8 to $10 million range. Typically, these costs are not borne by the government and absorbed by the aviation industry through fees for avionics upgrades on a per aircraft basis. In order to perform a relevant comparison to anticipated benefits, these industry costs are included with government costs in this cost analysis.

The costs were calculated using several general sources and assumptions:

- FAA Study of ADS-B In adoption rates and metrics used in the Surveillance and Broadcast Services (SBS) Joint Resources Council decision (May, 2012).
- MITRE Study "US Fleet Forecast 2010 – 2050" of air carrier and transport aircraft.
- Implementation would begin in FY12 and continue to the end of the analysis, FY43.
- Existing aircraft begin retrofit of FIM capability, at a cost of $15K per aircraft.
- For new aircraft, a lower $10K per aircraft cost is assumed for FIM functionality.
- The implementation schedule appears in the table below.

Table 176: FIM Equipage

FIM Equipage	Retrofit	Forward Fit	Total Equipped
2012	16	7	23
2013	16	29	45
2014	0	39	39
2015	0	93	93
2016	0	127	127
2017	0	146	146
2018	0	170	170
2019	0	195	195
2020	491	235	726
2021	491	275	766
2022	491	269	760
2023	491	368	859
2024	506	484	990
2025	0	494	494
2026	0	545	545
2027	0	515	515
2028	0	539	539
2029	0	569	569
2030	0	608	608
2031	0	424	424
2032	0	429	429
2033	0	493	493
2034	0	449	449
2035	0	392	392
2036	0	450	450
2037	0	450	450
2038	0	450	450
2039	0	450	450
2040	0	450	450
2041	0	450	450

2042	0	450	450
2043	0	450	450
Total	**2,502**	**11,494**	**13,996**

Table 177: Prime mission product application software development cost by year

FIM Cost Summary: TY $K	FY12	FY13	FY14	FY15	FY16	FY17-FY43	Total
3.1.3 Prime Mission Product Application Software	310.0	538.7	402.9	978.4	1,360.3	202,526.5	206,116.8

WBS Element 3.1.5 Prime Mission Product Platform Integration. This PMP contractor activity associated with technical and engineering services to the platform manufacture or integrator during installation and integration of the prime mission product into a larger host system or operational environment.

The fee charged by the third party vendor to upgrade avionics with FIM capability is assumed to include integration so this cost element is not separately estimated.

WBS Element 3.1.6.4 Training. All PMP contractor activity associated with planning, developing, and establishing training for operators and maintainers; provisioners, item managers, and deport repair technicians; maintenance of common and peculiar support equipment and test and measurement equipment; second-level engineering support; computer resources support; and packaging, handling, storage, and transportation of training materials.

No ground side/controller training is required for the FIM concept. Whatever training might be required by air carriers to provide to their pilots/technicians is assumed to be outside the scope of this analysis and not separately estimated.

WBS Element 3.2 Program Management. All government activity associated with business and administrative planning, organizing, directing, coordinating, controlling, and approval actions to accomplish overall program objectives. This includes all program management support contracts.

The cost buildup appears in the table below, which depicts the FAA headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 178: Program management staff requirement by year

Labor Category	Pay	FY14
Program Manager	GS14	1
Assistant PM	GS13	1
Senior Engineers	GS13	1
Engineers	GS12	1
Contracting Officer (COTR)	GS12	0.5
Logistics Analyst	GS12	0.5

Configuration Management	GS12	0.25
Subtotal		**5.3**

Table 179: Program management staff cost by year

FIM Cost Summary: TY $K	FY14	Total
3.2 Program Management	783.9	783.9

WBS Element 3.3 Systems Engineering. All government technical and engineering activities associated with planning, directing, and controlling a totally integrated engineering effort for a solution. Specific activities include: requirements definition and allocation; analysis, design, and integration; supportability, maintainability, and reliability engineering; quality assurance; interface management; human factors engineering; security engineering; safety engineering; technical risk management; and specialty engineering.

The cost buildup appears in the table below, which depicts the FAA headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 180: System engineering staff requirement by year

Labor Category	Pay	FY14
Senior Engineers	GS13	1
Engineers	GS12	1
Subtotal		**2.0**

Table 181: System engineering staff cost by year

FIM Cost Summary: TY $K	FY14	Total
3.3 Systems Engineering	284.4	284.4

WBS Element 3.5.1 Development Test and Evaluation. All government activities associated with testing during product development to determine whether engineering design and development activities are complete; whether the product will meet specifications, security certification, and authorization criteria; and whether it is operating properly so as to achieve government acceptance. This includes all government activities associated with hardware and software validation and verification, factory acceptance testing, and site acceptance testing. It includes all government test support activities (e.g., technical assistance, maintenance, labor, material, support elements and testing spares, etc.), as well as all government activities associated with development and construction of special test facilities, test tools, and models required for performance of developmental tests.

The cost buildup appears in the table below, which depicts the FAA headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 182: Development test and evaluation staff requirement

Labor Category	Pay	FY12
Senior Engineers	GS14	1
Engineers	GS13	1
Subtotal		**2.0**

Table 183: Development test and evaluation staff cost

FIM Cost Summary: TY $K	FY12	Total
3.5.1 Development Test and Evaluation	326.3	326.3

WBS Element 3.5.2 Operational Test and Evaluation. All government activities associated with tests and evaluations conducted to assess product utility, operational effectiveness, operational suitability, and logistics supportability (including compatibility, interoperability, reliability, maintainability, logistics requirements, safety requirements, security administration, etc.). This includes all test support activities (e.g., technical assistance, maintenance, labor, material, support elements, and testing spares) as well as all activities associated with development and construction of special test facilities, test tools, and models required for performance of operational tests. Operational testing also includes site operational testing (covered in WBS element 3.7.8) and support by test and evaluation personnel during field familiarization.

The cost buildup appears in the table below, which depicts the FAA headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 184: Operational test and evaluation staff requirement

Labor Category	Pay	FY13
Senior Engineers	GS14	1
Engineers	GS13	1
Subtotal		**2.0**

Table 185: Operational test and evaluation staff cost

FIM Cost Summary: TY $K	FY13	Total
3.5.2 Operational Test and Evaluation	331.7	331.7

WBS Element 3.5.3 Independent Software Verification and Validation. All activities performed by organizations other than the developer to determine the degree to which software fulfills the specifications. Verification is a rigorous mathematical demonstration to ensure the source code conforms to its requirements. Validation evaluates a software product throughout the development process to determine compliance with product requirements.

The cost buildup appears in the table below, which depicts the FAA and contractor headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 186: Independent software verification and validation staff requirement

Labor Category	Pay	FY14
Senior Engineers	GS14	1
Engineers	GS13	1
Senior Engineers	SrContr	1
Engineers	MdContr	1
Subtotal		**4.0**

Table 187: Independent software verification and validation staff cost by year

FIM Cost Summary: TY $K	FY14	Total
3.5.3 Independent Software Verification and Validation	827.7	827.7

WBS Element 3.6.8 Technical Data. All government activities associated with planning and reviewing program and contractor technical data. Technical data includes items such as engineering drawings, notebooks, maintenance handbooks, operator manuals, maintenance manuals, installation drawings, and all contract data deliverables. This includes delivery and maintenance of documentation in place by contractors with government access, as well as activity related to treatment of intellectual property rights and third-party retention of data and documentation.

The third party vendor is assumed to perform this function as part of its software development activities and this function is not separately estimated.

WBS Element 3.7.1 Implementation Planning, Management, and Control. All government activities associated with implementation planning, control, contract management, and business management. Specific activities include:

- Planning, organizing, directing, coordinating, estimating, scheduling, controlling, and approving actions to accomplish program implementation, including project-specific input to agency-level planning documents such as the call for estimates, blue sheets, white sheets, the capital investment plan, and the enterprise architecture.
- Development and dissemination of deployment planning information to regional and site personnel.
- Tailoring the in-service review (ISR) checklist, conducting ISR checklist status reviews, developing action plans and briefing package to obtain the in-service decision, conducting stakeholder meetings, obtaining the in-service decision, tracking ISD action plans, and updating the implementation strategy and planning document.

- All activities associated with awarding and managing program-related contracts, including technical support contracts.

The cost buildup appears in the table below, which depicts the FAA headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 188: Implementation planning, management and control staff requirement by year

Labor Category	Pay	FY15	FY16	FY17	FY18	FY19
Program Manager	GS14	1	1	1	1	1
Assistant PM	GS13	1	1	1	1	1
Senior Engineers	GS13	1	1	1	0.5	0.5
Engineers	GS12	1	1	1	0.5	0.5
Contracting Officer (COTR)	GS12	0.5	0.5	0.5	0.5	0.5
Logistics Analyst	GS12	0.5	0.5	0.5	0.5	0.5
Configuration Management	GS12	0.25	0.25	0.25	0.25	0.25
Subtotal		**5.3**	**5.3**	**5.3**	**4.3**	**4.3**

Table 189: Implementation planning, management and control staff cost by year

FIM Cost Summary: TY $K	FY15	FY16	FY17	FY18	FY19	Total
3.7.1 Implementation Planning, Management, and Control	798.4	812.9	827.4	689.1	701.5	3,829.4

WBS Element 3.7.3 Implementation Engineering. All government engineering activity associated with site surveys, design, analysis, and studies. Specific activities include:

- Civil, electrical, mechanical, architectural, industrial, and other "non-electronic" engineering positions.
- Drafting and developing site plans and specifications.
- All electronic engineering activities associated with the study, analysis, and design of electronic installation.
- Spectrum analysis and engineering.
- Coordination with organizations associated with site engineering.
- Development of installation drawings.
- Physical integration associated with site modification requirements to ensure the solution integrates into the NAS.
- Assessment of site conditions, physical requirements of the solution, and transition requirements.
- Transition and operational requirements for physical security.

The cost buildup appears in the table below, which depicts the FAA headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 190: Implementation engineering staff requirement by year

Labor Category	Pay	FY15	FY16	FY17	FY18	FY19
Senior Engineer	GS14	1	1	1	0.5	0.5
Engineer	GS13	1	1	1	0.5	0.5
Subtotal		**2.0**	**2.0**	**2.0**	**1.0**	**1.0**

Table 191: Implementation engineering staff cost by year

FIM Cost Summary: TY $K	FY15	FY16	FY17	FY18	FY19	Total
3.7.3 Implementation Engineering	343.3	349.5	355.8	181.0	184.3	1,413.9

WBS Element 3.7.9 Site Preparation, Installation, Test, and Activation. All activity associated with site preparation, installation, acceptance testing, operations testing, and checkout of hardware, software, and equipment to achieve operational status. This includes coordination with all applicable organizations, unions, and the public during installation and transition. Specific activities include:

- Preparation and Installation: All activities associated with site preparation, equipment installation, acceptance testing, and checkout of hardware and software to achieve operational status. This includes coordination with all applicable organizations, unions, and the public during installation and transition.
- Test and Evaluation: All government test and evaluation activities (from WBS 3.5) to verify and validate operational readiness at each site. This includes test support activities (e.g., technical assistance, maintenance, labor, material, support elements, and testing spares) as well as all activities associated with development and construction of special test facilities, test tools, and models required for performance of operational tests; Support of T&E personnel during field familiarization. Field familiarization is the conduct of activities that allow the facility to gain confidence in the asset and attain a higher level of hands-on familiarization.
- Joint Acceptance Inspection and Commissioning: All activities associated with preparing for and achieving declaration of operational readiness, initial operational capability, full operational capability, joint acceptance inspection, service availability, and commissioning. Specific activities include: Development or modification of operational procedures; Issuance of Notice to Airmen; field familiarization activities; preliminary and final commissioning; flight inspections and other applicable testing; Initial certification activities, initial standards testing and evaluation, and initial publication of certification standards.
- Decommissioning and removal of replaced assets: All activities associated with the termination and removal of a decommissioned system or equipment. This includes planning and engineering; environmental assessments, cleanup, abatement, and disposal of hazardous materials as stipulated by laws and regulations engineering; dismantling demolishing, and removing decommissioned systems or equipment; restoring a site to acceptable condition; and all actions to revert real estate to the owner and close the project.

This cost element is assumed to be not applicable, as the third party vendor is assumed install IP software upgrades to the avionics of air carrier/transport aircraft and that cost is included in the software price.

WBS Element 4.5 Watch Standing Coverage. All activities associated with watch-standing coverage beyond stated staffing requirements.
This cost element is assumed to be not applicable, as the software upgrades to the avionics of air carrier/transport aircraft will not affect controllers.

WBS Element 4.6.1 Program Planning, Authorization, Management and Control. All activities associated with planning, authorizing, and managing actions that must be accomplished for operation and maintenance. Specific activities include:

- Preparing project-specific input to agency-level planning documents such as the call for estimates and the enterprise architecture.
- Security control.
- Activities to ensure cost, schedule, operational performance, and benefit objectives are met.

The cost buildup appears in the table below, which depicts the FAA and contractor headcount by labor category and pay grade and phased by year. The associated costs are summarized in the second table below.

Table 192: Program planning, authorization, management and control staff requirement

Labor Category	Pay	FY20	FY21	FY22	FY23	FY24	Each year FY25 –FY43
Senior Engineer	GS14	0.5	0.5	0.5	0.5	0.5	0.5
Engineer	GS13	0.5	0.5	0.5	0.5	0.5	0.5
Senior Engineer	SrContr	0.5	0.5	0.5	0.5	0.5	0.5
Engineer	MdContr	0.5	0.5	0.5	0.5	0.5	0.5
Subtotal		**2.0**	**2.0**	**2.0**	**2.0**	**2.0**	**2.0**

Table 193: Program planning, authorization, management and control staff cost by year

FIM Cost Summary: TY $K	FY20	FY21	FY22	FY23	FY24	FY25-FY43	Total
4.6.1 Program Planning, Authorization, Management and Control	460.8	469.1	477.5	486.0	494.6	11,260.3	13,648.2

WBS Element 4.7.8 Technical Data. All activities associated with product-specific documentation including engineering drawings, operator manuals, maintenance manuals, repair and test procedures, provisioning data, logistics management information, and other technical data used by or directly associated with operations, maintenance, and support of operational systems, facilities, and equipment.

The third party vendor is assumed to perform this function as part of its software development activities and this function is not separately estimated.

WBS Element 4.8.3 Software and Hardware Modification and Support. All activities associated with the analysis, design, test, and implementation of computer resources modifications, operational and support elements, and sustainment of the NAS including site adaptation.

This cost is not applicable from the government perspective, but is being explored further to determine what, if any, costs air carriers could be expected to pay to maintain FIM software once installed.

Table 194: Base Year 2012 Life Cycle Cost Table Phased By Year, $K

FIM Cost Summary: BY12 $K	FY12	FY13	FY14	FY15	FY16	FY17	FY18	FY19	FY20	FY21	FY22	FY23-FY43	Total
Phase 1 MISSION ANALYSIS	**928.0**	**928.0**	**928.0**	**326.3**	**326.3**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**3,436.8**
1.3.1 Research, Engineering, and Development	928.0	928.0	928.0	326.3	326.3	-	-	-	-	-	-	-	3,436.8
Phase 2 INVESTMENT ANALYSIS	**884.7**	**1,010.5**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**1,895.2**
2.1 Initial Investment Analysis	884.7	-	-	-	-	-	-	-	-	-	-	-	884.7
2.3 Final Investment Analysis	-	1,010.5	-	-	-	-	-	-	-	-	-	-	1,010.5
Phase 3 SOLUTION IMPLEMENTATION	**636.3**	**856.3**	**2,225.6**	**2,015.3**	**2,355.3**	**2,545.3**	**2,484.4**	**2,734.4**	**9,715.0**	**10,115.0**	**10,055.0**	**114,045.0**	**159,782.9**
3.1.3 Prime Mission Product Application Software	310.0	530.0	390.0	930.0	1,270.0	1,460.0	1,700.0	1,950.0	9,715.0	10,115.0	10,055.0	114,045.0	152,470.0
3.1.5 Prime Mission Product Platform Integration	-	-	-	-	-	-	-	-	-	-	-	-	-
3.1.6.4 Training	-	-	-	-	-	-	-	-	-	-	-	-	-
3.2 Program Management	-	-	758.9	-	-	-	-	-	-	-	-	-	758.9
3.3 Systems Engineering	-	-	275.4	-	-	-	-	-	-	-	-	-	275.4
3.5.1 Development Test and Evaluation	326.3	-	-	-	-	-	-	-	-	-	-	-	326.3
3.5.2 Operational Test and Evaluation	-	326.3	-	-	-	-	-	-	-	-	-	-	326.3
3.5.3 Independent Software Verification and Validation	-	-	801.3	-	-	-	-	-	-	-	-	-	801.3
3.6.8 Technical Data	-	-	-	-	-	-	-	-	-	-	-	-	-
3.7.1 Implementation Planning, Management, and Control	-	-	-	758.9	758.9	758.9	621.3	621.3	-	-	-	-	3,519.3
3.7.3 Implementation Engineering	-	-	-	326.3	326.3	326.3	163.2	163.2	-	-	-	-	1,305.3
3.7.9 Site Preparation, Installation, Test, and Activation	-	-	-	-	-	-	-	-	-	-	-	-	-
Phase 4 IN-SERVICE MANAGEMENT	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**400.7**	**400.7**	**400.7**	**8,414.0**	**9,616.0**
4.5 Watch Standing Coverage	-	-	-	-	-	-	-	-	-	-	-	-	-
4.6.1 Program Planning, Authorization, Management and Control	-	-	-	-	-	-	-	-	400.7	400.7	400.7	8,414.0	9,616.0
4.7.8 Technical Data	-	-	-	-	-	-	-	-	-	-	-	-	-
4.8.3 Software and Hardware Modification and Support	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	**$ 2,449.1**	**$ 2,794.9**	**$ 3,153.7**	**$ 2,341.6**	**$ 2,681.6**	**$2,545.3**	**$2,484.4**	**$2,734.4**	**$10,115.7**	**$10,515.7**	**$10,455.7**	**$122,459.0**	**$174,730.9**

Table 195: Then Year Life Cycle Cost Table Phased By Year, $K

FIM Cost Summary: TY $K	FY12	FY13	FY14	FY15	FY16	FY17	FY18	FY19	FY20	FY21	FY22	FY23-FY43	Total
Phase 1 MISSION ANALYSIS	**928.0**	**943.3**	**958.6**	**343.3**	**349.5**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**3,522.8**
1.3.1 Research, Engineering, and Development	928.0	943.3	958.6	343.3	349.5	-	-	-	-	-	-	-	3,522.8
Phase 2 INVESTMENT ANALYSIS	**884.7**	**1,027.2**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**1,911.9**
2.1 Initial Investment Analysis	884.7	-	-	-	-	-	-	-	-	-	-	-	884.7
2.3 Final Investment Analysis	-	1,027.2	-	-	-	-	-	-	-	-	-	-	1,027.2
Phase 3 SOLUTION IMPLEMENTATION	**636.3**	**870.4**	**2,299.0**	**2,120.1**	**2,522.8**	**2,774.8**	**2,755.9**	**3,087.8**	**11,172.7**	**11,843.2**	**11,982.3**	**367,314.5**	**213,914.3**
3.1.3 Prime Mission Product Application Software	310.0	538.7	402.9	978.4	1,360.3	1,591.7	1,885.8	2,202.0	11,172.7	11,843.2	11,982.3	364,375.4	206,116.8
3.1.5 Prime Mission Product Platform Integration	-	-	-	-	-	-	-	-	-	-	-	-	-
3.1.6.4 Training	-	-	-	-	-	-	-	-	-	-	-	-	-
3.2 Program Management	-	-	783.9	-	-	-	-	-	-	-	-	-	783.9
3.3 Systems Engineering	-	-	284.4	-	-	-	-	-	-	-	-	-	284.4
3.5.1 Development Test and Evaluation	326.3	-	-	-	-	-	-	-	-	-	-	-	326.3
3.5.2 Operational Test and Evaluation	-	331.7	-	-	-	-	-	-	-	-	-	-	331.7
3.5.3 Independent Software Verification and Validation	-	-	827.7	-	-	-	-	-	-	-	-	-	827.7
3.6.8 Technical Data	-	-	-	-	-	-	-	-	-	-	-	-	-
3.7.1 Implementation Planning, Management, and Control	-	-	-	798.4	812.9	827.4	689.1	701.5	-	-	-	2,218.1	3,829.4
3.7.3 Implementation Engineering	-	-	-	343.3	349.5	355.8	181.0	184.3	-	-	-	721.0	1,413.9
3.7.9 Site Preparation, Installation, Test, and Activation	-	-	-	-	-	-	-	-	-	-	-	-	-
Phase 4 IN-SERVICE MANAGEMENT	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**460.8**	**469.1**	**477.5**	**25,889.1**	**13,648.2**
4.5 Watch Standing Coverage	-	-	-	-	-	-	-	-	-	-	-	-	-
4.6.1 Program Planning, Authorization, Management and Control	-	-	-	-	-	-	-	-	460.8	469.1	477.5	25,889.1	13,648.2
4.7.8 Technical Data	-	-	-	-	-	-	-	-	-	-	-	-	-
4.8.3 Software and Hardware Modification and Support	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	**$2,449.1**	**$2,840.9**	**$3,257.6**	**$2,463.5**	**$2,872.3**	**$2,774.8**	**$2,755.9**	**$3,087.8**	**$11,633.5**	**$12,312.4**	**$12,459.7**	**$393,203.6**	**$232,997.2**

18 System Benefit and Cost Analysis Results

Economic analyses combine costs and benefits to produce metrics (such as Net Present Value [NPV] and Payback Year) valuable to the decision-maker when weighing alternatives.

Economic analyses are generally performed using present value (PV) units where the cost and benefit streams are both discounted to account for the time value of money. The OMB and FAA guidance suggest using a 7 percent discount factor in PV analyses.

In general, NPV is the difference between the PV benefits and the PV costs. If the NPV is greater than zero, then the program is cost-beneficial. The payback year is the first year when the cumulative PV benefits outweigh the cumulative PV costs.

The current economic analysis can be considered a point estimate because no risk-adjustments were performed. Risk-adjusting involves using Monte Carlo analysis to determine high-confidence estimates for the benefits (20th percentile) and the costs (80th percentile). The high-confidence estimates and underlying distributions are then combined in the economic analysis.

18.1 Lifecycle

In general, the analysis lifecycle of an application for FAA investment ends 20 years after the final implementation. For this effort, the standard approach is a little difficult, because each application has different implementation years and FIM depends on a voluntary equipage curve over several years. To be conservative, we chose to end the economic analysis at year 2037 (20 years after the assumed final implementation of EDA).

The scenarios described in previous sections and monetized in Section 13 can be grouped into concept migration paths. The paths are defined in Section 11. Each migration path is constructed from multiple applications. In a standard FAA cost benefit analysis, the initial application receives the benefit associated with its implementation and additional applications are considered incremental. We have followed that approach in the following, finding economic metrics associated with each migration path as a whole and also determining metrics for the increments of the path depending on the order of implementation. The result of this approach is that an application can be associated with different economic metrics for each migration path.

In this section we do not comment on the relative viability of the concept migration paths.

The economic metrics are also produced assuming different valuations of the benefit acknowledging that different stakeholders may put different weights on ADOC, PVT, and OPD. In the following we produce metrics for the following cases:

- Considering ADOC benefits only
- Considering OPD benefits only
- Considering all benefits (ADOC + PVT + OPD).

18.2 Migration Path 1

Migration path 1 considers a baseline of TMA followed by implementation of TM+CMS and FIM in order. Table 196 presents the economic metrics for this path assuming FIM is

incremental to TM+CMS for the three benefits valuation cases. The assumed lifecycle is FY2012 through FY2037. Since the FIM estimates did not provide additional benefits beyond TM+CMS in the scenarios, the NPV for that increment is necessarily negative.

Table 196: Economic metrics using Migration Path 1

Migration Path 1 (TM+CMS+FIM)	Benefit (PV $M)	Cost (PV $M)	B/C	NPV (PV $M)	Payback Year
ADOC delay benefits only					
Combined path	$838	$125	6.7	$713	2022
TM+CMS only	$838	$60	13.9	$778	2021
incremental FIM	$0	$65	0.0	($65)	N/A
OPD benefits only					
Combined path	$688	$125	5.5	$563	2022
TM+CMS only	$688	$60	11.4	$628	2021
incremental FIM	$0	$65	0.0	($65)	N/A
All benefits (ADOC+PVT+OPD)					
Combined path	$3,177	$125	25.3	$3,052	2020
TM+CMS only	$3,177	$60	52.6	$3,117	2020
incremental FIM	$0	$65	0.0	($65)	N/A

Figure 47, Figure 48, and Figure 49 display the cumulative present value per year for Migration Path 1 and the increments for the three valuation cases.

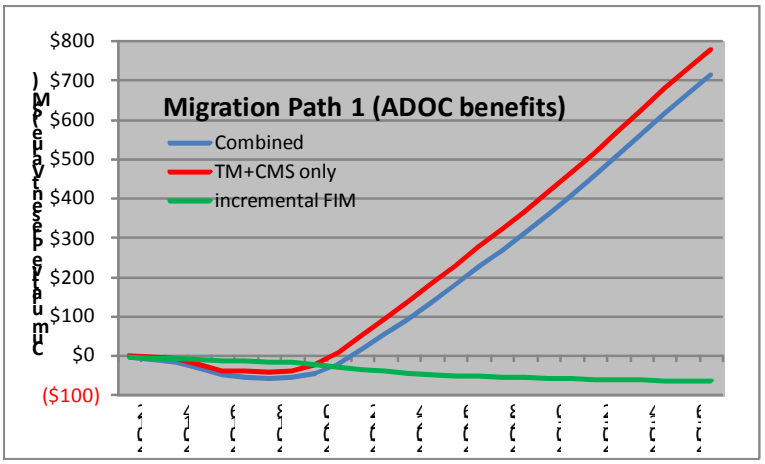

Figure 47: Cumulative Present Value for Migration Path 1 and increments (ADOC only)

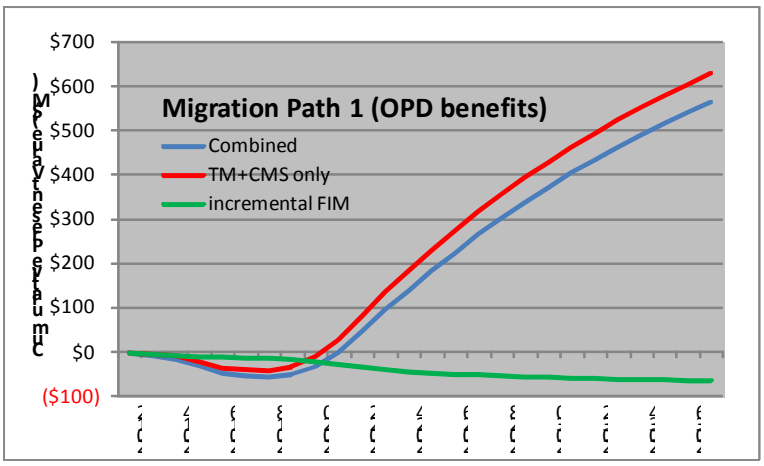

Figure 48: Cumulative Present Value for Migration Path 1 and increments (OPD only)

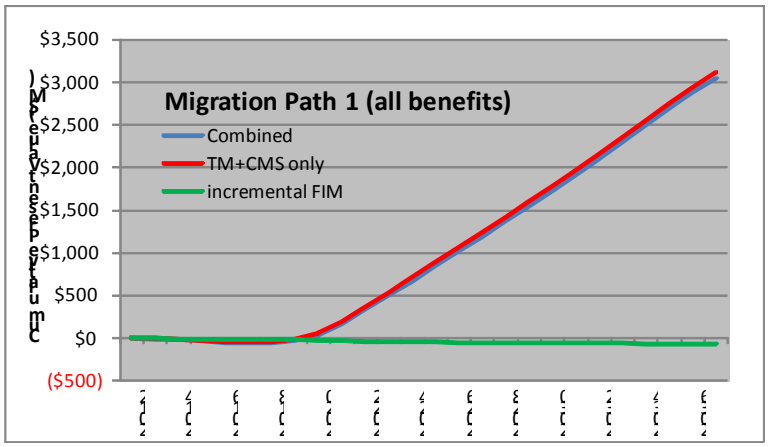

Figure 49: Cumulative Present Value for Migration Path 1 and increments (all)

18.3 Migration Path 2

Migration path 2 considers a baseline of TMA followed by implementation of EDA and TM+FIM in order. Table 197 presents the economic metrics for this path assuming TM+FIM is incremental to EDA for the three benefits valuation cases. The assumed lifecycle is FY2012 through FY2037. In this path, both the EDA and TM+FIM increments result in a positive NPV.

Table 197: Economic metrics using migration path 2

Migration Path 2 (EDA+TM+FIM)	Benefit (PV $M)	Cost (PV $M)	B/C	NPV (PV $M)	Payback Year
ADOC delay benefits only					
Combined path	$723	$152	4.8	$571	2020
EDA	$566	$45	12.6	$521	2018
incremental TM+FIM	$157	$107	1.5	$50	2031
OPD benefits only					
Combined path	$556	$152	3.7	$404	2020

EDA	$360	$45	8.0	$315	2018
incremental TM+FIM	$196	$107	1.8	$89	2034
All benefits (ADOC+PVT+OPD)					
Combined path	$2,688	$152	17.7	$2,536	2018
EDA	$2,016	$45	44.8	$1,971	2017
incremental TM+FIM	$672	$107	6.3	$565	2028

Figure 50, Figure 51, and Figure 52 display the cumulative present value per year for Migration Path 2 and the increments for the three valuation cases.

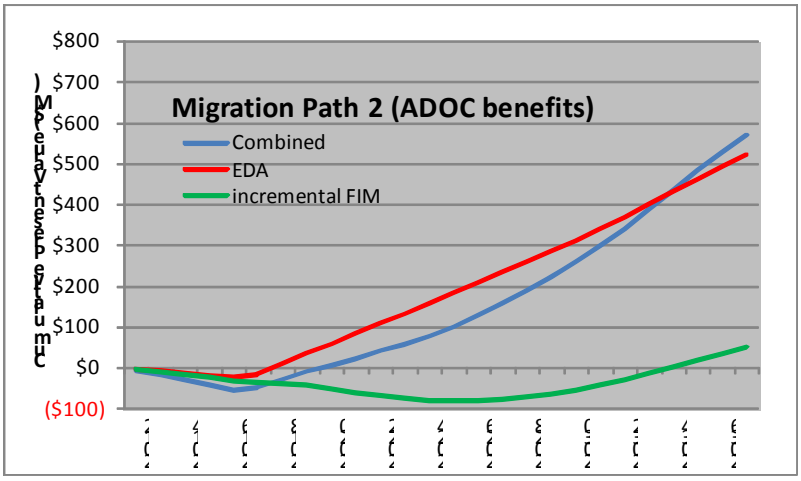

Figure 50: Cumulative Present Value for Migration Path 2 and increments (ADOC only)

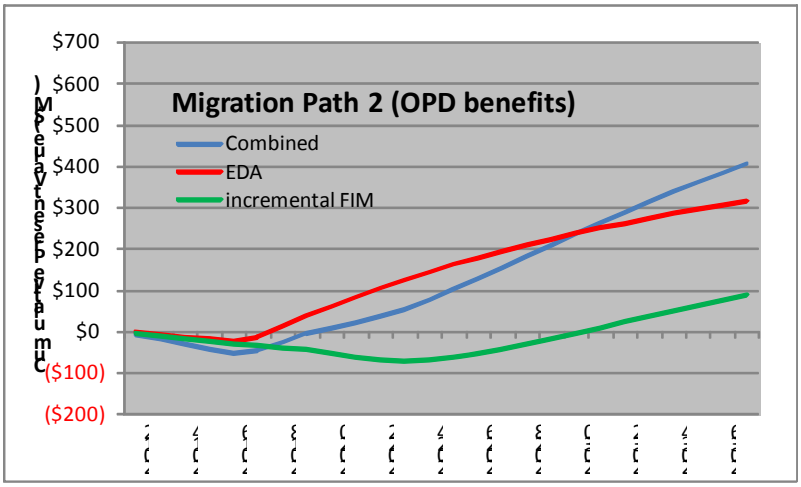

Figure 51: Cumulative Present Value for Migration Path 2 and increments (OPD only)

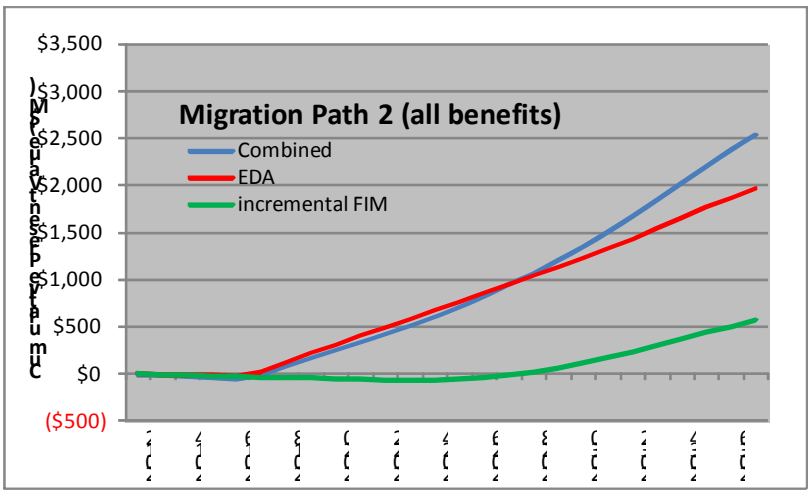

Figure 52: Cumulative Present Value for Migration Path 2 and increments (all)

18.4 Migration Path 3

Migration path 3 considers a baseline of TMA followed by implementation of EDA, TM+CMS, and FIM in order. Table 198 presents the economic metrics for this path assuming TM+CMS is incremental to EDA and FIM is incremental to EDA and TM+CMS for the three benefits valuation cases. The assumed lifecycle is FY2012 through FY2037. Since the FIM estimates did not provide additional benefits beyond TM+CMS in the scenarios, the NPV for that increment is necessarily negative.

Table 198: Economic metrics using Migration Path 3

Migration Path 3 (EDA+TM+CMS+FIM)	Benefit (PV $M)	Cost (PV $M)	B/C	NPV (PV $M)	Payback Year
ADOC delay benefits only					
Combined	$903	$170	5.3	$732	2021
EDA only	$566	$45	12.6	$521	2018
incremental CMS+TM	$337	$60	5.6	$276	2023
incremental FIM	$0	$65	0.0	($65)	N/A
OPD benefits only					
Combined	$746	$170	4.4	$575	2021
EDA only	$360	$45	8.0	$315	2018
incremental CMS+TM	$386	$60	6.4	$325	2023
incremental FIM	$0	$65	0.0	($65)	N/A
All benefits (ADOC+PVT+OPD)					
Combined	$3,404	$170	20.0	$3,234	2018
EDA only	$2,016	$45	44.8	$1,971	2017
incremental CMS+TM	$1,388	$60	23.0	$1,328	2022
incremental FIM	0	$65	0	($65)	N/A

Figure 53, Figure 54, and Figure 55 display the cumulative present value per year for Migration Path 3 and the increments for the three valuation cases.

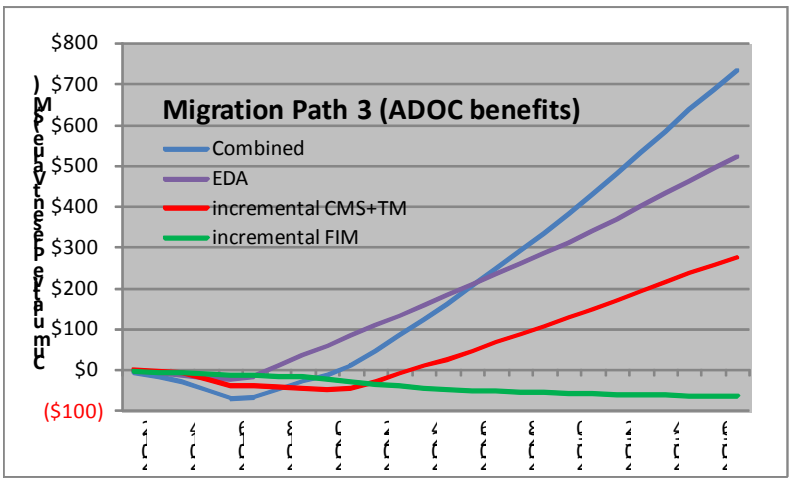

Figure 53: Cumulative Present Value for Migration Path 3 and increments (ADOC only)

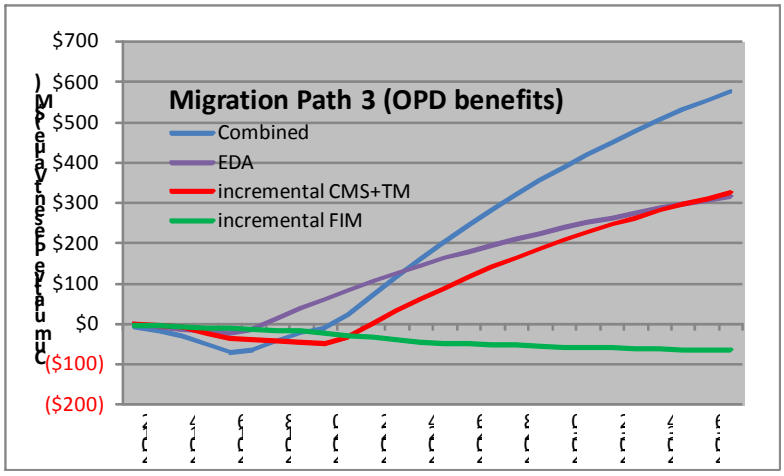

Figure 54: Cumulative Present Value for Migration Path 3 and increments (OPD only)

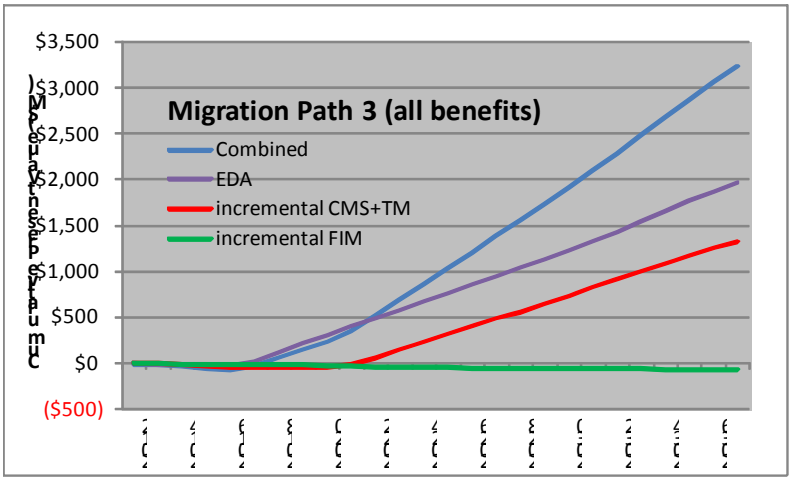

Figure 55: Cumulative Present Value for Migration Path 3 and increments (all)

As mentioned previously, the economic analyses presented above can be considered point estimates because no attempt was made to risk-adjustment the results. There are several possible variables that could be used to risk-adjust both the benefits and cost models including projected

demand, implementation schedule, and system effectiveness. Changes in many of these variables would impact each scenario similarly; however, we expect significant changes to the original inter-arrival time error assumptions would dramatically impact the results. With the current assumptions there is no real difference in the inter-arrival time error assumptions of CMS and FIM at the runway threshold, therefore the delay savings benefits directly overlap. A more direct examination of the inter-arrival time error of CMS and FIM using the same environment may be needed to better distinguish the impacts.

19 Work Performed during Extension Period

NASA expressed interest in examining five airports' throughput improvements for different Concepts and Technologies (C&T) in detail based on the analysis the Saab Sensis team performed during the Option Year 1. These five airports are:

- Hartsfield-Jackson Atlanta International Airport (ATL),
- Boston Logan International Airport (BOS),
- Houston George Bush Intercontinental Airport (IAH),
- Las Vegas McCarran International Airport (LAS), and
- Phoenix Sky Harbor International Airport (PHX).

As a result, a three-month extension was granted for completing the request. During the extension, the Saab Sensis team conducted the following two research activities to address the five airports' throughput improvements for different C&T. These two activities were:

1. Airport arrival configuration analysis

   This research activity examined the number of commonly used arrival runway configurations at an airport to create a set of dominant arrival configurations. For each airport arrival configuration, data was collected, such as routes based on observed trajectories and time to fly between meter fixes, way points, and runway thresholds. A new modeling step was implemented and completed during this extension period. In the previous work, all runways were assumed to be independent; but in this work, it was known BOS and LAS had dependent runway configurations. Thus, inter-arrival times between two runways were collected for addressing dependent runway modeling. These inter-arrival times were collected into a matrix and are referred to as dependent runway timing matrices in the rest of this document. These tasks set the stage for estimating throughput improvements for different C&Ts.

2. Throughput estimation for dependent runway operations

   This research activity extended the independent runway throughput modeling the Saab Sensis team performed during the Option Year 1 analysis to include dependent runway throughput modeling. Of the five airports of interest, BOS and LAS were identified as airports with arrival operations at dependent runways. Therefore, the scheduling model was extended to take advantage of the dependent runway timing matrices at those two airports. Then, the throughput was estimated for all five airports for all dominant arrival configurations at each airport.

Table 199 below shows the five airport's dominant arrival configurations, whether they are independent or dependent runway configurations, the FAA OIS VMC ac/hr, and the peak throughput observed from the track data.

Table 199. Runway Configurations for five Extension Airports

Airport	Runway Configuration	FAA OIS VMC ac/hr	Track Data Max ac/hr	Arrival Configuration
ATL	26R/27L/28	126	111	Independent
ATL	08L/09R/10	126	110	Independent
BOS	04L/04R	61	49	Dependent
BOS	22L/27	59	44	Dependent
IAH	26L/26R/27	108	75	Independent
IAH	08L/08R/09	84	74	Independent
LAS	01L/25L	68	41	Dependent
LAS	07R/19R	60	36	Dependent
LAS	19R/25L	60	45	Dependent
PHX	25L/26	78	76	Independent
PHX	07R/08	74	69	Independent

This chapter is divided into three sub-sections: Section 19.1 describes the analysis performed for addressing different airport arrival configurations at five airports as well as data collected and estimated from different sources; Section 19.2 describes the additional modeling efforts made to calculate the throughput values for dependent runway operations; Section 19.3 provides a summary on throughput improvements for different C&Ts at the five airports. In addition, Appendix B provides detailed results (e.g., CIR chart, throughput improvements, dependent runway metrics, etc.) for each arrival configuration by airport.

19.1 Airport Arrival Configuration Analysis

The Saab Sensis team's previous analysis of the benefits of arrival management concepts and technologies considered only a single runway configuration at each of the evaluated airports. In addition, for each airport having arrival runway configurations involving multiple runways, the landings to each runway were independent of landings to the other runways in the configuration. This analysis considers multiple possible runway configurations of a single airport, and considers that the runways in that configuration may not operate independently of one another.

The Saab Sensis team analyzed Federal Aviation Administration (FAA) Aviation System Performance Metrics (ASPM) data [FAA] for 2011 to identify the most commonly used arrival runway configurations for each of the five airports specified for this study. Subsequently, the physical layouts of the runways in each arrival runway configuration were analyzed to identify potential dependencies in spacing arrival aircraft landing to different runways in each configuration.

The FAA ASPM data lists, for each significant airport in the National Airspace System (NAS), the airport-reported arrival and departure runway configurations used in each quarter-hour local time period for each day throughout the year 2011. In the ASPM data, the arrival runway

configuration is delimited from the departure runway configuration by a vertical bar, and the individual runways in the arrival and departure runway configurations are delimited by commas. The Saab Sensis team developed Matlab scripts to analyze the ASPM arrival runway configuration data for each of the five airports to identify the distinct arrival runway configurations and to compute their percentage usage throughout all the reported time periods in 2011. The distinct arrival runway configurations for each of the five airports were sorted in order of decreasing percentage usage. In turn, the most-used runway configurations for each airport were identified for subsequent benefits analysis.

For each most-used arrival runway configuration for each airport, we assessed the dependency of the runways in that configuration in two ways. First, we analyzed the physical layout of the runways by observing a map of the airport planview obtained from [AI2012]. Second, for parallel runways, we measured the lateral distances between the runways using the Terminal Area Route Generation, Evaluation and Traffic Simulation Software (TARGETS) [TA2012].

The following subsections discuss the results of the arrival runway configurations analysis for each of the 5 airports.

19.1.1 Hartsfield-Jackson Atlanta International Airport (ATL)

The figure below depicts the arrival runway configurations for ATL in order of decreasing percentage usage throughout 2011, as reported in the FAA ASPM data.

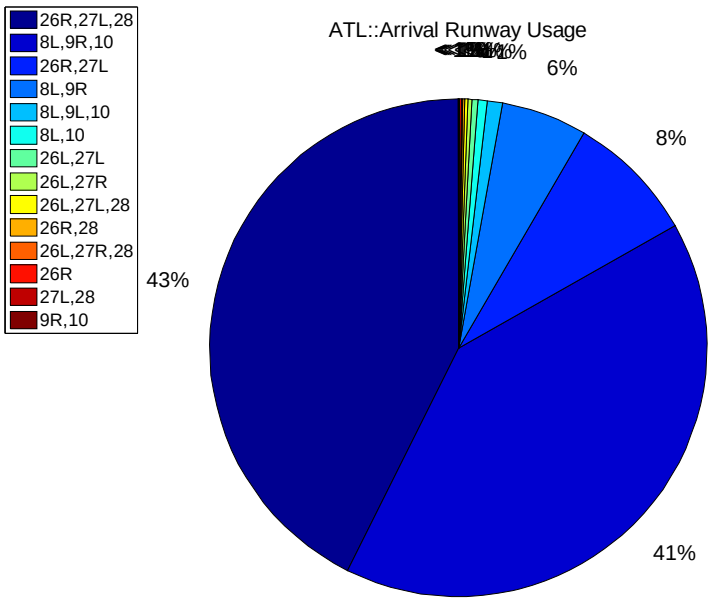

Figure 56. ATL Arrival Runway Configurations By Percentage Usage Throughout 2011

The results indicate ATL was landing arriving aircraft to runways 26R, 27L and 28 for 43% of the time and to runways 8L, 9R and 10 for 41% of the time. The remaining arrival runway configurations use subsets of the runways of these two configurations.

The figure below depicts the ATL runway layout, with color-coded arrows identifying the particular runways used for each of the two arrival runway configurations.

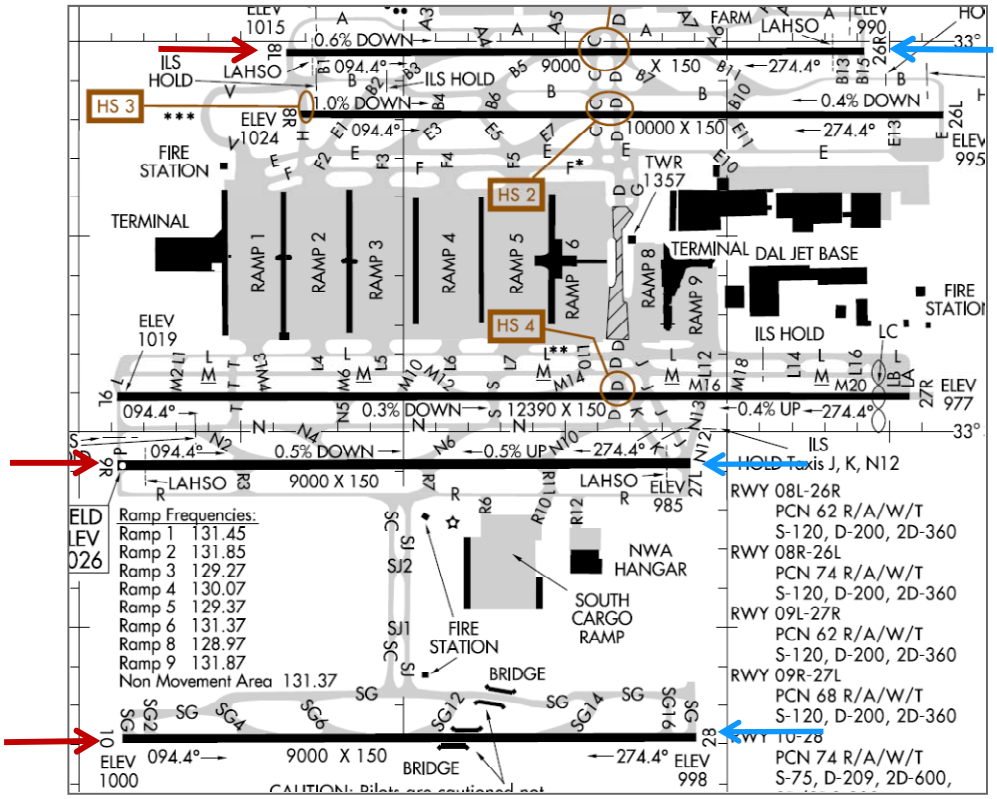

Figure 57. ATL Plan View With Arrival Runway Configurations Depicted

The figure shows runways 26R, 27L and 28 (blue arrows) form a west-flow parallel runways configuration, and runways 8L, 9R and 10 (red arrows) form an east-flow parallel runways configuration.

The table below details the layouts of the individual runways for each configuration of ATL arrival runways.

Table 200. Layouts of ATL Arrival Runway Configurations

Arrival Runways	Runways Pair	Configuration
26R, 27L, 28	26R-27L	Parallel, ~6450 ft.
	27L-28	Parallel, ~4130 ft.
	26R-28	Parallel, >6450 ft.
8L, 9R, 10	8L-9R	Parallel, ~6450 ft.
	9R-10	Parallel, ~4130 ft.
	8L-10	Parallel, >6450 ft.

The results indicate each of the following parallel arrival runway pairs, 27L-28 and 9R-10, are separated by less than 4300 ft. Thus, they fall below the threshold of 4300 ft. minimum lateral separation for arrival aircraft to land independently to each runway in the runway pair without the aid of a controller-manned Precision Runway Monitoring system [GMU]. Based on the

discussion with experts that are familiar with ATL operations, ATL is currently operating independently for all arrival runway pairs for the configurations mentioned above. Therefore, the two arrival configurations of interest are assumed to be operating independently in this analysis.

19.1.2 Boston Logan International Airport (BOS)

The figure below depicts the arrival runway configurations for BOS in order of decreasing percentage usage throughout 2011, as reported in the FAA ASPM data.

Figure 58. BOS Arrival Runway Configurations By Percentage Usage Throughout 2011

The results indicate BOS was landing arriving aircraft to runways 22L and 27 for 29% of the time, to runways 4L and 4R for 24% of the time, and to runways 27 and 32 for 13% of the time. Another distinct arrival configuration is runways 33L and 33R used 4% of the time. Other major arrival configurations are operating with just one single arrival runway (e.g., 4R, 22L, 33L, or 27).

The figure below depicts the BOS runway layout, with color-coded arrows identifying the particular runways used for each of the three arrival runway configurations.

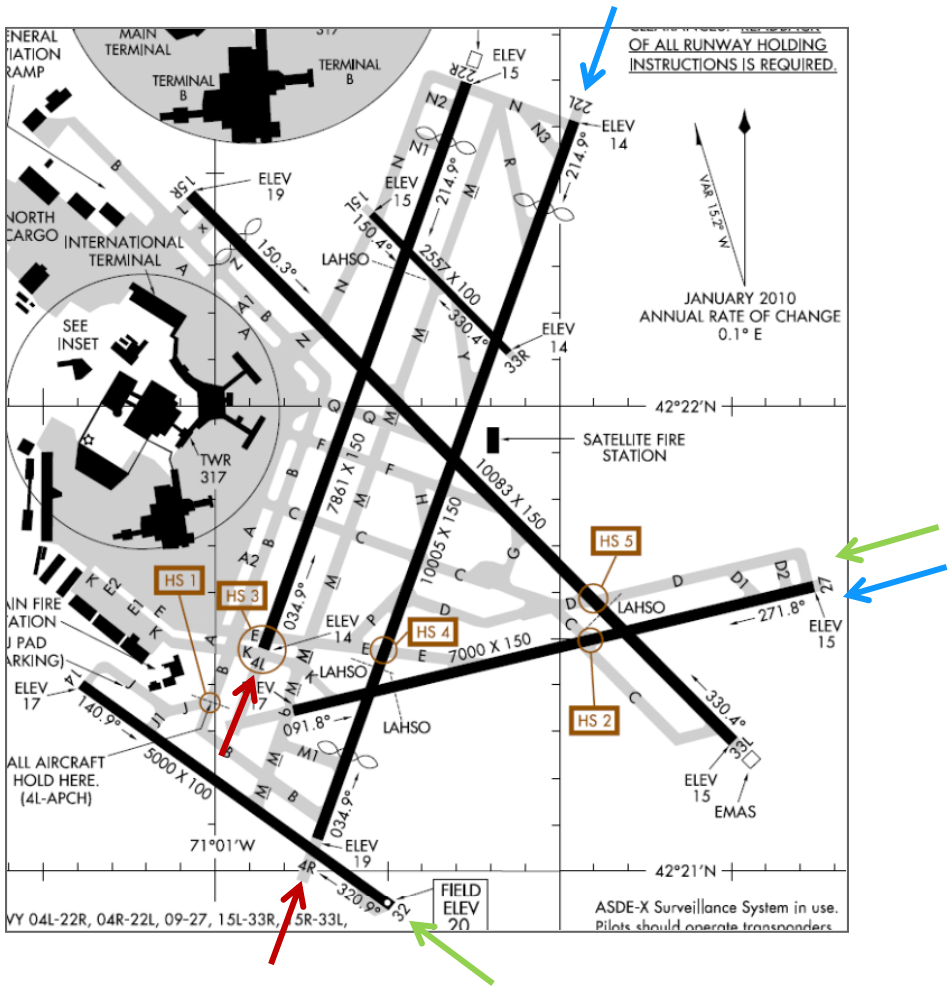

Figure 59. BOS Plan View With Arrival Runway Configurations Depicted

The figure shows BOS runways 27L and 27 (blue arrows) form a converging runways configuration, runways 4L and 4R (red arrows) form a parallel runways configuration, and runways 27 and 32 (green arrows) form a converging runways configuration.

The table below details the layouts of the individual runways for each configuration of BOS arrival runways.

Table 201. Layouts of BOS Arrival Runway Configurations

Arrival Runways	Runways Pair	Configuration
22L, 27	22L, 27	Crossing
4L, 4R	4L, 4R	Parallel, ~1500 ft.
27, 32	27, 32	Converging

The results indicate each configuration comprises a pair of dependent runways. Parallel arrival runway pair 4L-4R are categorized as very closely spaced.

19.1.3 Houston George Bush Intercontinental Airport (IAH)

The figure below depicts the arrival runway configurations for IAH in order of decreasing percentage usage throughout 2011, as reported in the FAA ASPM data.

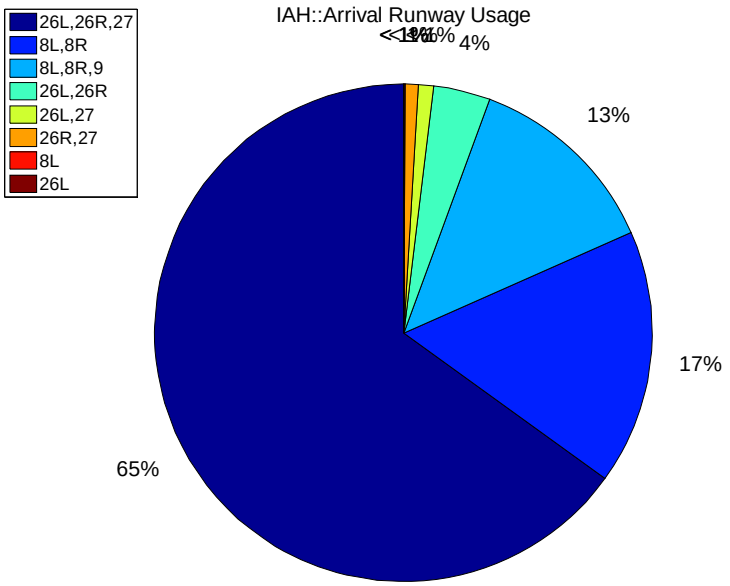

Figure 60. IAH Arrival Runway Configurations By Percentage Usage Throughout 2011

The results indicate IAH was landing arriving aircraft to runways 26L, 26R and 27 for 65% of the time, to runways 8L and 8R for 17% of the time, and to runways 8L, 8R and 9 for 13% of the time. The second configuration uses a subset of the runways used in the third configuration, thus we were intended to assess the broader configuration of 8L, 8R and 9. In the Appendix B, we discovered that the ASDE-X data obtained has limited operations at runway 9. As a result, the configuration 8L and 8R are used for analysis instead.

The figure below depicts the IAH runway layout, with color-coded arrows identifying the particular runways used for each of the two arrival runway configurations.

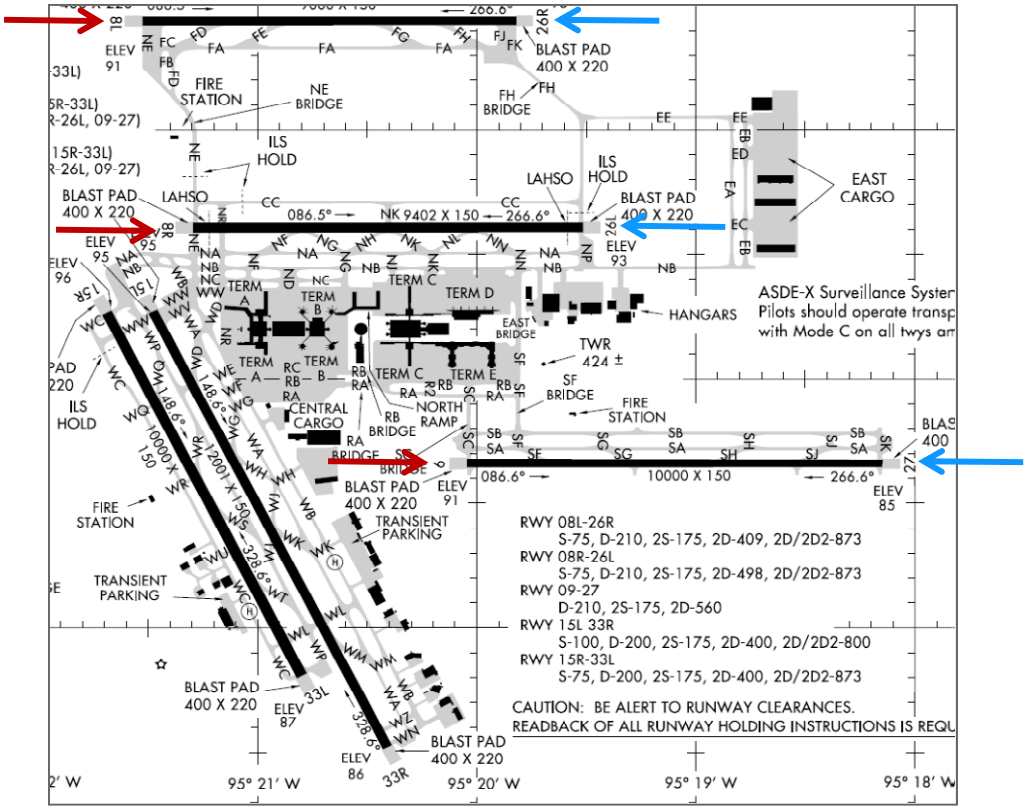

Figure 61. IAH Plan View With Arrival Runway Configurations Depicted

The figure shows IAH runways 26L, 26R and 27 (blue arrows) form a west-flow parallel runways configuration, and runways 8L, 8R and 9 (red arrows) form an east-flow parallel runways configuration, similar to ATL.

The table below details the layouts of the individual runways for each configuration of the IAH arrival runways.

Table 202. Layouts of IAH Arrival Runway Configurations

Arrival Runways	Runways Pair	Configuration
26L, 26R, 27	26L-26R	Parallel, ~4990 ft.
	26L-27	Parallel, ~5740 ft.
	26R-27	Parallel, >5740 ft.
8L, 8R, 9	8L-8R	Parallel, ~4990 ft.
	8R-9	Parallel, ~5740 ft.
	8L-9	Parallel, >5740 ft.

The results indicate all the parallel arrival runway pairs in each configuration are laterally separated by greater than 4300 ft., the threshold minimum lateral separation for arrival aircraft to land independently to each runway in the pair.

19.1.4 Las Vegas McCarran International Airport (LAS)

The figure below depicts the arrival runway configurations for LAS in order of decreasing percentage usage throughout 2011, as reported in the FAA ASPM data.

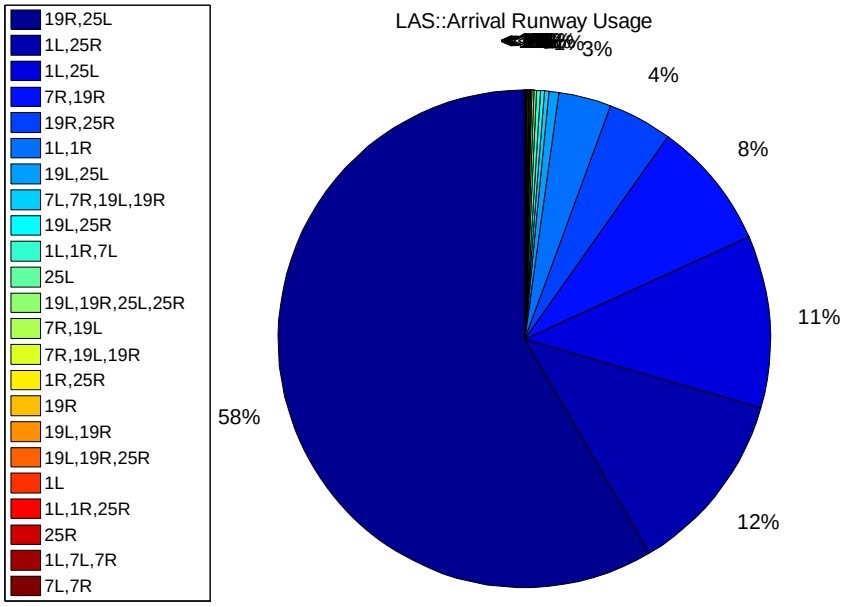

Figure 62. LAS Arrival Runway Configurations By Percentage Usage Throughout 2011

The results indicate LAS was landing arriving aircraft to runways 19R and 25L for 58% of the time, to runways 1L and 25L for 11% of the time, and to runways 7R and 19R for 8% of the time. While LAS exhibits a breadth of additional runway configurations, they are derivatives of or very similar to these three representative configurations.

The figure below depicts the LAS runway layout, with color-coded arrows identifying the particular runways used for each of the two arrival runway configurations.

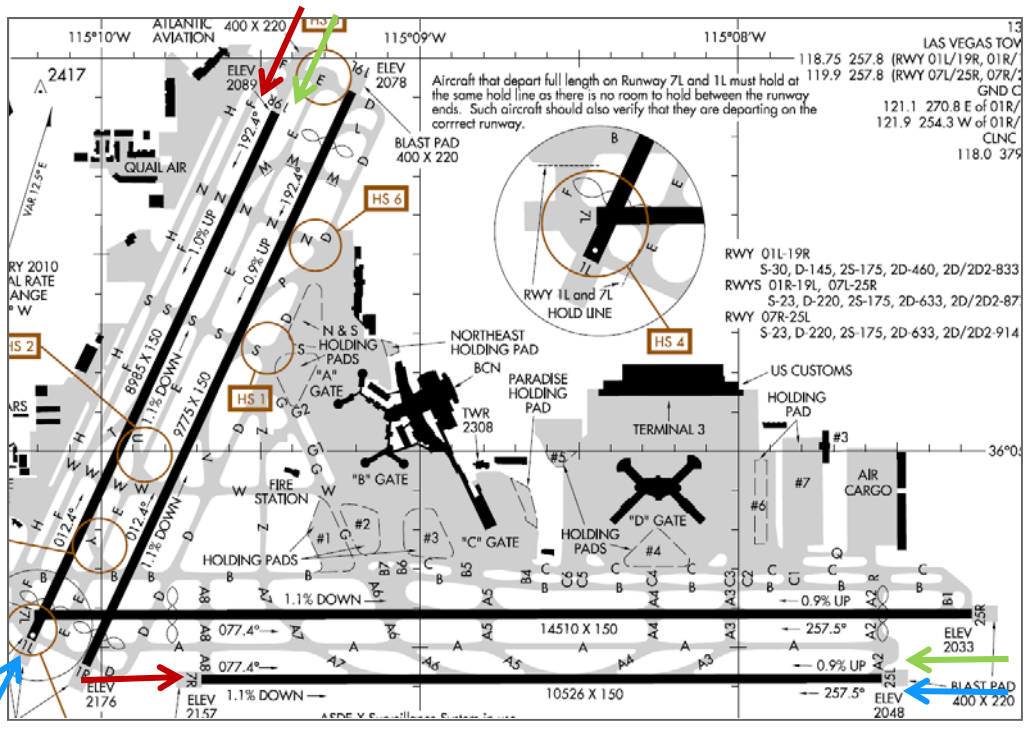

Figure 63. LAS Plan View With Arrival Runway Configurations Depicted

The figure shows LAS runways 19R and 25L (green arrows) form a converging runways configuration, runways 1L and 25L (blue arrows) form a pseudo-crossing runways configuration, and runways 7R and 19R form another pseudo-crossing runways configuration.

The table below details the layouts of the individual runways for each configuration of LAS arrival runways.

Table 203. Layouts of LAS Arrival Runway Configurations

Arrival Runways	Runways Pair	Configuration
19R, 25L	19R, 25L	Converging
1L, 25L	1L, 25L	Pseudo-crossing
7R, 19R	7R, 19R	Pseudo-crossing

The results indicate each configuration comprised a pair of dependent runways.

19.1.5 Phoenix Sky Harbor International Airport (PHX)

The figure below depicts the arrival runway configurations for PHX in order of decreasing percentage usage throughout 2011, as reported in the FAA ASPM data.

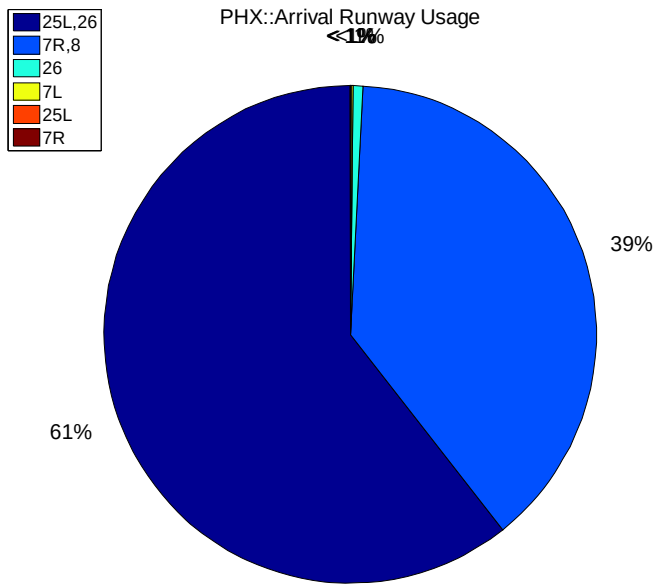

Figure 64. PHX Arrival Runway Configurations By Percentage Usage Throughout 2011

The results indicate PHX was landing arriving aircraft to runways 25L and 26 for 61% of the time, and to runways 7R and 8 for 39% of the time.

The figure below depicts the PHX runway layout, with color-coded arrows identifying the particular runways used for each of the two arrival runway configurations.

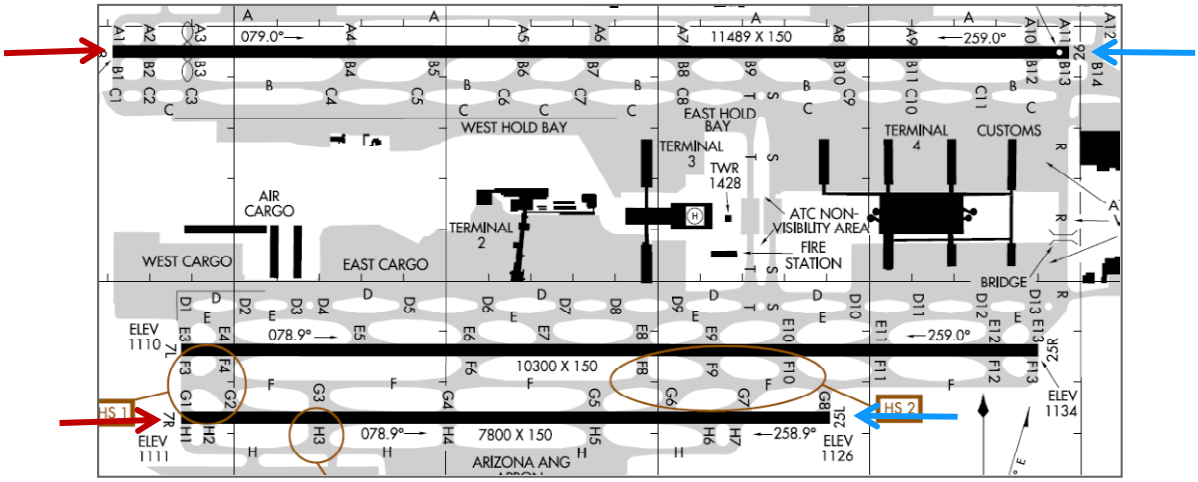

Figure 65. PHX Plan View With Arrival Runway Configurations Depicted

The figure shows PHX runways 25L and 26 (blue arrows) form a west-flow parallel runways configuration, and runways 7R and 8 (red arrows) form an east-flow parallel runways configuration, similar to ATL.

The table below details the layouts of the individual runways for each configuration of the PHX arrival runways.

Table 204. Layouts of PHX Arrival Runway Configurations

Arrival Runways	Runways Pair	Configuration

25L, 26	25L, 26	Parallel, ~4380 ft.
7R, 8	7R, 8	Parallel, ~4380ft.

The results indicate each of the parallel arrival runway pairs, 25L-26 and 7R-8, are separated by approximately 4300 ft. Thus, they are right on the threshold of 4300 ft. minimum lateral separation for arrival aircraft to land independently to each runway in the runway pair without the aid of a controller-manned Precision Runway Monitoring system [GMU]. The team confirmed with Mr. John Robinson from NASA Ames Research Center that the PHX arrival configurations discussed above are independent arrival runway configurations, based on his discussion with air traffic controllers at PHX. Therefore, in this study, we assume the PHX is operating independently for the two arrival configurations of interest.

19.2 Throughput Estimation for Dependent Runway Operations

The Option Year One approach for estimating throughput with different C&Ts for independent arrival runway operations was described in Section 8. This approach took advantage of the airport model, described in Section 7, along with additional dependent runway information and estimated a throughput capacity for a set of C&Ts. The Option Year One process assumed all runways were independent, but the extension work required analysis of airports with dependent runways. The following sections describe the work done to model and simulate dependent runway operations.

19.2.1 Dependent Runway Timing Matrices

To estimate the arrival throughput for dependent runway operations, we need to identify the interdependency between two consecutive arrival flights at the dependent arrival runways pairs. Unlike independent arrival configurations, where we can treat flight operations at each arrival runway independently, flights arriving at an arrival runway A with dependency with another runway B are required to ensure a minimum separation from the flights arriving at runway B. As a result, the inter-arrival time between two dependent runways is estimated to ensure such minimum separation is met in our modeling.

Inter-arrival time between two dependent runways was captured from track data. These inter-arrival times were gathered into a matrix, named the dependent runway timing matrix, for the four different aircraft types, Heavy (H), B757, Large (L), and Small (S). The following tables are an example case at BOS with the arrival configuration 4L and 4R. This particular case considered the leading aircraft landing to 4L and trailing aircraft landing to 4R. Our analysis first collected all the aircraft and sorted them based on leading/trailing aircraft type, e.g. a heavy leading at 4L and a large jet following at 4R. Table 205 shows how many aircraft were counted for each aircraft type pair. Table 206 shows for each aircraft weight class combination, the 10th percentile of minimum time between successive aircraft pairs landing at these two runways, as observed from the track data. As can be seen, not all aircraft weight class combinations were represented, thus a weighted mean of the inter-flight spacing for the weight class combinations for which there was data was used to estimate the inter-flight spacing for those weight class combinations for which there was not data, and for those weight class combinations for which only a few aircraft pairs were counted, as shown in Table 207.

This process was repeated for all airport arrival configurations that required dependent runway operations. It was identified that all arrival configurations at BOS and LAS required dependent runway modeling, and thus dependent runway timing matrices (i.e., the inter-flight time spacing matrices) were captured and are provided in Appendix B.

Table 205: Number of aircraft observed for BOS with 4L leading and 4R trailing

4L Leading, 4R Trailing				
Count (aircraft) (Leading/Trailing)	**H**	**B757**	**L**	**S**
H	0	0	0	0
B757	0	0	4	0
L	10	37	232	6
S	1	4	54	1

Table 206: Observed times for the above counted aircraft at BOS for 4L leading and 4R trailing

4L Leading, 4R Trailing				
Observed Time (seconds) (Leading/Trailing)	**H**	**B757**	**L**	**S**
H	0	0	0	0
B757	0	0	33.41	0
L	37.5	22.13	14.15	18.94
S	285.46	6.01	13.1	4

Table 207: Dependent runway timing matrix at BOS with 4L leading and 4R trailing

4L Leading, 4R Trailing				
Time (seconds) (Leading/Trailing)	**H**	**B757**	**L**	**S**
H	16.46	16.46	16.46	16.46
B757	16.46	16.46	16.46	16.46
L	16.46	22.13	14.15	16.46
S	16.46	16.46	13.10	16.46

19.2.2 Scheduling Model Delays Aircraft Based On Dependent Runway Operations

The scheduling model applied the dependent runway timing matrices to ensure aircraft were separated at the dependent runways. In the previous work, an aircraft would be separated only from an aircraft which landed on the same runway, based on the separation requirements in Table 208. The scheduling model calculated an aircraft's separation requirements based on both the same runway separation table and the dependent runway timing matrices table. The aircraft's schedule was set based on the separation requirement with the most delay. Table 209 shows a

significant number of aircraft required additional delays above the same runway separation requirements for both BOS arrival runway configurations.

Table 208: Same runway separation table

Distance (nmi) (Leading/Trailing)	H	B757	L	S
H	4	5	5	6
B757	4	4	4	5
L	2.5	2.5	2.5	4
S	2.5	2.5	2.5	2.5

Table 209: Percentage of scheduled aircraft that required additional delay due to dependent runway separation requirements at a set of runway buffers at both of BOS's arrival configurations.

Runway Buffer (nmi)	22L/27	04L/04R
0.0	52%	52%
0.1	52%	51%
0.2	51%	51%
0.3	51%	51%
0.4	52%	51%
0.5	51%	52%
0.6	51%	51%
0.7	50%	52%

19.3 Throughput Improvements at Five Airports

The goal of this analysis was to link improved arrival scheduling conformance with improved airport throughput. As described in section 8, there were three C&Ts, including EDA, CMS, and FIM, which were compared to the TMA baseline. Based on previous work, it was shown that each C&T, EDA, CMS, and FIM, intended to reduce inter-arrival spacing requirements by improving arrival scheduling conformance, i.e., aircraft conformance to their scheduled times of arrival, when compared with TMA. If each C&T improved arrival scheduling conformance, then this tool found out how much inter-flight spacing was reduced, and thus how much throughput was improved.

The extension work intended to calculate these results at five selected airports, each with multiple arrival runway configurations. Each airport arrival configuration is a unique case and was studied separately. The main point of comparison was how much the scheduling runway buffer can be reduced if a C&T improved arrival conformance. The runway buffer was defined as the extra scheduling buffer added to the minimum wake vortex requirements between two successive aircraft landing at the same runway.

An arrival conformance simulation was used to link improved arrival conformance and reduced runway buffers. The arrival conformance simulation provides a Controller Intervention Rate (CIR) for each C&T's differing arrival conformance levels. If a C&T improved the arrival conformance at the runway, when compared with TMA, then it is expected the runway buffer

can be reduced. Figure 66: Controller Intervention Rate versus Runway Buffer for every C&T at PHX 7R and 8 As can be seen, EDA, CMS, and FIM all improved the CIR and thus were able to have reduced runway buffers. Details on the CIR simulation are in section 8.3.

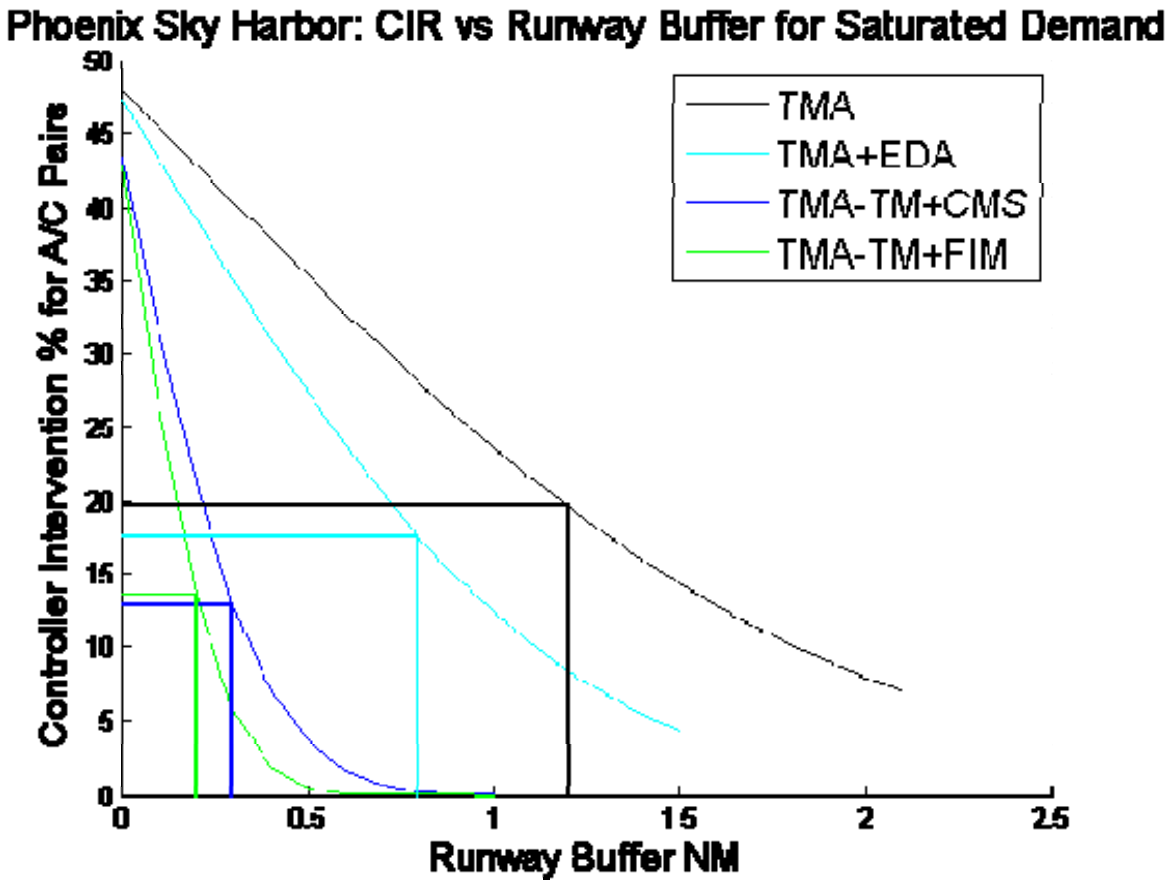

Figure 66: Controller Intervention Rate versus Runway Buffer for every C&T at PHX 7R and 8

The CIR and reduced runway buffers were calculated at every airport configuration, as shown in Table 210: Runway buffers for each C&T at each airport's runway configuration set. These results were then used to calculate the improved throughput at each airport configuration. As can be seen in Figure 67, results vary based on airport and even by airport arrival configuration, a benefit of this airport and arrival configuration-specific model and simulation. Specifically, we observed that the TMA's throughput efficiency, which is defined by the ratio between TMA's throughput value and the theoretical maximum capacity value, at an airport can also vary dramatically. Previously, we have observed that, at different airports, the TMA's throughput efficiency can vary between 70% and 90%. In this extension work, we discovered that the TMA's throughput efficiency at Las Vegas varies between 65% and 90%, depending on the arrival configurations.

These results took advantage of the new dependent runway separation matrices and were able to show throughput improvements for all required dependent runway configurations at BOS and LAS.

Table 210: Runway buffers for each C&T at each airport's runway configuration set

Airport	TMA Buffer (nmi)	EDA Buffer (nmi)	CMS Buffer (nmi)	FIM Buffer (nmi)
ATL_26R_27L_28	0.5	0.3	0.1	0.1
ATL_08L_09R_10	0.3	0.2	0.1	0.1
BOS_22L_27	1.4	0.9	0.3	0.2
BOS_04L_04R	1.3	0.8	0.3	0.2
IAH_26L_26R_27	1.3	0.8	0.3	0.2
IAH_08L_08R	1	0.7	0.2	0.2
LAS_19R_25L	2.1	1.3	0.4	0.3
LAS_01L_25L	1.7	1.1	0.3	0.2
LAS_07R_19R	0.5	0.3	0.1	0.1
PHX_25L_26	1.6	1	0.3	0.3
PHX_07R_08	1.2	0.8	0.3	0.2

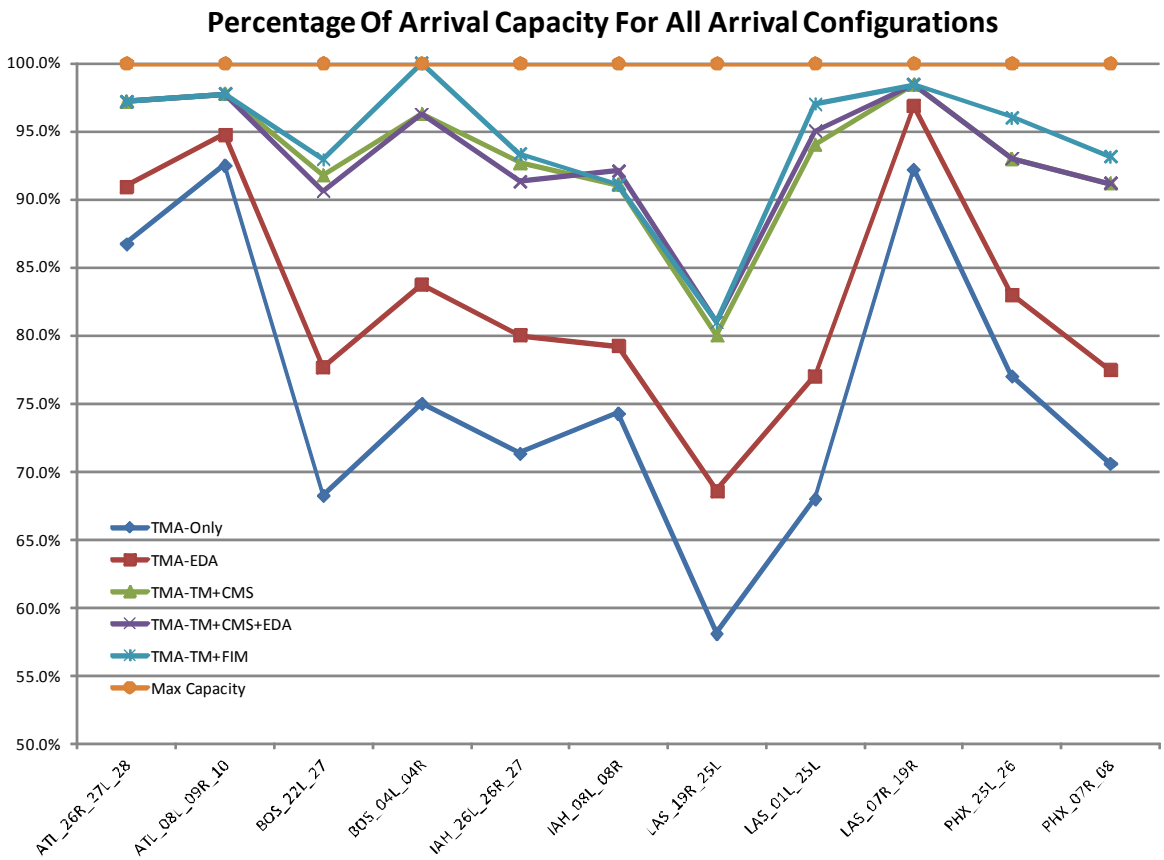

Figure 67: Throughput percentage of maximum capacity for every airport and every runway configuration

20 Conclusion

This NRA addressed the following modeling efforts to estimate the throughput improvement for different arrival configurations for different C&Ts:

- The team created a unified methodology for estimating arrival throughput improvements for different C&Ts at any airport;
- The team automated the process for generating airport specific configuration information;
- The team devised a simulation to examine the relationship between Controller Intervention Rate and runway buffers;
- The team, during the extension time period, created a method to address not only throughput improvement for independent arrival runway configurations, but also throughput improvement for dependent arrival runway configuration, and
- The team automated the process for estimating throughput improvements for different C&Ts for multiple arrival runway configurations at an airport.

From the benefit and cost analysis performed in this SAIE NRA contract, the Saab Sensis team concludes that:

- There are plenty of opportunities for cost beneficial automation tools to assist with meter fix and runway performance,
- Many of the C&Ts have overlapping benefits because they have the same benefit mechanisms, such as
  - CMS vs. FIM
  - EDA vs. CMS
  - EDA vs. FIM
- The incremental benefit of a C&T is greatly determined by the sequence of the C&T in the migration path, and
- Any delay or change to the existing C&T implementation schedule may greatly change the incremental benefit of a C&T in the migration path.

21 References

TAPSS

NASA ASD, "TAPSS – Terminal Area Precision Scheduling System," Retrieved November 11, 2010, http://www.aviationsystemsdivision.arc.nasa.gov/research/tactical/tapss.shtml.

Swenson, H., Thipphavong, J., "Airspace Super Density Operations Terminal Precision Scheduling and Spacing System (TAPSSS): Preliminary Results," Presentation delivered on November 3rd, 2010.

Thipphavong, J., Mulfinger, D., "Design Considerations for a New Terminal Area Arrival Scheduler," Proceedings of the AIAA Aviation Technology, Integration and Operations (ATIO) Conference, Fort Worth, TX, Sep. 2010.

Isaacson, D., Robinson III, J., Swenson, H., Denery, D.,"A Concept for Robust, High Density Terminal Air Traffic Operations," Proceedings of the AIAA Aviation Technology, Integration and Operations (ATIO) Conference, Fort Worth, TX, Sep. 2010.

Swenson, H., "Airspace Super Density Operations Precision Scheduling Human In the Loop Simulation Plans: Plans for ASDO Terminal Area Scheduling and Arrival Management HITL Simulation," Presentation dated September 10th, 2009.

Swenson, H., Thipphavong, J., Sadovsky, A., Chen, L., Sullivan, C., Martin, L., "Design and Evaluation of the Terminal Area Precision Scheduling and Spacing System," Ninth USA/Europe Air Traffic Management Research and Development Seminar (ATM2011).

Swenson, H., communication via electronic mail, November 2011.

EDA

Coppenbarger, R., Mead, R., Sweet, D., "Field Evaluation of the Tailored Arrivals Concept for Datalink-Enabled Continuous Descent Approach," Proceedings of the AIAA Aviation Technology, Integration and Operations (ATIO) Conference, Belfast, Northern Ireland, Sep. 2007.

Coppenbarger, R., Lanier, R., Sweet, D., Dorsky, S., "Design and Development of the En route Descent Advisor (EDA) for Conflict-Free Arrival Metering," Proceedings of the AIAA Guidance, Navigation and Control Conference, Providence, RI, Aug. 2004.

Haraldsdottir, A., Berge, M., Kang, L., Schoemig, E., Alcabin, M., Repetto, B., Carter, M., "Required Navigation Performance and 3D Paths in High-Traffic ATM Operations," Proceedings of the 25th Digital Avionics Systems Conference, Portland, Oregon, Oct. 2006.

Schoemig, E., Haraldsdottir, A., Scharl, J., Tong, K., Boyle, D., "Application of Required Navigation Performance in High-Traffic Conditions for Houston Airspace," Proceedings of the AIAA Aviation Technology, Integration and Operations (ATIO) Conference, Wichita, KS, Sep. 2006.

Sweet, D., Dorsky, S., Mueller, T., "Data Analysis Report for the July, 2004 En Route Descent Advisor Simulation," Contract report prepared by Seagull Technology, Inc., Advanced Air

Transportation Technologies Project, NASA Ames Research Center, Moffett Field, CA, Oct. 2004.

Wang, J., "Single-Year, NAS-Wide Benefits Assessment of En Route Descent Advisor (EDA)," Contract report prepared by Landrum & Brown Worldwide Services, Inc., Efficient Flight Path Management Project, NASA Ames Research Center, Moffett Field, CA, May. 2006.

FIM

Murdoch, J., Barmore, B., Baxley, B., Capron, W., Abbott, T., "Evaluation of an Airborne Spacing Concept to Support Continuous Descent Arrival Operations," Proceedings of the 8th USA-Europe Research and Development Seminar - ATM 2009, Napa, CA, Jun. 2009.

Abbott, T., "A Brief History of Airborne Self-Spacing Concepts," NASA/CR–2009-215695, 2009

FAA/Eurocontrol Cooperative R&D, "Action Plan 23: Long Term ADS-B and ASAS Applications; D3 – Operational Role of Airborne Surveillance in Separating Traffic," version 0.2, Nov. 2008.

Barmore, B., Abbott, T., Capron, W., Baxley, B., "Simulation Results for Airborne Precision Spacing along Continuous Descent Arrivals," Proceedings of the AIAA Aviation Technology, Integration and Operations (ATIO) Conference, Anchorage, AK, Sep. 2008.

Baxley, B., "Flight Deck Merging and Spacing," Presentation dated March 19th, 2008.

Bone, R., Marksteiner, J., "Flight Deck-Based Merging and Spacing (FDMS) Initial Implementation Application Description Version 2.1," Feb. 2008.

Moertl, P., Beaton, E., Lee, P., Battiste, V., Smith, N., "An Operational Concept and Evaluation of Airline Based En Route Sequencing and Spacing," Proceedings of the AIAA Aviation Technology, Integration and Operations (ATIO) Conference, Wichita, KS, Sep. 2006.

Baxley, B., Barmore, B., Abbott, T., Capron, W., "Operational Concept for Flight Crews to Participate in Merging and Spacing of Aircraft," Proceedings of the AIAA Guidance, Navigation and Control Conference and Exhibit, Hilton Head, SC, Aug. 2007.

Barmore, B., "Airborne Precision Spacing: A Trajectory-Based Approach to Improve Terminal Area Operations," Proceedings of the 25th Digital Avionics Systems Conference, Portland, Oregon, Oct. 2006.

Baxley, B., Barmore, B., Abbott, T., Capron, W., "Operational Concept for Flight Crews to Participate in Merging and Spacing of Aircraft," Proceedings of the AIAA Guidance, Navigation and Control Conference and Exhibit, Hilton Head, SC, Aug. 2007.

Barmore, B., "Airborne Precision Spacing: A Trajectory-Based Approach to Improve Terminal Area Operations," Proceedings of the 25th Digital Avionics Systems Conference, Portland, Oregon, Oct. 2006.

CMS

Isaacson, D., Robinson, J., Swenson, H., "A Concept for Robust, High Density Terminal Air Traffic Operations," 10th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, Fort Worth, TX, Sept 2010.

Kupfer, M., Callantine, T., Mercer, J., Martin, L., "Controller-Managed Spacing – A Human-In-The-Loop Simulation of Terminal-Area Operations," AIAA Guidance, Navigation, and Control Conference, Toronto, Ontario, Canada, 2010.

Kupfer, M., Callantine, T., Martin, L., Mercer, J., "Controller Support Tools for Schedule-Based Terminal-Area Operations," Ninth USA/Europe Air Traffic Management Research and Development Seminar, 2011.

Palmer, E., Callantine, T., Prevot, T., Mercer, J., Williams, D., "Controller Managed Spacing Study I," Presentation at the EWG Operations Standing Committee Meeting, Georgia Institute of Technology, Atlanta, GA, USA, 2008.

Palmer, E., Callantine, T., Kupfer, M., "Human-In-The-Loop Simulation of Trajectory-Based Terminal-Area Operations," 27th International Congress of the Aeronautical Sciences, 2009.

Callentine, T., communication via electronic mail, November 2011.

General References

Airnav.com, "Airport Information," http://www.airnav.com/airports/, accessed 23 October 2012.

CSSI, Inc., "Terminal Area Route Generation, Evaluation and Traffic Simulation (TARGETS)," http://targets.cssiinc.com, accessed 23 October 2012.

Federal Aviation Administration, "Aviation System Performance Metrics Data," https://aspm.faa.gov/aspm/entryASPM.asp, accessed 23 October 2012.

George Mason University, Center for Air Transportation Systems Research, "Runway Systems Capacity,"

Ren, L., and J.-P. Clarke, "A Separation Analysis Methodology for Designing Area Navigation Arrival Procedures," Journal of Guidance, Control, and Dynamics 30(5): 1319-1330, September-October 2007.

A. Appendix: Airport Adaptation and Simulation Results for All Airports

Each airport in Table 211 is listed alphabetically in the following appendix. Each sub-section contains the route table, route and meter fix usage percentages, Controller Intervention Rate plots, and Monte Carlo simulation results.

Table 211: Airports with available simulation results

ATL	CLT	DEN	DTW	EWR
IAH	JFK	LAX	MCO	MEM
MIA	MKE	ORD	SDF	SEA
		STL		

A.1 ATL 'Hartsfield-Jackson Atlanta' Airport Simulation Results

Table 212: All identified routes for ATL.

Meter Fix	Merge Point	Merge Point	Runway
DIRTY	COSEL	BRNII	26R
PECHY	COSEL	BRNII	26R
CANUK	-	-	26R
HONIE	NOFIV	-	26R
ERLIN	NOFIV	-	26R
HERKO	NOFIV	-	26R
DIRTY	BYRDS	-	27L/28
PECHY	BYRDS	-	27L/28
CANUK	HEDEG	-	27L/28
HONIE	FOGOG	HEDEG	27L/28
ERLIN	FOGOG	HEDEG	27L/28
HERKO	FOGOG	HEDEG	27L/28

Table 213: Meter Fix Separation and route and meter fix usage percentages for ATL.

Meter Fix	26R%	27L%	28%	Total %	Observed Separation (nmi)
CANUK	0.67%	22.71%	13.14%	36.52%	5 nmi
DIRTY	25.47%	7.00%	0.01%	32.48%	5 nmi
ERLIN	12.13%	1.28%	0.33%	13.74%	8 nmi
HERKO	0.91%	0.34%	0.16%	1.41%	14 nmi
HONIE	2.73%	5.16%	7.32%	15.22%	9 nmi
PECHY	0.46%	0.17%	0.00%	0.63%	23 nmi

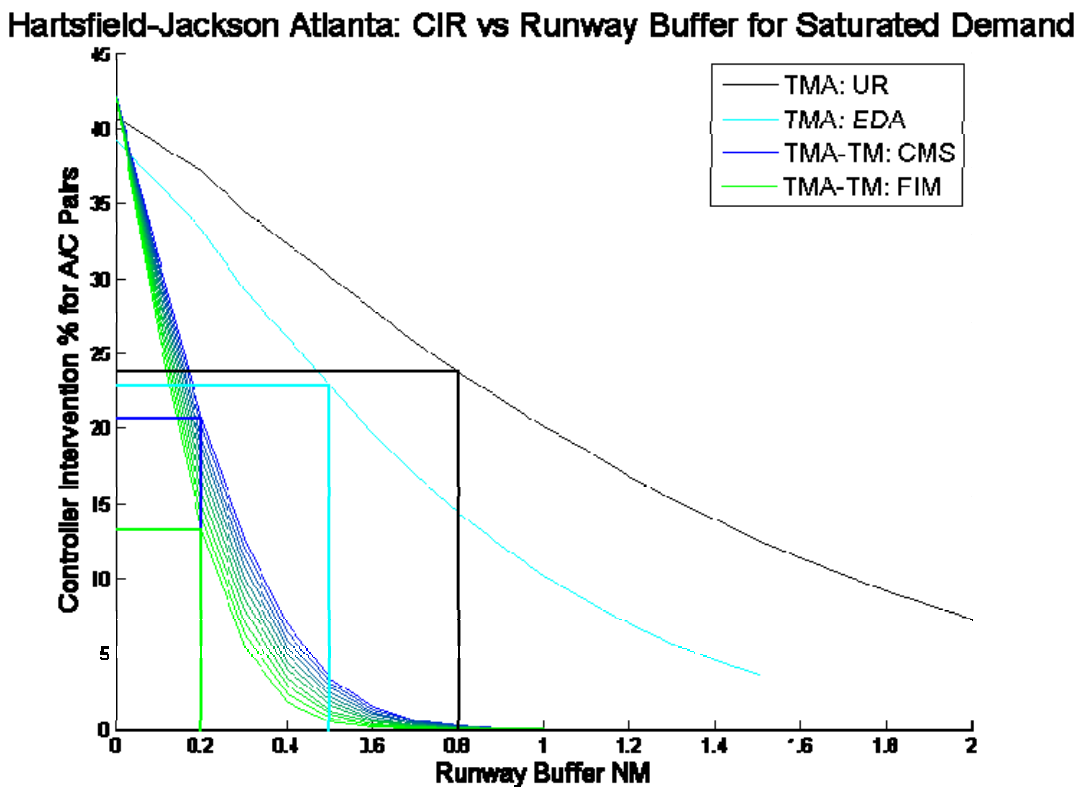

Figure 68: Controller Intervention Rate for each C&T at the ATL model.

Table 214: Potential arrival throughput capacity for ATL given the CIR analysis and resulting meter fix and runway buffers.

Concept and Technology	Throughput Capacity (ac/hr)	Percentage of Theoretical Max	Runway Buffer (nmi)	Meter Fix Separation (nmi)
TMA-only	124 ac/hr	86%	0.8 nmi	(5, 5, 8, 14, 9, 23)
TMA+EDA	132 ac/hr	91%	0.5 nmi	(5, 5, 7, 9, 7, 9)
TMA-TM+CMS	138 ac/hr	96%	0.2 nmi	(5, 5, 8, 14, 9, 23)
TMA-TM+CMS+EDA	138 ac/hr	96%	0.2 nmi	(5, 5, 7, 9, 7, 9)
TMA-TM+FIM	138 ac/hr	96%	0.2 nmi	(5, 5, 7, 9, 7, 9)
Theoretical Max	144 ac/hr	100%	0	(5, 5, 5, 5, 5, 5)

A.2. CLT 'Charlotte Douglas' Airport Simulation Results

Table 215: All identified routes for CLT.

Meter Fix	Merge Point	Merge Point	Runway
ADENA	EBAWI	-	23
CTF	-	-	23
JOHNS	EBAWI	WEGTI	23
MAJIC	WEGTI	-	23

Table 216: Meter Fix Separation and route and meter fix usage percentages for CLT.

Meter Fix	23%	Total %	Observed Separation (nmi)
ADENA	14.18%	14.18%	8 nmi
CTF	32.32%	32.32%	9 nmi
JOHNS	8.87%	8.87%	16 nmi
MAJIC	44.63%	44.63%	8 nmi

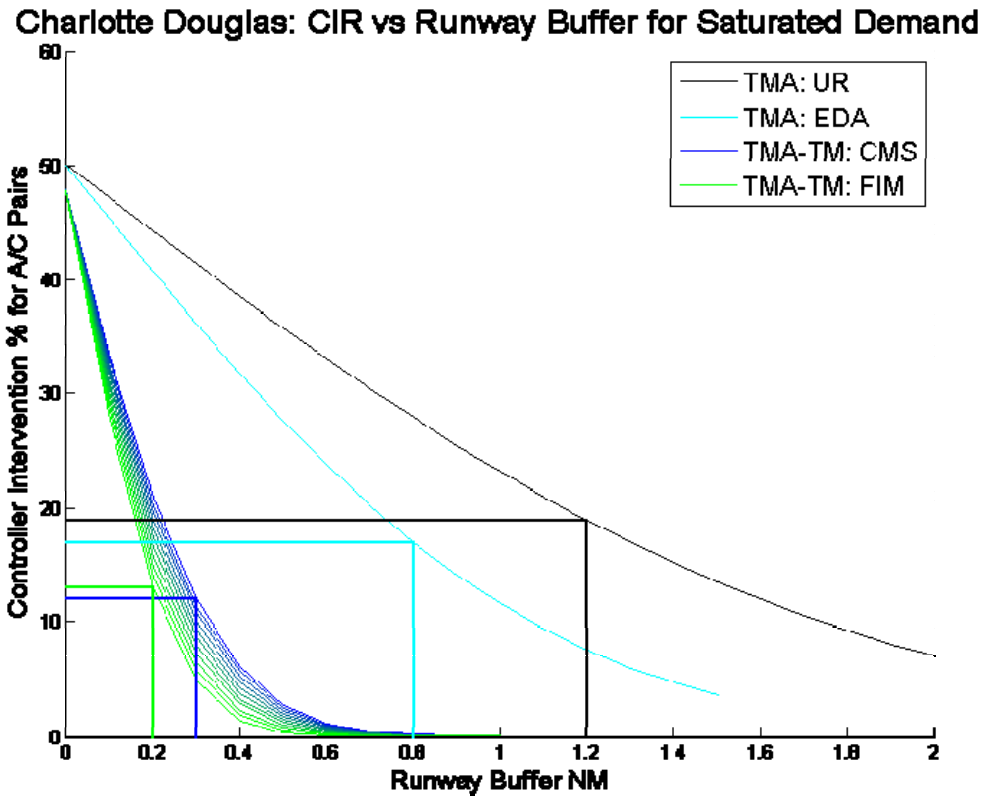

Figure 69: Controller Intervention Rate for each C&T at the CLT model.

Table 217: Potential arrival throughput capacity for CLT given the CIR analysis and resulting meter fix and runway buffers.

Concept and Technology	Throughput Capacity (ac/hr)	Percentage of Theoretical Max	Runway Buffer (nmi)	Meter Fix Separation (nmi)
TMA only	35	69%	1.2	(8, 9, 16, 8)
TMA+EDA	39	77%	0.8	(6, 7, 8, 6)
TMA-TM+CMS	44	88%	0.3	(8, 9, 16, 8)
TMA-TM+CMS+EDA	45	90%	0.3	(6, 7, 8, 6)
TMA-TM+FIM	47	93%	0.2	(6, 7, 8, 6)
Theoretical Max	50	100%	0	(5, 5, 5, 5)

A.3. DEN 'Denver International' Airport Simulation Results

Table 218: All identified routes for DEN.

Meter Fix	Merge Point	Merge Point	Runway
LANDR	ACTOR	-	34L/35L
SAYGE	ACTOR	-	34L/35L
LANDR	LAYGE	-	35R
SAYGE	LAYGE	-	35R
DANDD	DILVE	BOOBU	34L/35L
DANDD	BEKEE	-	35R
QUAIL	DILVE	BOOBU	34L/35L
QUAIL	BEKEE	-	35R
LARKS	CASSE	BOOBU	34L/35L
LARKS	WAPGU	BEKEE	35R
POWDR	CASSE	BOOBU	34L/35L
POWDR	WAPGU	BEKEE	35R
TOMSN	SHAFT	-	34L/35L
TOMSN	DILVE	BEKEE	35R
RAMMS	SHAFT	-	34L/35L
RAMMS	DILVE	BEKEE	35R

Table 219: Meter Fix Separation and route and meter fix usage percentages for DEN.

Meter Fix	34R%	35L%	35R%	Total %	Observed Separation (nmi)
DANDD	0.01%	1.64%	2.32%	3.98%	12 nmi
LANDR	0.51%	3.34%	8.05%	11.89%	8 nmi
LARKS	0.43%	6.81%	0.79%	8.03%	9 nmi
POWDR	1.18%	14.95%	0.70%	16.83%	7 nmi
QUAIL	2.03%	23.67%	15.05%	40.75%	5 nmi
RAMMS	1.43%	2.68%	1.06%	5.17%	16 nmi
SAYGE	0.19%	0.86%	1.73%	2.79%	8 nmi
TOMSN	3.01%	6.32%	1.24%	10.57%	9 nmi

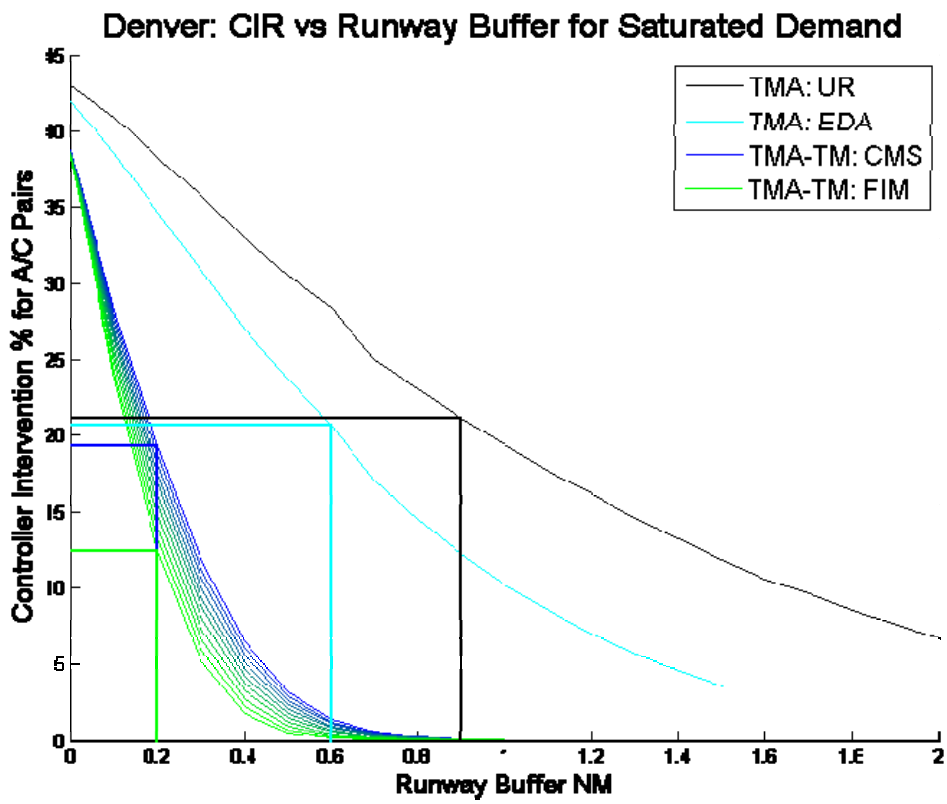

Figure 70: Controller Intervention Rate for each C&T at the DEN model.

Table 220: Potential arrival throughput capacity for DEN given the CIR analysis and resulting meter fix and runway buffers.

Concept and Technology	Throughput Capacity (ac/hr)	Percentage of Theoretical Max	Runway Buffer (nmi)	Meter Fix Separation (nmi)
TMA only	114	78%	0.9	(12, 8, 9, 7, 5, 16, 8, 9)
TMA+EDA	123	84%	0.6	(9, 7, 7, 6, 5, 9, 7, 7)
TMA-TM+CMS	135	92%	0.2	(12, 8, 9, 7, 5, 16, 8, 9)
TMA-TM+CMS+EDA	135	92%	0.2	(9, 7, 7, 6, 5, 9, 7, 7)
TMA-TM+FIM	135	92%	0.2	(8, 7, 7, 6, 5, 8, 7, 7)
Theoretical Max	146	100%	0	(5, 5, 5, 5, 5, 5, 5, 5)

A.4. DTW 'Detroit Metro' Airport Simulation Results

Table 221: All identified routes for DTW.

Meter Fix	Merge Point	Merge Point	Runway
GEMNI	WADVU	-	21L
GEMNI	SOSIC	-	22R
MIZAR	WADVU	-	21L
MIZAR	SOSIC	-	22R

Table 222: Meter Fix Separation and route and meter fix usage percentages for DTW.

Meter Fix	21L%	22R%	Total %	Observed Separation (nmi)
GEMNI	24.65%	6.64%	31.28%	6 nmi
MIZAR	24.48%	44.24%	68.72%	5 nmi

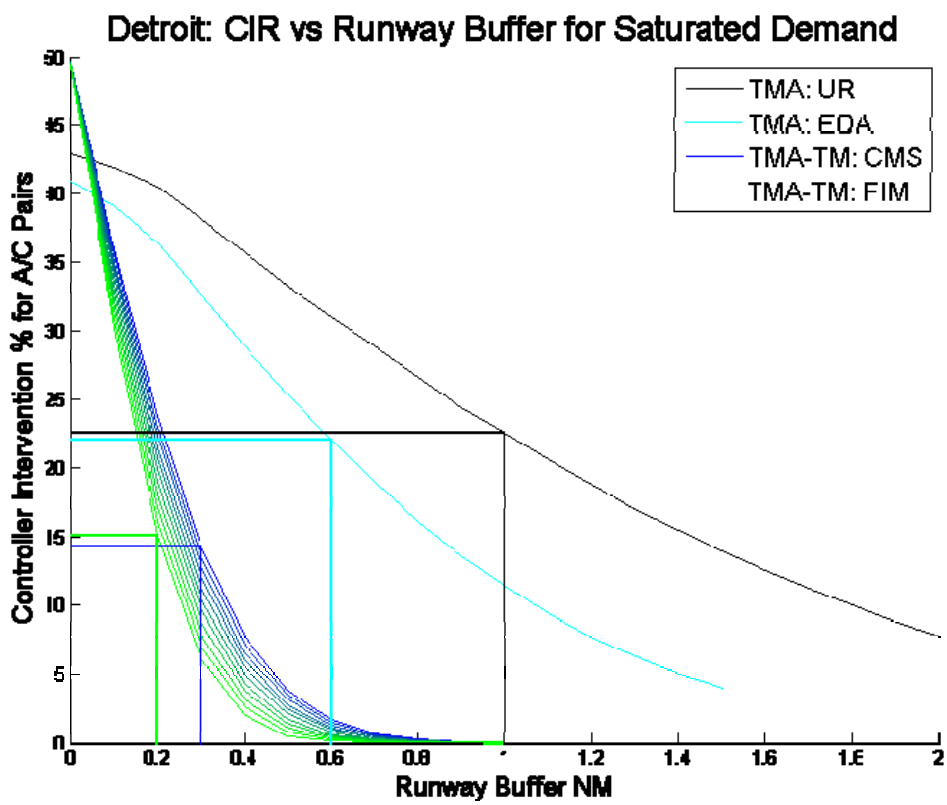

Figure 71: Controller Intervention Rate for each C&T at the DTW model.

Table 223: Potential arrival throughput capacity for DTW given the CIR analysis and resulting meter fix and runway buffers.

Concept and Technology	Throughput Capacity (ac/hr)	Percentage of Theoretical Max	Runway Buffer (nmi)	Meter Fix Separation (nmi)
TMA only	75	80%	1	(6, 5)
TMA+EDA	83	89%	0.6	(6, 5)
TMA-TM+CMS	91	97%	0.3	(6, 5)
TMA-TM+CMS+EDA	91	97%	0.3	(6, 5)
TMA-TM+FIM	93	99%	0.2	(6, 5)
Theoretical Max	94	100%	0	(5, 5)

A.5. EWR 'Newark Liberty' Airport Simulation Results

Table 224: All identified routes for EWR.

Meter Fix	Merge Point	Merge Point	Merge Point	Runway
CMK	LENDY	-	-	22L
COATE	LELME	LENDY	-	22L
ARD	JOKMI	LELME	LENDY	22L
RBV	JOKMI	LELME	LENDY	22L
SHAFF	LELME	LENDY	-	22L
PENNS	JOKMI	LELME	LENDY	22L

Table 225: Meter Fix Separation and route and meter fix usage percentages for EWR.

Meter Fix	22L%	Total %	Observed Separation (nmi)
ARD	28.24%	28.24%	9 nmi
CMK	0.41%	0.41%	5 nmi
COATE	1.43%	1.43%	5 nmi
PENNS	28.31%	28.31%	9 nmi
RBV	16.91%	16.91%	5 nmi
SHAFF	24.70%	24.70%	9 nmi

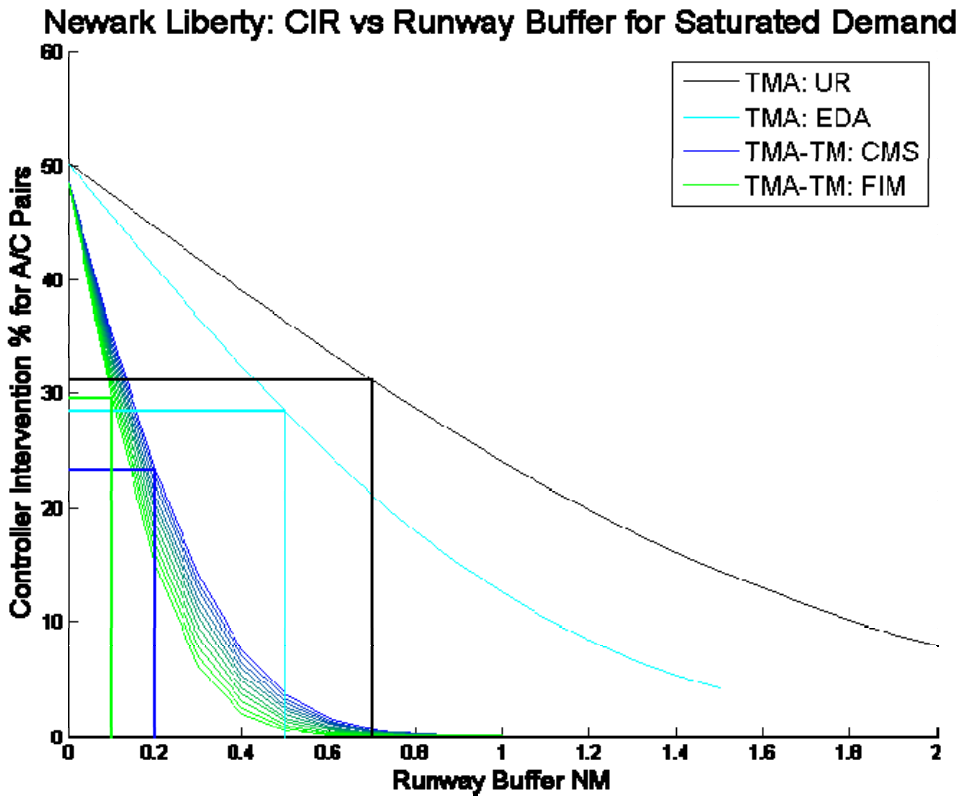

Figure 72: Controller Intervention Rate for each C&T at the EWR model.

Table 226: Potential arrival throughput capacity for EWR given the CIR analysis and resulting meter fix and runway buffers.

Concept and Technology	Throughput Capacity (ac/hr)	Percentage of Theoretical Max	Runway Buffer (nmi)	Meter Fix Separation (nmi)
TMA only	37	81%	0.7	(9, 5, 5, 9, 5, 9)
TMA+EDA	40	86%	0.5	(5, 5, 5, 5, 5, 5)
TMA-TM+CMS	44	94%	0.2	(9, 5, 5, 9, 5, 9)
TMA-TM+CMS+EDA	44	94%	0.2	(5, 5, 5, 5, 5, 5)
TMA-TM+FIM	45	97%	0.1	(5, 5, 5, 5, 5, 5)
Theoretical Max	46	100%	0	(5, 5, 5, 5, 5, 5)

A.6. IAH 'Houston Intercontinental' Airport Simulation Results

Table 227: All identified routes for IAH.

Meter Fix	Merge Point	Merge Point	Runway
DAS	-	-	26L/26R
DAS	SILLS	-	27
BRKMN	-	-	26L/26R/27
WOLDE	-	-	26L/26R
WOLDE	SILLS	-	27
GLAND	-	-	26L/26R
GLAND	SILLS	-	27

Table 228: Meter Fix Separation and route and meter fix usage percentages for IAH.

Meter Fix	26L%	26R%	27%	Total %	Observed Separation (nmi)
BRKMN	12.08%	5.58%	3.49%	21.16%	7 nmi
DAS	28.47%	3.86%	15.48%	47.82%	5 nmi
GLAND	2.58%	0.36%	12.35%	15.29%	11 nmi
WOLDE	2.21%	0.04%	13.49%	15.74%	8 nmi

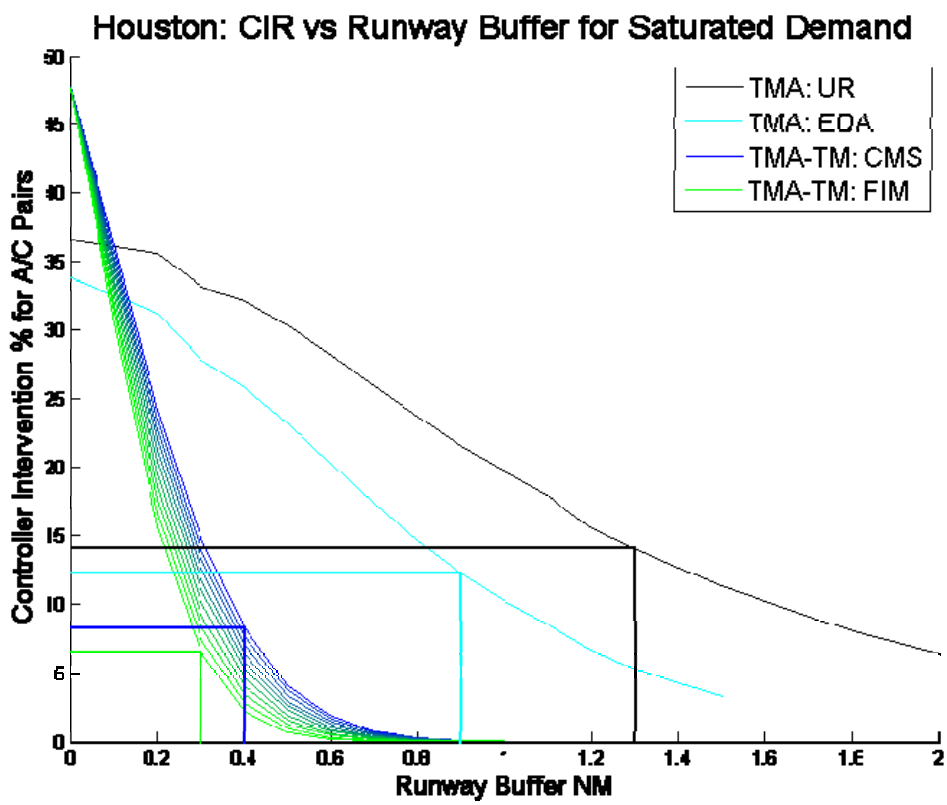

Figure 73: Controller Intervention Rate for each C&T at the IAH model.

Table 229: Potential arrival throughput capacity for EWR given the CIR analysis and resulting meter fix and runway buffers.

Concept and Technology	Throughput Capacity (ac/hr)	Percentage of Theoretical Max	Runway Buffer (nmi)	Meter Fix Separation (nmi)
TMA only	107	79%	1.3	(7, 5, 11, 8)
TMA+EDA	117	87%	0.9	(6, 5, 8, 7)
TMA-TM+CMS	130	97%	0.4	(7, 5, 11, 8)
TMA-TM+CMS+EDA	131	97%	0.4	(6, 5, 8, 7)
TMA-TM+FIM	132	99%	0.3	(6, 5, 8, 7)
Theoretical Max	134	100%	0	(5, 5, 5, 5)

A.7. JFK 'John F. Kennedy' Airport Simulation Results

Table 230: All identified routes for JFK.

Meter Fix	Merge Point	Merge Point	Runway
CAMRN	CHANT	-	31L/31R
LENDY	CHANT	-	31L/31R
ROBER	-	-	31L/31R

Table 231: Meter Fix Separation and route and meter fix usage percentages for JFK.

Meter Fix	31L%	31R%	Total %	Observed Separation (nmi)
CAMRN	10.21%	30.70%	40.91%	6 nmi
LENDY	12.81%	24.32%	37.12%	9 nmi
ROBER	1.70%	20.26%	21.97%	8 nmi

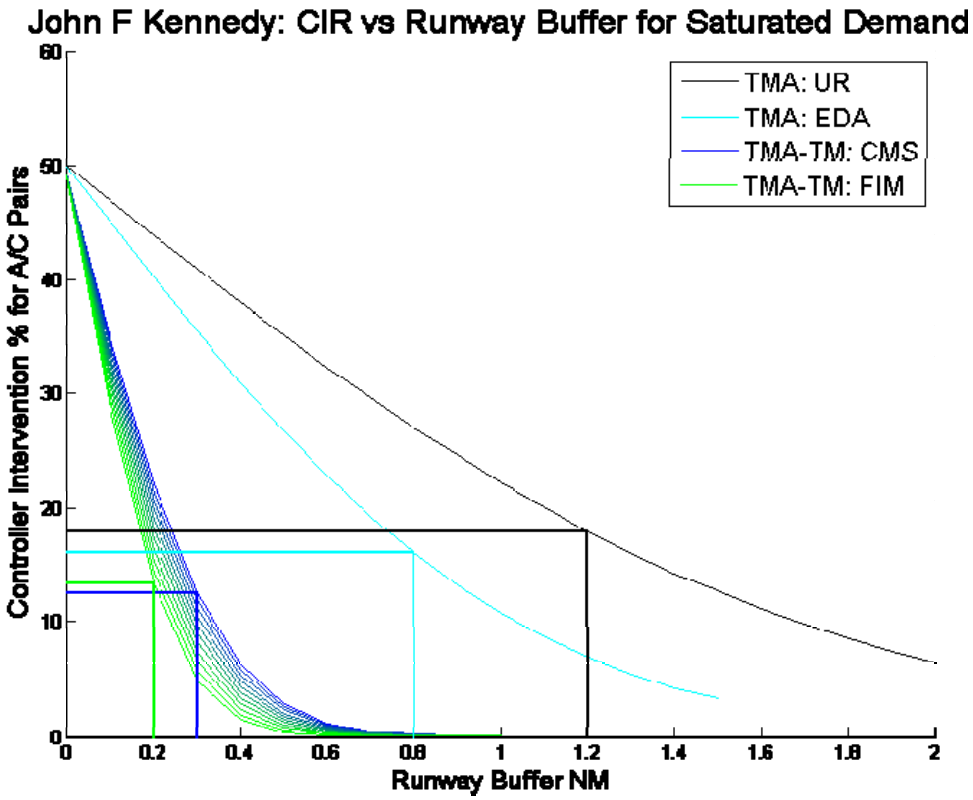

Figure 74: Controller Intervention Rate for each C&T at the JFK model.

Table 232: Potential arrival throughput capacity for JFK given the CIR analysis and resulting meter fix and runway buffers.

Concept and Technology	Throughput Capacity (ac/hr)	Percentage of Theoretical Max	Runway Buffer (nmi)	Meter Fix Separation (nmi)
TMA only	57	73%	1.2	(6, 9, 8)
TMA+EDA	63	80%	0.8	(5, 7, 7)
TMA-TM+CMS	72	91%	0.3	(6, 9, 8)
TMA-TM+CMS+EDA	72	91%	0.3	(5, 7, 7)
TMA-TM+FIM	74	94%	0.2	(5, 7, 6)
Theoretical Max	79	100%	0	(5, 5, 5)

A.8. LAX 'Los Angeles' Airport Simulation Results

According to the FAA OIS, LAX is operating at near capacity, thus the runway buffer reduction for each tool appears minimal. Table 18 shows a comparison between the FAA OIS and observed throughput from the ASDE-X track data. In it, it shows LAX has an observed throughput of 60 ac/hr while the FAA OIS claims a maximum throughput of 80 ac/hr. Also, in this runway configuration, 24R and 25L are solely used as arrival runways while the outside runways, 24L and 25R, are only used for departures. Combining the FAA OIS capacity and the runway configuration, our model predicted LAX was at near maximum arrival capacity.

Table 233: All identified routes for LAX.

Meter Fix	Merge Point	Merge Point	Merge Point	Runway
BOGET	KIMMO	-	-	24R/25L
JEFFY	KIMMO	-	-	24R/25L
GRAAM	LUVYN	GAATE	-	24R/25L
KONZL	SEAVU	LUVYN	GAATE	24R/25L
LAADY	SEAVU	LUVYN	GAATE	24R/25L
SHIVE	SLI	GAATE	-	24R/25L
SXC	SLI	-	-	24R/25L
FIM	SADDE	-	-	24R/25L
VTU	SADDE	-	-	24R/25L

Table 234: Meter Fix Separation and route and meter fix usage percentages for LAX.

Meter Fix	24R%	25L%	Total %	Observed Separation (nmi)
BOGET	16.85%	2.85%	19.70%	5 nmi
FIM	4.58%	0.65%	5.23%	11 nmi
GRAMM	6.48%	15.19%	21.67%	8 nmi
JEFFY	1.20%	0.14%	1.33%	5 nmi
KONZL	3.95%	12.89%	16.84%	10 nmi
LAADY	0.70%	1.94%	2.64%	15 nmi
SHIVE	0.39%	7.10%	7.49%	12 nmi
SXC	0.11%	5.28%	5.39%	9 nmi
VTU	14.76%	4.96%	19.72%	5 nmi

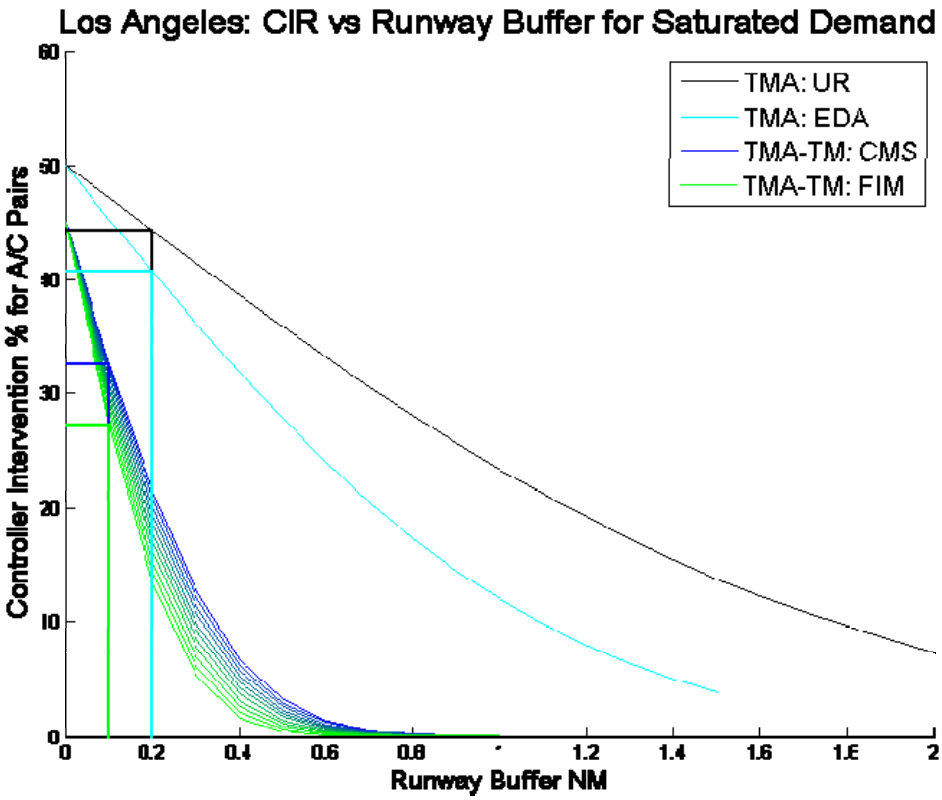

Figure 75: Controller Intervention Rate for each C&T at the LAX model.

Table 235: Potential arrival throughput capacity for LAX given the CIR analysis and resulting meter fix and runway buffers.

Concept and Technology	Throughput Capacity (ac/hr)	Percentage of Theoretical Max	Runway Buffer (nmi)	Meter Fix Separation (nmi)
TMA only	80	94%	0.2	(5, 11, 8, 5, 10, 15, 12, 9, 5)
TMA+EDA	80	95%	0.2	(5, 7, 5, 5, 6, 7, 7, 6, 5)
TMA-TM+CMS	82	97%	0.1	(5, 11, 8, 5, 10, 15, 12, 9, 5)
TMA-TM+CMS+EDA	82	97%	0.1	(5, 7, 5, 5, 6, 7, 7, 6, 5)
TMA-TM+FIM	82	97%	0.1	(5, 7, 5, 5, 6, 7, 7, 6, 5)
Theoretical Max	85	100%	0	(5, 5, 5, 5, 5, 5, 5, 5, 5)

A.9. MCO 'Orlando International' Airport Simulation Results

Table 236: All identified routes for MCO.

Meter Fix	Merge Point	Merge Point	Runway
BAIRN	-	-	17L
BAIRN	TINKR	-	18R
LAMMA	HERVI	HABRA	RW:17L/18R
LEESE	HABRA	-	17L/18R
MALET	HERVI	HABRA	RW:17L/18R
MINEE	-	-	17L
MINEE	TINKR	-	18R

Table 237: Meter Fix Separation and route and meter fix usage percentages for MCO.

Meter Fix	17L%	18R%	Total %	Observed Separation (nmi)
BAIRN	3.93%	4.93%	8.86%	5 nmi
LAMMA	25.88%	10.96%	36.85%	8 nmi
LEESE	8.09%	27.33%	35.42%	8 nmi
MALET	5.32%	3.71%	9.03%	7 nmi
MINEE	2.59%	7.25%	9.84%	11 nmi

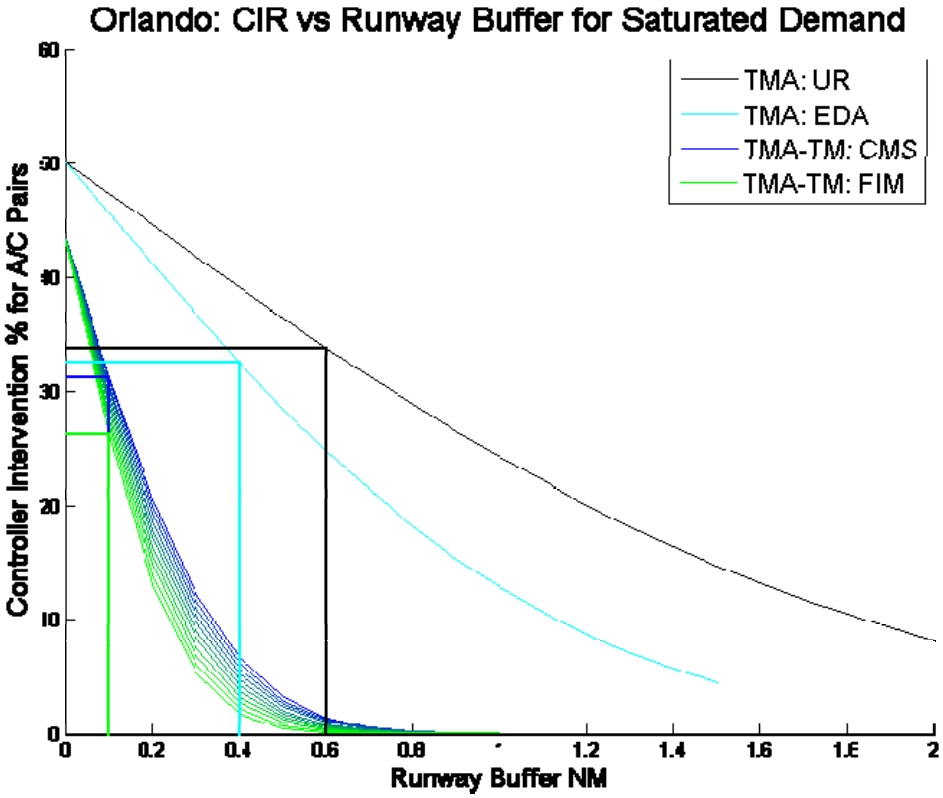

Figure 76: Controller Intervention Rate for each C&T at the MCO model.

Table 238: Potential arrival throughput capacity for MCO given the CIR analysis and resulting meter fix and runway buffers.

Concept and Technology	Throughput Capacity (ac/hr)	Percentage of Theoretical Max	Runway Buffer (nmi)	Meter Fix Separation (nmi)
TMA only	78	83%	0.6	(5, 8, 8, 7, 11)
TMA+EDA	83	88%	0.4	(5, 6, 6, 5, 8)
TMA-TM+CMS	89	94%	0.2	(5, 8, 8, 7, 11)
TMA-TM+CMS+EDA	89	94%	0.2	(5, 6, 6, 5, 8)
TMA-TM+FIM	92	97%	0.1	(5, 6, 6, 5, 7)
Theoretical Max	95	100%	0	(5, 5, 5, 5, 5)

A.10. MEM 'Memphis International' Airport Simulation Results

Table 239: All identified routes for MEM.

Meter Fix	Merge Point	Merge Point	Runway
GQE	LAURI	-	18L
HLI	LAURI	-	18L
UJM	LAURI	-	18L
WLDER	LAURI	-	18L
GQE	VAGDY	-	18R
HLI	VAGDY	-	18R
UJM	VAGDY	-	18R
WLDER	VAGDY	-	18R

Table 240: Meter Fix Separation and route and meter fix usage percentages for MEM.

Meter Fix	18L%	18R%	Total %	Observed Separation (nmi)
GQE	5.65%	24.79%	30.44%	5 nmi
HLI	17.35%	4.50%	21.85%	9 nmi
UJM	4.50%	15.74%	20.24%	9 nmi
WLDER	26.10%	1.37%	27.47%	8 nmi

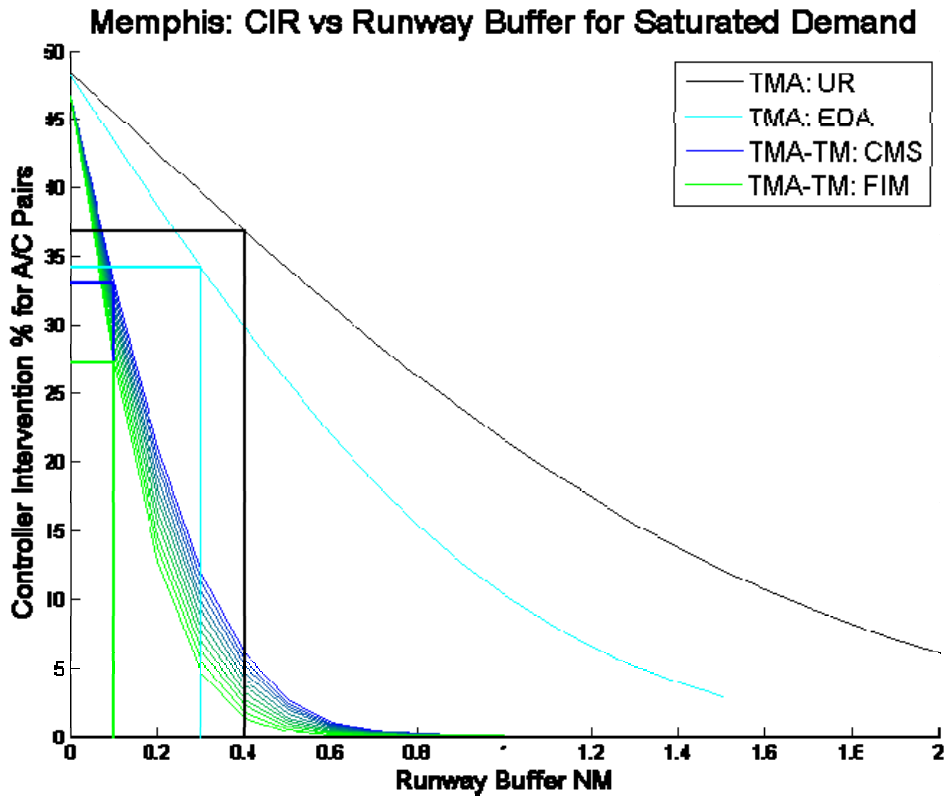

Figure 77: Controller Intervention Rate for each C&T at the MEM model.

Table 241: Potential arrival throughput capacity for MEM given the CIR analysis and resulting meter fix and runway buffers.

Concept and Technology	Throughput Capacity (ac/hr)	Percentage of Theoretical Max	Runway Buffer (nmi)	Meter Fix Separation (nmi)
TMA only	72	89%	0.4	(5, 9, 9, 8)
TMA+EDA	74	91%	0.3	(5, 7, 7, 7)
TMA-TM+CMS	78	97%	0.1	(5, 9, 9, 8)
TMA-TM+CMS+EDA	78	97%	0.1	(5, 7, 7, 7)
TMA-TM+FIM	78	97%	0.1	(5, 7, 7, 7)
Theoretical Max	81	100%	0	(5, 5, 5, 5)

A.11. MIA 'Miami Wilcox Field' Airport Simulation Results

Table 242: All identified routes for MIA.

Meter Fix	Merge Point	Merge Point	Runway
FAMIN	CICIV	-	08L
JUNUR	CICIV	-	08L
FAMIN	KROME	-	09
JUNUR	KROME	-	09

Table 243: Meter Fix Separation and route and meter fix usage percentages for MIA.

Meter Fix	08L%	9%	Total %	Observed Separation (nmi)
FAMIN	32.22%	33.73%	65.95%	5 nmi
JUNUR	5.53%	28.52%	34.05%	9 nmi

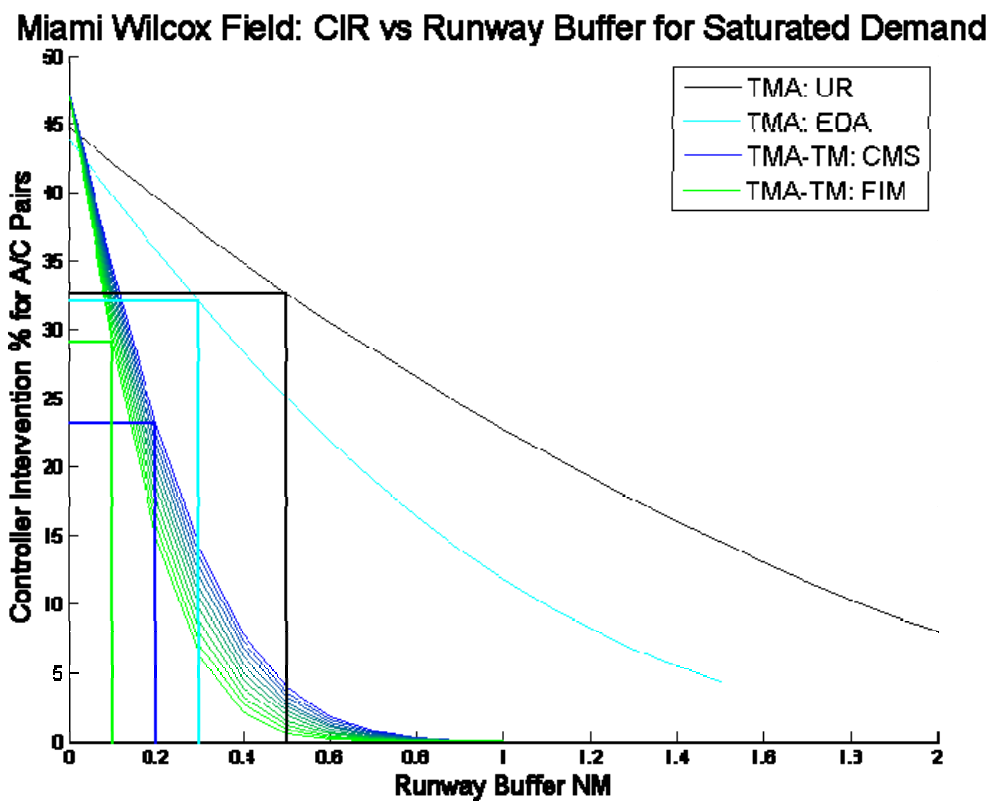

Figure 78: Controller Intervention Rate for each C&T at the MIA model.

Table 244: Potential arrival throughput capacity for MEM given the CIR analysis and resulting meter fix and runway buffers.

Concept and Technology	Throughput Capacity (ac/hr)	Percentage of Theoretical Max	Runway Buffer (nmi)	Meter Fix Separation (nmi)
TMA only	70	88%	0.5	(5, 9)
TMA+EDA	74	93%	0.3	(5, 7)
TMA-TM+CMS	76	95%	0.2	(5, 9)
TMA-TM+CMS+EDA	76	95%	0.2	(5, 7)
TMA-TM+FIM	78	97%	0.1	(5, 7)
Theoretical Max	80	100%	0	(5, 5)

A.12. MKE 'Milwaukee - Mitchell' Airport Simulation Results

Table 245: All identified routes for MKE.

Meter Fix	Merge Point	Merge Point	Runway
VEENA	CUTMO	-	25L
FOVOJ	CUTMO	-	25L

Table 246: Meter Fix Separation and route and meter fix usage percentages for MKE.

Meter Fix	25L%	Total %	Observed Separation (nmi)
FOVOJ	6.67%	6.67%	27 nmi
VEENA	93.33%	93.33%	5 nmi

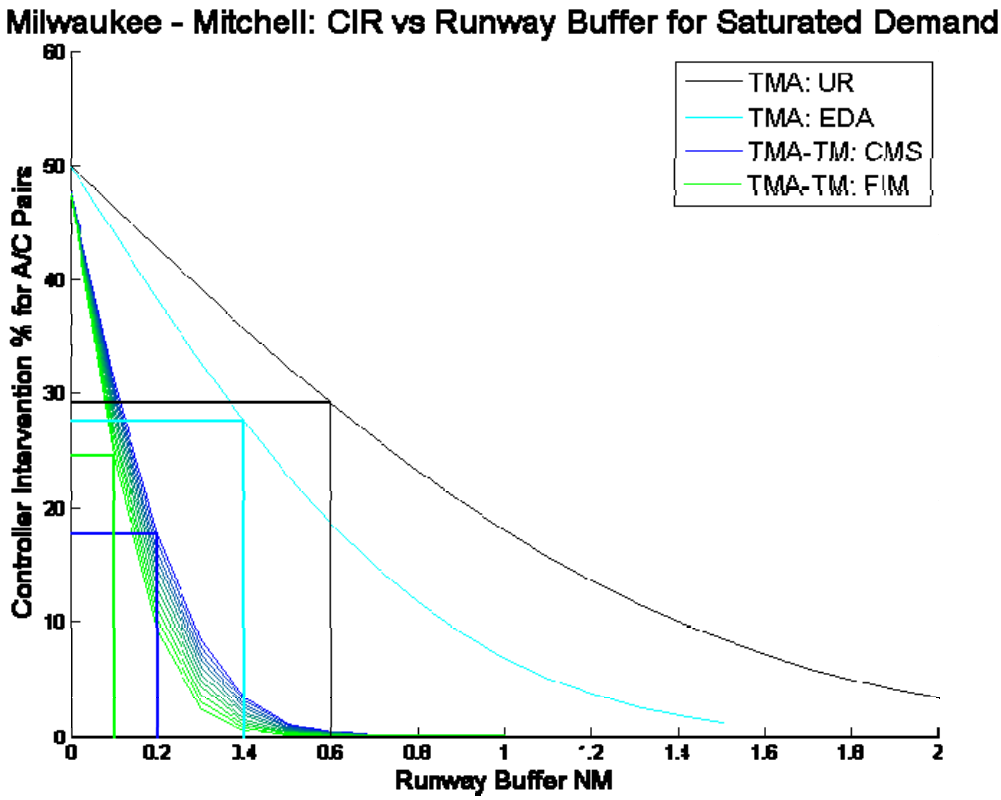

Figure 79: Controller Intervention Rate for each C&T at the MKE model.

Table 247: Potential arrival throughput capacity for MKE given the CIR analysis and resulting meter fix and runway buffers.

Concept and Technology	Throughput Capacity (ac/hr)	Percentage of Theoretical Max	Runway Buffer (nmi)	Meter Fix Separation (nmi)
TMA only	32	84%	0.6	(27, 5)
TMA+EDA	34	88%	0.4	(9, 5)
TMA-TM+CMS	35	91%	0.2	(27, 5)
TMA-TM+CMS+EDA	35	91%	0.2	(9, 5)
TMA-TM+FIM	36	93%	0.1	(8, 5)
Theoretical Max	39	100%	0	(5, 5)

A.13. ORD "O'Hare" Airport Simulation Results

Table 248: All identified routes for ORD.

Meter Fix	Merge Point	Merge Point	Runway
LOOTH	ROCSE	-	27L
NEWRK	-	-	27L
KRENA	-	-	27L/27R
KUBBS	ROCSE	-	27L
KUBBS	WILLA	-	27R
LOOTH	WILLA	-	27R
NEWRK	WILLA	-	27R

Table 249: Meter Fix Separation and route and meter fix usage percentages for ORD.

Meter Fix	27L%	27R%	Total %	Observed Separation (nmi)
KRENA	5.43%	2.28%	7.71%	13 nmi
KUBBS	20.99%	42.25%	63.25%	5 nmi
LOOTH	6.80%	0.52%	7.33%	9 nmi
NEWRK	20.81%	0.90%	21.72%	8 nmi

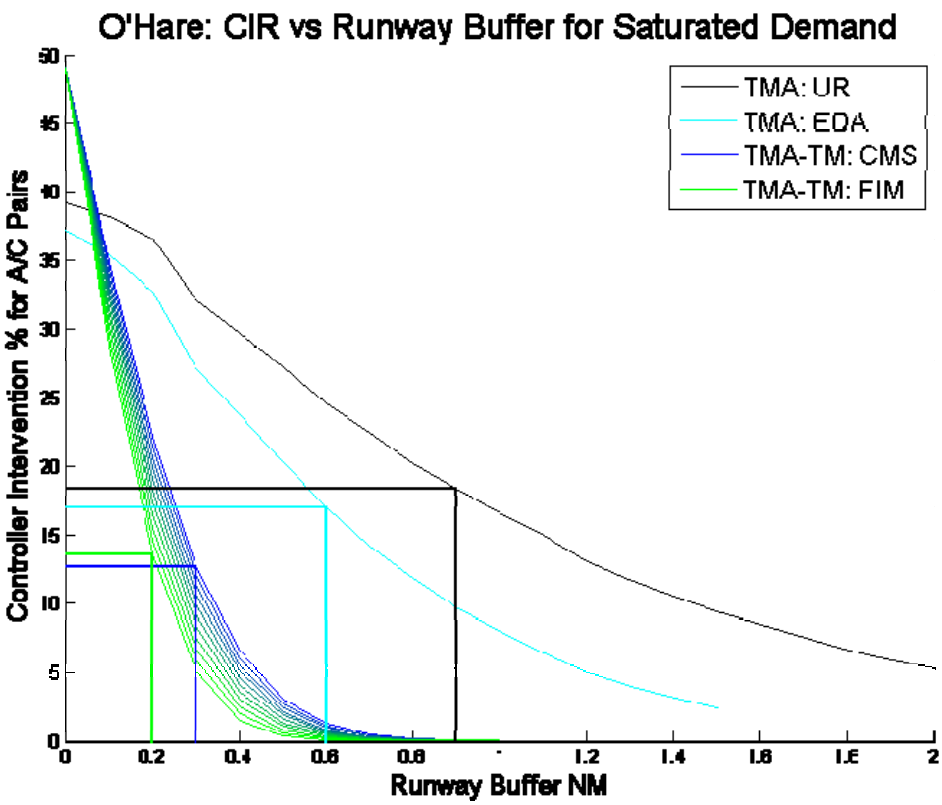

Figure 80: Controller Intervention Rate for each C&T at the ORD model.

Table 250: Potential arrival throughput capacity for ORD given the CIR analysis and resulting meter fix and runway buffers.

Concept and Technology	Throughput Capacity (ac/hr)	Percentage of Theoretical Max	Runway Buffer (nmi)	Meter Fix Separation (nmi)
TMA only	71	83%	0.9	(13, 5, 9, 8)
TMA+EDA	77	89%	0.6	(9, 5, 7, 7)
TMA-TM+CMS	82	96%	0.3	(13, 5, 9, 8)
TMA-TM+CMS+EDA	82	96%	0.3	(9, 5, 7, 7)
TMA-TM+FIM	83	97%	0.2	(8, 5, 7, 7)
Theoretical Max	86	100%	0	(5, 5, 5, 5)

A.14. SDF 'Louisville Intl Standiford Field' Airport Simulation Results

There was one interesting note at this airport. The TMA+EDA throughput was higher than the TMA-TM+CMS and TMA-TM+FIM throughput. The reason is the terminal merge point scheduler causes a significant reduction in throughput due to the limitations of this airport model. The traffic from CHERI is travelling east while the traffic from FFT is travelling west. Both of these routes meet up near the final approach fix. There was no obvious solution other than placing a single merge point for both runways. When the TMA-TM+EDA case was run, it had a much lower throughput than TMA+EDA, TMA-TM+CMS, and TMA-TM+FIM, as can be seen in Figure 77.

Table 251: All identified routes for SDF.

Meter Fix	Merge Point	Merge Point	Runway
CHERI	CRNDL	-	35L/35R
FFT	CRNDL	-	35L/35R

Table 252: Meter Fix Separation and route and meter fix usage percentages for SDF.

Meter Fix	35L%	35R%	Total %	Observed Separation (nmi)
CHERI	43.69%	10.47%	54.15%	5 nmi
FFT	14.97%	30.88%	45.85%	6 nmi

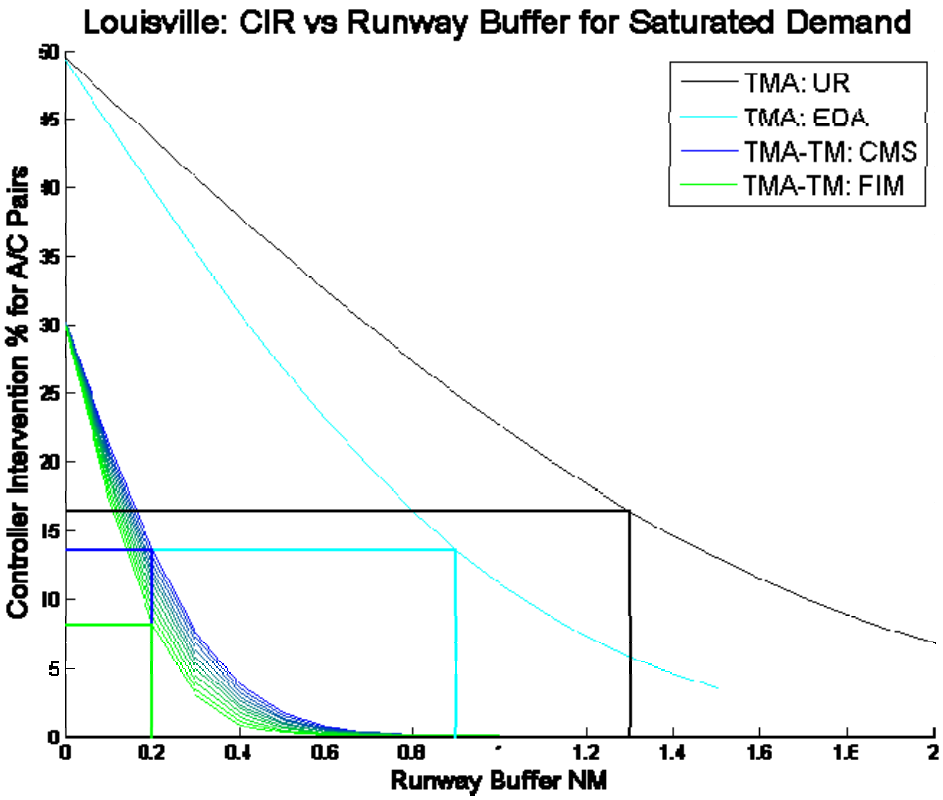

Figure 81: Controller Intervention Rate for each C&T at the SDF model.

Table 253: Potential arrival throughput capacity for SDF given the CIR analysis and resulting meter fix and runway buffers. Of **note, TMA-TM causes significant delay due to a single merge point directly in front of both runways. All traffic must merge at that point.**

Concept and Technology	Throughput Capacity (ac/hr)	Percentage of Theoretical Max	Runway Buffer (nmi)	Meter Fix Separation (nmi)
TMA only	52	74%	1.3	(5, 6)
TMA+EDA	57	82%	0.9	(5, 6)
TMA-TM+CMS	55	79%	0.2	(5, 6)
TMA-TM+CMS+EDA	55	79%	0.2	(5, 6)
TMA-TM+FIM	55	79%	0.2	(5, 6)
Theoretical Max	70	100%	0	(5, 5)
TMA-TM+EDA	49	70%	0.9	(5, 6)

A.15. SEA "Seattle-Tacoma" Airport Simulation Results

Of note here, the most used runway configuration has only one runway, 16R. On the FAA OIS webpage, the runway configuration with the largest arrival capacity is 16R and 16L, with 16C for departures only and 16L for a mix of departures and arrivals. The FAA OIS has a capacity of 48 arrival aircraft per hour, but since our track data indicated only 16R was being used at a rate of 21 aircraft per hour, we chose to use only the one runway. Since there was no indication of the capacity of 16R in the FAA OIS database, we used half the capacity of 16R and 16L, since it was still larger than the observed. Since the arrival capacity is so low, the model predicts the airport is not being used efficiently. There is likely some other explanation as to why the arrival rates are so low. This may include many reasons outlined in section 6:

Concept Modeling Approach.

Table 254: All identified routes for SEA.

Meter Fix	Merge Point	Merge Point	Runway
JAKSN	WOODI	-	16R
OLM	HULIK	-	16R
JAWBN	HULIK	-	16R

Table 255: Meter Fix Separation and route and meter fix usage percentages for SEA.

Meter Fix	16R%	Total %	Observed Separation (nmi)
JAKSN	55.39%	55.39%	8 nmi
JAWBN	17.97%	17.97%	22 nmi
OLM	26.64%	26.64%	12 nmi

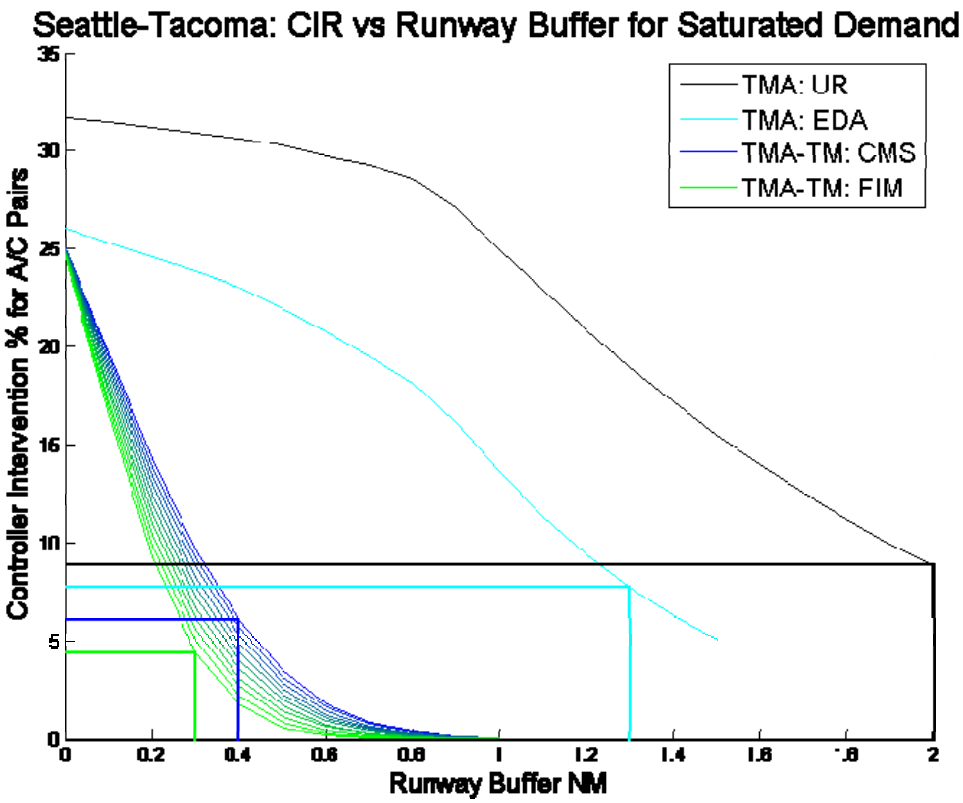

Figure 82: Controller Intervention Rate for each C&T at the SEA model.

Table 256: Potential arrival throughput capacity for SEA given the CIR analysis and resulting meter fix and runway buffers.

Concept and Technology	Throughput Capacity (ac/hr)	Percentage of Theoretical Max	Runway Buffer (nmi)	Meter Fix Separation (nmi)
TMA only	28	77%	2	(8, 22, 12)
TMA+EDA	33	90%	1.3	(6, 8, 8)
TMA-TM+CMS	37	100%	0.4	(8, 22, 12)
TMA-TM+CMS+EDA	37	100%	0.4	(6, 8, 8)
TMA-TM+FIM	37	100%	0.3	(5, 8, 8)
Theoretical Max	37	100%	0	(5, 5, 5)

A.16. STL "Lambert-St. Louis" Airport Simulation Results

Table 257: All identified routes for STL.

Meter Fix	Merge Point	Merge Point	Runway
QBALL	FARIS	-	12L
KAYLA	EUBIE	-	12L
MIKOE	EUBIE	-	12L
PETTI	EUBIE	-	12L
QBALL	FARIS	-	12R
KAYLA	FARIS	-	12R
LORLE	CFJYO	-	12R
PETTI	FARIS	-	12R

Table 258: Meter Fix Separation and route and meter fix usage percentages for STL.

Meter Fix	12L%	12R%	Total %	Observed Separation (nmi)
KAYLA	14.02%	12.62%	26.64%	16 nmi
LORLE	6.56%	4.18%	10.74%	21 nmi
MIKOE	0.70%	0.56%	1.26%	5 nmi

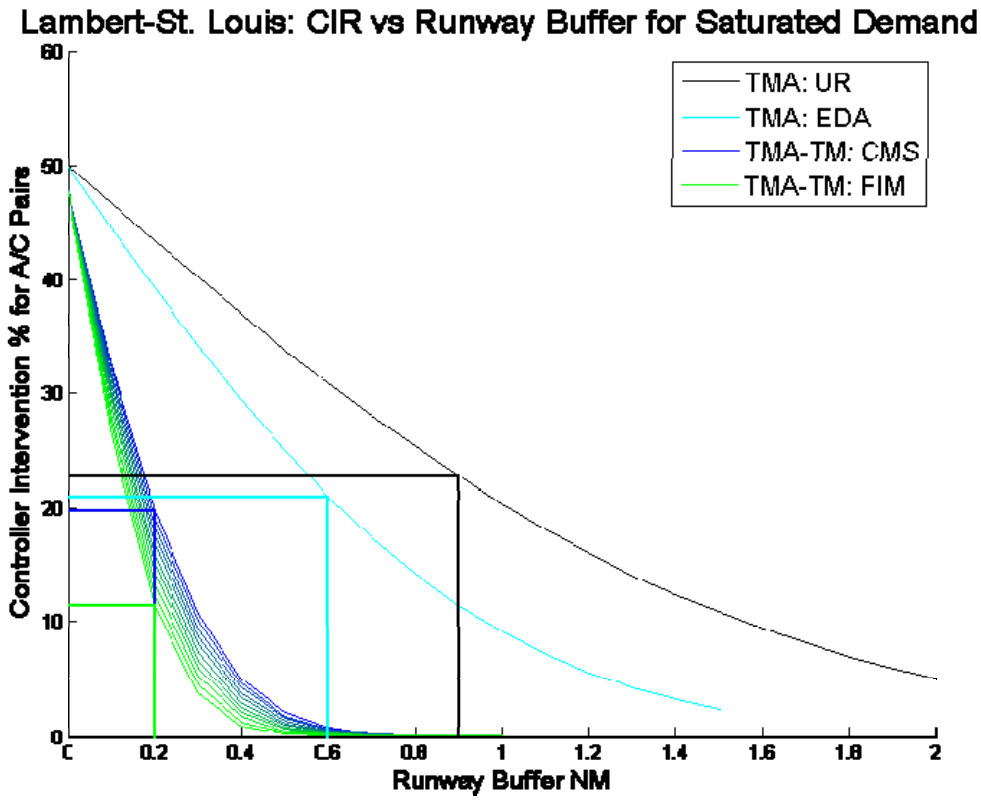

Figure 83: Controller Intervention Rate for each C&T at the STL model.

Table 259: Potential arrival throughput capacity for STL given the CIR analysis and resulting meter fix and runway buffers.

Concept and Technology	Throughput Capacity (ac/hr)	Percentage of Theoretical Max	Runway Buffer (nmi)	Meter Fix Separation (nmi)
TMA only	63	75%	0.9	(16, 21, 5, 11, 15)
TMA+EDA	69	82%	0.6	(9, 9, 5, 8, 9)
TMA-TM+CMS	78	93%	0.2	(16, 21, 5, 11, 15)
TMA-TM+CMS+EDA	79	94%	0.2	(9, 9, 5, 8, 9)
TMA-TM+FIM	79	94%	0.2	(9, 9, 5, 7, 9)
Theoretical Max	84	100%	0	(5, 5, 5, 5, 5)

B. Appendix: Airport Adaptation and Simulation Results for Extension Airports

This appendix contains the airport configuration modeling results. This includes all route and meter fix data, controller intervention rate plots, throughput summary, and the dependent runway timing matrices. The routes and route data were observed from track data as explained in previous sections. The controller intervention rate plots and throughput summary were provided by the scheduling and arrival conformance simulations. The dependent runway timing matrices were observed from the track data. The dependent runway timing matrices were not required at all airports. During VMC conditions, all runway configurations at ATL, IAH, and PHX contain independent runways, while all runway configurations at BOS and LAS contain dependent runways. Dependent runway timing matrices were provided for all BOS and LAS arrival configurations. The leading aircraft is on the rows and the trailing aircraft is on the columns for every dependent runway timing matrix.

B.1. Hartsfield-Jackson Atlanta International Airport (ATL)

B.1.1. Arrival Runways 26R, 27L, 28 Configuration

Table 260: All identified routes for ATL arrival runways 26R, 27L, 28.

Meter Fix	Merge Point	Merge Point	Runway
DIRTY	-	-	26R
HONIE	NOFIV	-	26R
ERLIN	NOFIV	-	26R
PECHY	-	-	26R
CANUK	-	-	27L
HONIE	FOGOG	-	27L
DIRTY	-	-	27L
CANUK	HEDEG	-	28
HONIE	FOGOG	-	28
ERLIN	FOGOG	HEDEG	27L
CANUK	-	-	27L

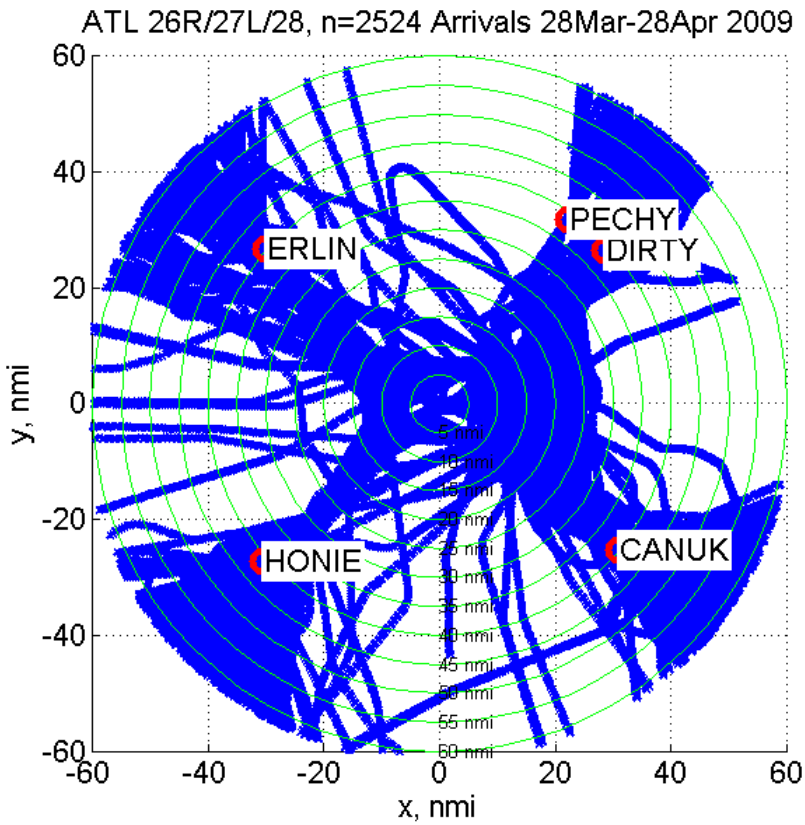

Figure 84: Arrival Flows and Modeled Entry Points for ATL arrival runways 26R, 27, 28.

Table 261: Meter Fix Separation and route and meter fix usage percentages for ATL 26R, 27L, 28.

Meter Fix	26R%	27L%	28%	Total %	Observed Separation (nmi)
CANUK	0.71%	22.29%	12.77%	35.77%	5 nmi
DIRTY	24.77%	7.63%	0.01%	32.41%	5 nmi
ERLIN	13.77%	1.48%	0.42%	15.67%	7 nmi
HONIE	3.48%	5.34%	6.67%	15.50%	8 nmi
PECHY	0.45%	0.20%	0.00%	0.65%	9 nmi

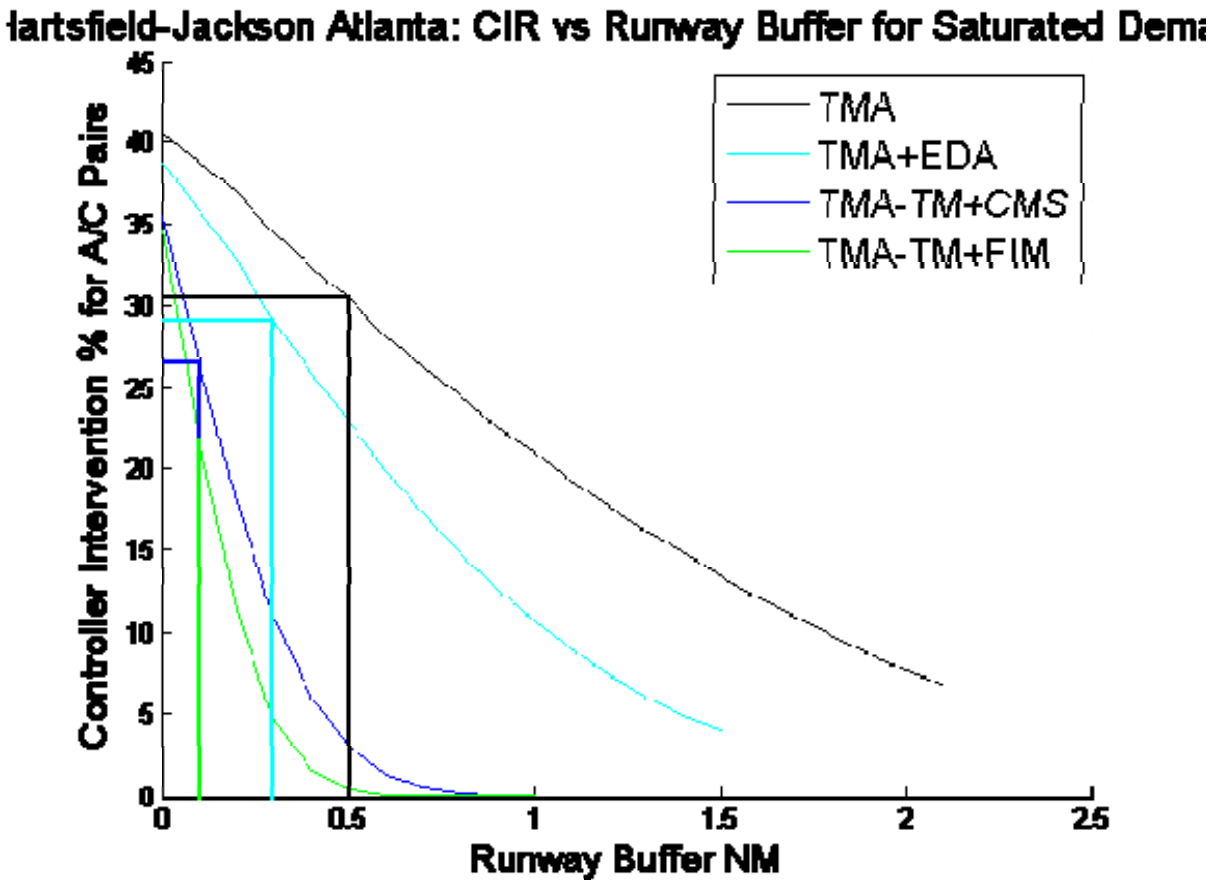

Figure 85: Controller Intervention Rate versus Runway Buffer for every C&T at ATL 26R, 27, and 28.

Table 262: Potential arrival throughput capacity for ATL 26R, 27L, 28 given the CIR analysis and resulting meter fix and runway buffers.

Concept and Technology	Throughput Capacity (ac/hr)	Percentage of Theoretical Max	Runway Buffer (nmi)	Meter Fix Separation (nmi)
TMA only	124	87%	0.5	(5, 5, 7, 8, 9)
TMA+EDA	130	91%	0.3	(5, 5, 6, 7, 7)
TMA-TM+CMS	139	97%	0.1	(5, 5, 7, 8, 9)
TMA-TM+CMS+EDA	139	97%	0.1	(5, 5, 6, 7, 7)
TMA-TM+FIM	139	97%	0.1	(5, 5, 6, 7, 7)
Theoretical Max	143	100%	0	(5, 5, 5, 5, 5)

B.1.2. Arrival Runways 8L, 9R, 10 Configuration

Table 263: All identified routes for ATL arrival runways 8L, 9R, 10.

Meter Fix	Merge Point	Merge Point	Runway
DIRTY	DOEVR	-	8L
CANUK	DOEVR	-	8L
ERLIN	-	-	8L
PECHY	DOEVR	-	8L
DIRTY	DNCBD	-	9R
CANUK	DNCBD	-	9R
HONIE	-	-	9R
ERLIN	-	-	9R
CANUK	DNCBD	PENCL	10
HONIE	PENCL	-	10
DIRTY	DNCBD	PENCL	10
ERLIN	-	-	10

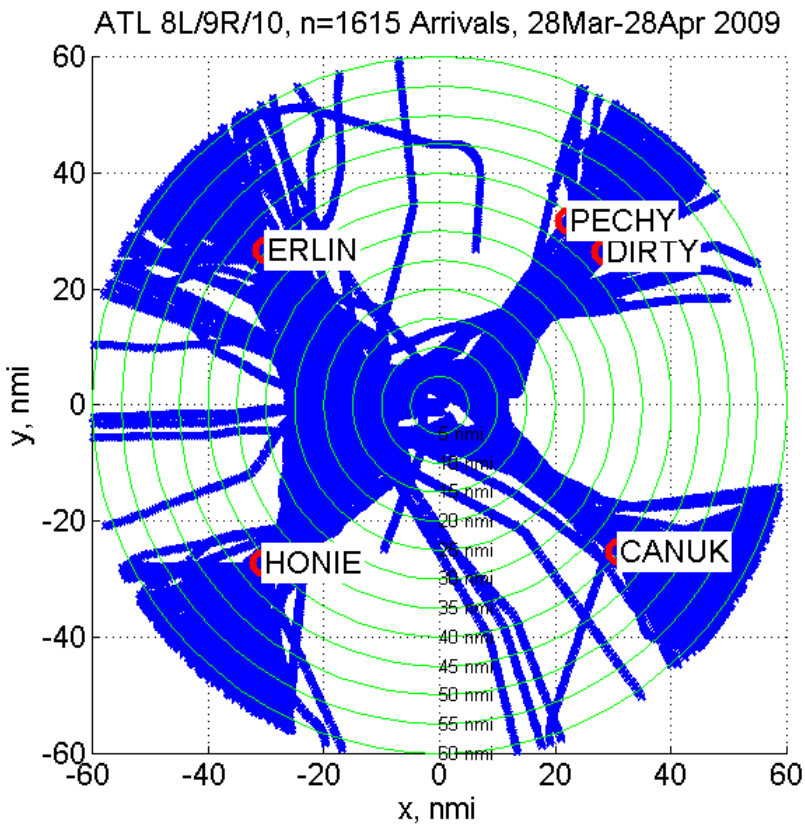

Figure 86. Arrival Flows and Modeled Entry Points for ATL arrival runways 8L, 9R, 10.

Table 264: Meter Fix Separation and route and meter fix usage percentages for ATL 8L, 9R, 10.

Meter Fix	08L%	09R%	10%	Total %	Observed Separation (nmi)
CANUK	2.79%	6.40%	5.75%	14.94%	8 nmi
DIRTY	17.18%	1.48%	0.48%	19.13%	6 nmi
ERLIN	21.64%	6.52%	0.02%	28.19%	5 nmi
HONIE	0.62%	22.40%	13.67%	36.69%	5 nmi
PECHY	1.03%	0.02%	0.00%	1.06%	9 nmi

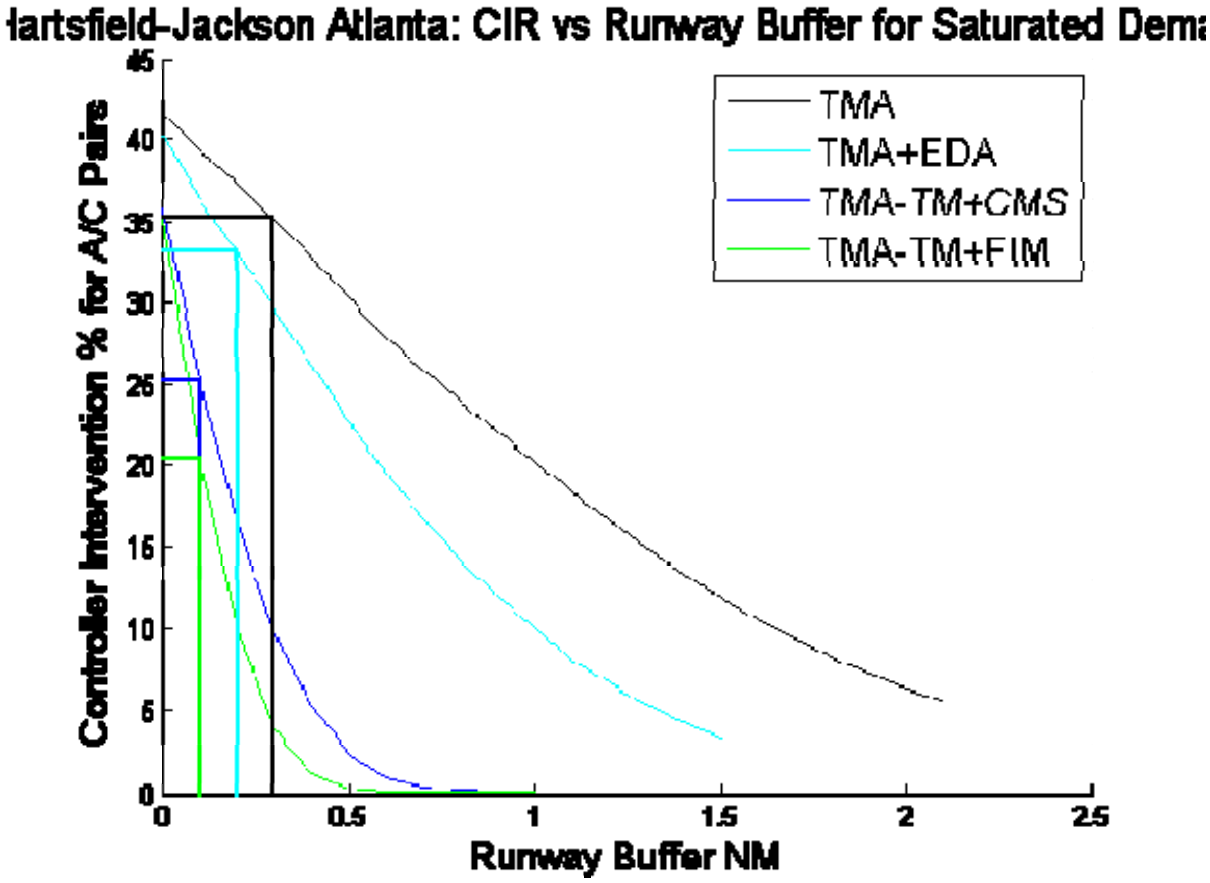

Figure 87: Controller Intervention Rate versus Runway Buffer for every C&T at ATL 8L, 9R, and 10.

Table 265: Potential arrival throughput capacity for ATL 8L, 9R, 10 given the CIR analysis and resulting meter fix and runway buffers.

Concept and Technology	Throughput Capacity (ac/hr)	Percentage of Theoretical Max	Runway Buffer (nmi)	Meter Fix Separation (nmi)
TMA only	123	92%	0.3	(8, 6, 5, 5, 9)
TMA+EDA	126	95%	0.2	(7, 6, 5, 5, 7)
TMA-TM+CMS	130	97%	0.1	(8, 6, 5, 5, 9)
TMA-TM+CMS+EDA	130	97%	0.1	(7, 6, 5, 5, 7)
TMA-TM+FIM	130	97%	0.1	(7, 6, 5, 5, 7)
Theoretical Max	133	100%	0	(5, 5, 5, 5, 5)

B.2. Boston Logan International Airport (BOS)

B.2.1. Arrival Runways 22L, 27 Configuration

Table 266: All identified routes for BOS arrival runways 22L, 27.

Meter Fix	Merge Point	Merge Point	Runway
FREDO	FENWY	-	27
PVD	FENWY	-	27
PVD	-	-	22L
GDM	-	-	22L/27
LWM	-	-	22L/27
SCUPP	-	-	27

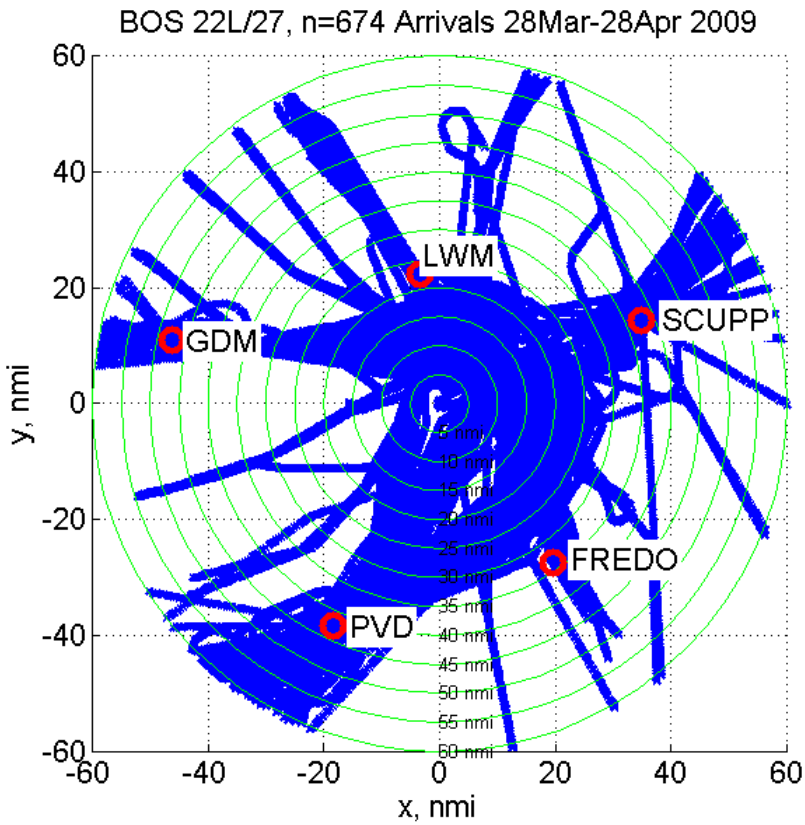

Figure 88. Arrival Flows and Modeled Entry Points for BOS arrival runways 22L, 27.

Table 267: Meter Fix Separation and route and meter fix usage percentages for BOS 22L, 27.

Meter Fix	22L%	27%	Total %	Observed Separation (nmi)
FREDO	0.82%	2.91%	3.72%	5 nmi
GDM	17.91%	14.39%	32.29%	10 nmi
LWM	2.28%	1.38%	3.66%	5 nmi
PVD	9.82%	43.26%	53.08%	7 nmi
SCUPP	1.31%	5.93%	7.24%	11 nmi

Table 268: Dependent runway timing matrix for BOS 22L leading and 27 trailing.

22L Leading, 27 Trailing				
Time (seconds) (Leading/Trailing)	**H**	**B757**	**L**	**S**
H	11.39	11.39	11.39	11.39
B757	11.39	11.39	14.40	11.39
L	11.39	6.28	9.47	2.68
S	11.39	11.39	11.39	11.39

Table 269: Dependent runway timing matrix for BOS 27 leading and 22L trailing.

27 Leading, 22L Trailing				
Time (seconds) (Leading/Trailing)	**H**	**B757**	**L**	**S**
H	13.80	13.80	13.80	13.80
B757	13.80	13.80	10.33	13.80
L	13.80	14.82	11.09	13.80
S	13.80	13.80	24.20	13.80

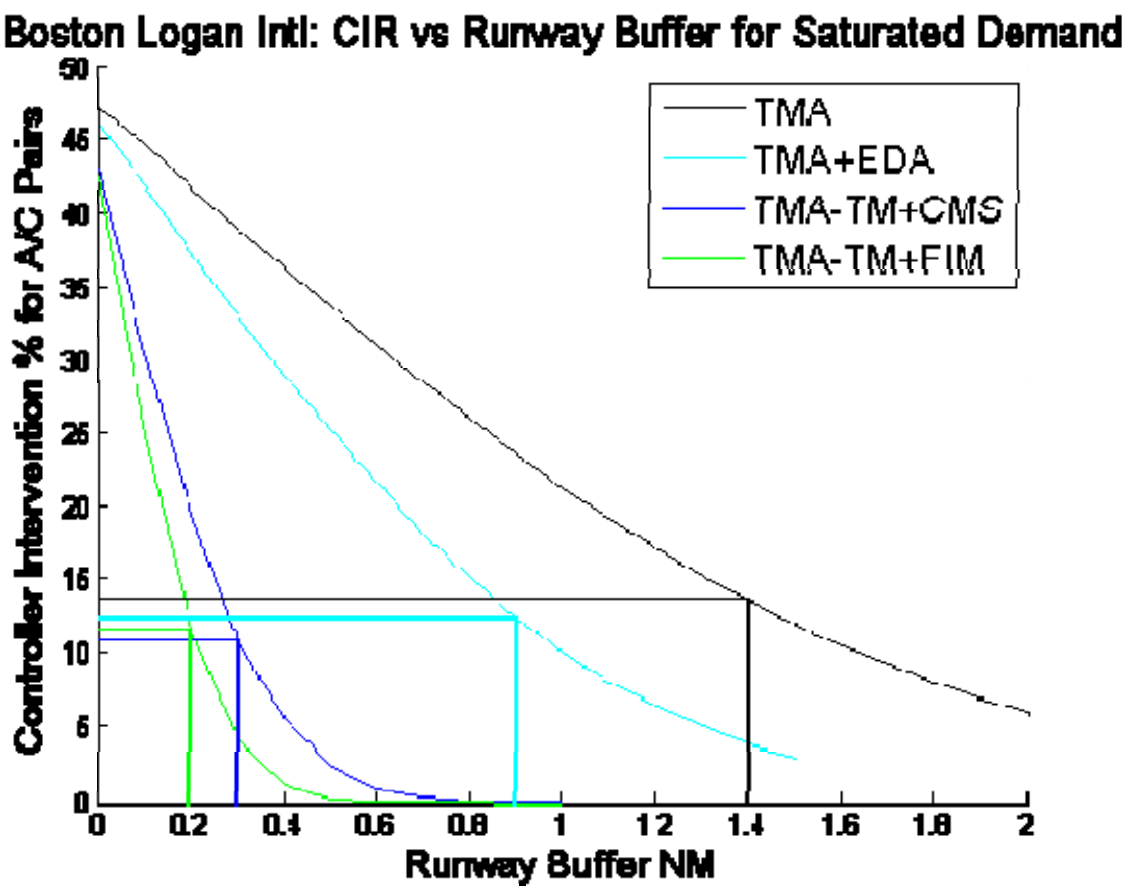

Figure 89: Controller Intervention Rate versus Runway Buffer for every C&T at BOS 22L and 27R.

Table 270: Potential arrival throughput capacity for BOS 22L, 27R given the CIR analysis and resulting meter fix and runway buffers.

Concept and Technology	Throughput Capacity (ac/hr)	Percentage of Theoretical Max	Runway Buffer (nmi)	Meter Fix Separation (nmi)
TMA only	58	69%	1.4	(5, 10, 5, 7, 11)
TMA+EDA	66	77%	0.9	(5, 7, 5, 6, 8)
TMA-TM+CMS	78	91%	0.3	(5, 10, 5, 7, 11)
TMA-TM+CMS+EDA	77	91%	0.3	(5, 7, 5, 6, 8)
TMA-TM+FIM	79	93%	0.2	(5, 7, 5, 6, 8)
Theoretical Max	85	100%	0	(5, 5, 5, 5, 5)

B.2.2. Arrival Runways 4L, 4R Configuration

Table 271: All identified routes for BOS arrival runways 4L, 4R.

Meter Fix	Merge Point	Merge Point	Runway
FREDO	-	-	04L
PVD	-	-	04L
WOONS	-	-	04L
GDM	VPSPF	-	04L
LWM	VPSPF	-	04L
SCUPP	VPSPF	-	04L
PVD	-	-	04R
WOONS	-	-	04R
FREDO	-	-	04R
LWM	-	-	04R
SCUPP	HUFEE	-	04R
GDM	HUFEE	-	04R

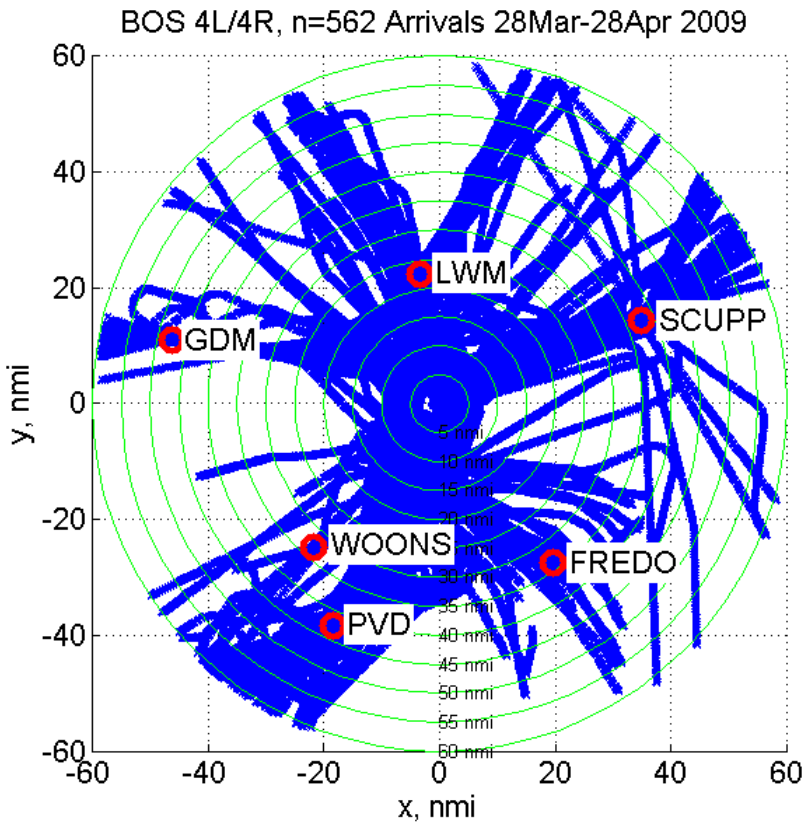

Figure 90. Arrival Flows and Modeled Entry Points for BOS arrival runways 4L, 4R.

Table 272: Meter Fix Separation and route and meter fix usage percentages for BOS 4L, 4R.

Meter Fix	04L%	04R%	Total %	Observed Separation (nmi)
FREDO	2.22%	2.10%	4.32%	21 nmi
GDM	7.24%	23.72%	30.96%	9 nmi
LWM	2.60%	1.67%	4.27%	21 nmi
PVD	9.12%	38.93%	48.05%	8 nmi
SCUPP	1.07%	6.06%	7.13%	12 nmi
WOONS	2.12%	3.15%	5.26%	9 nmi

Table 273: Dependent runway timing matrix for BOS 4L leading and 4R trailing.

4L Leading, 4R Trailing				
Time (seconds) (Leading/Trailing)	**H**	**B757**	**L**	**S**
H	16.46	16.46	16.46	16.46
B757	16.46	16.46	14.40	16.46
L	16.46	22.13	14.15	16.46
S	16.46	16.46	13.10	16.46

Table 274: Dependent runway timing matrix for BOS 4R leading and 4L trailing.

4R Leading, 4L Trailing				
Time (seconds) (Leading/Trailing)	**H**	**B757**	**L**	**S**
H	18.49	18.49	18.49	18.49
B757	18.49	18.49	24.57	18.49
L	18.49	18.49	11.38	26.63
S	18.49	18.49	18.49	18.49

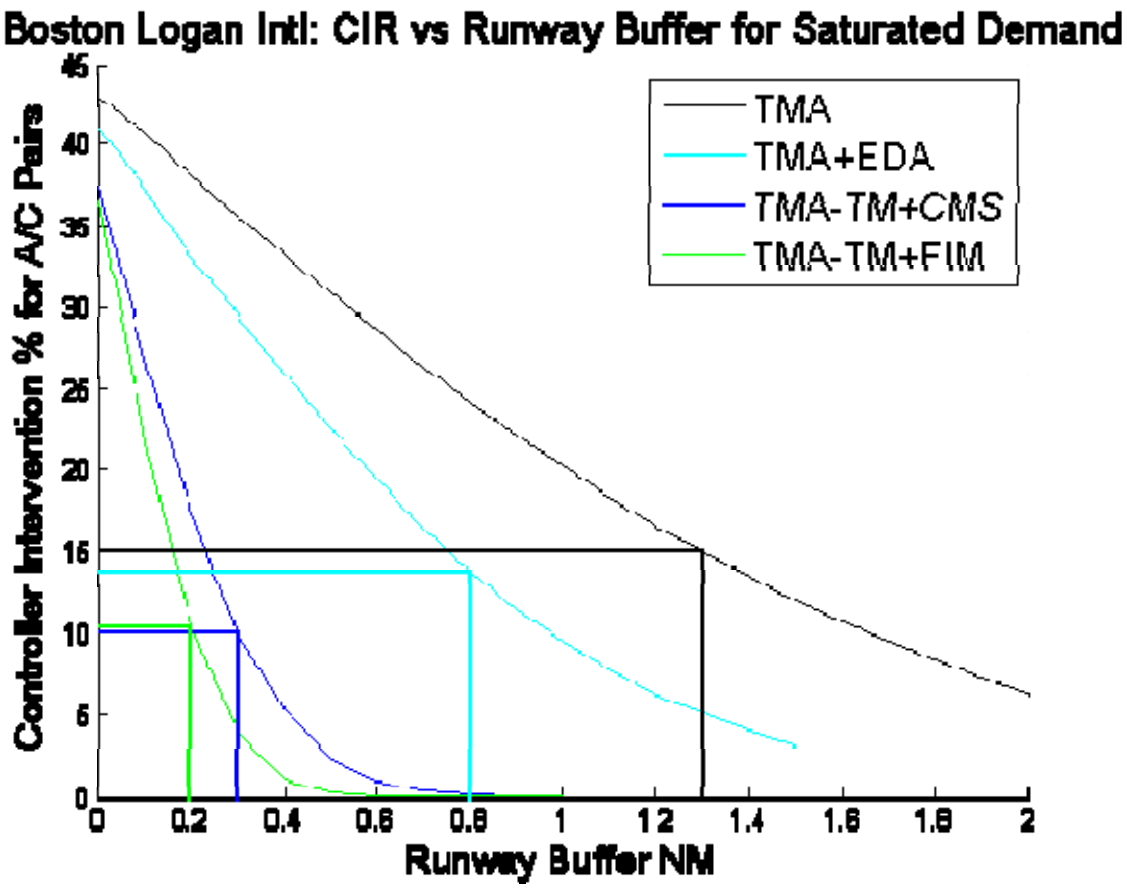

Figure 91: Controller Intervention Rate versus Runway Buffer for every C&T at BOS 4L and 4R.

Table 275: Potential arrival throughput capacity for BOS 4L, 4R given the CIR analysis and resulting meter fix and runway buffers.

Concept and Technology	Throughput Capacity (ac/hr)	Percentage of Theoretical Max	Runway Buffer (nmi)	Meter Fix Separation (nmi)
TMA only	60	74%	1.3	(21, 9, 21, 8, 12, 9)
TMA+EDA	67	83%	0.8	(9, 7, 9, 7, 9, 7)
TMA-TM+CMS	77	95%	0.3	(21, 9, 21, 8, 12, 9)
TMA-TM+CMS+EDA	77	96%	0.3	(9, 7, 9, 7, 9, 7)
TMA-TM+FIM	80	100%	0.2	(9, 7, 9, 6, 8, 7)
Theoretical Max	80	100%	0	(5, 5, 5, 5, 5, 5)

B.2.3. Arrival Runways 27, 32 Configuration

Table 276: All identified routes for BOS arrival runways 27, 32.

Meter Fix	Merge Point	Merge Point	Runway
FREDO	-	-	27
PVD	-	-	27
GDM	-	-	27
SCUPP	-	-	27

The results indicate that, for the trajectory data analyzed, ranging from 28 March to 28 April 2009, no aircraft were estimated to land at BOS runway 32.

B.3. Houston George Bush Intercontinental Airport (IAH)

B.3.1. Arrival Runways 26L, 26R, 27 Configuration

Table 277: All identified routes for IAH arrival runways 26L, 26R, 27.

Meter Fix	Merge Point	Merge Point	Runway
BRKMN	-	-	26L/26R
BRKMN	KERNS	-	27
WOLDE	-	-	26L
WOLDE	KERNS	-	27
DAS	KERNS	-	26L
DAS	KERNS	-	26R
DAS	-	-	27
STROS	KERNS	-	26L
STROS	-	-	26R/27

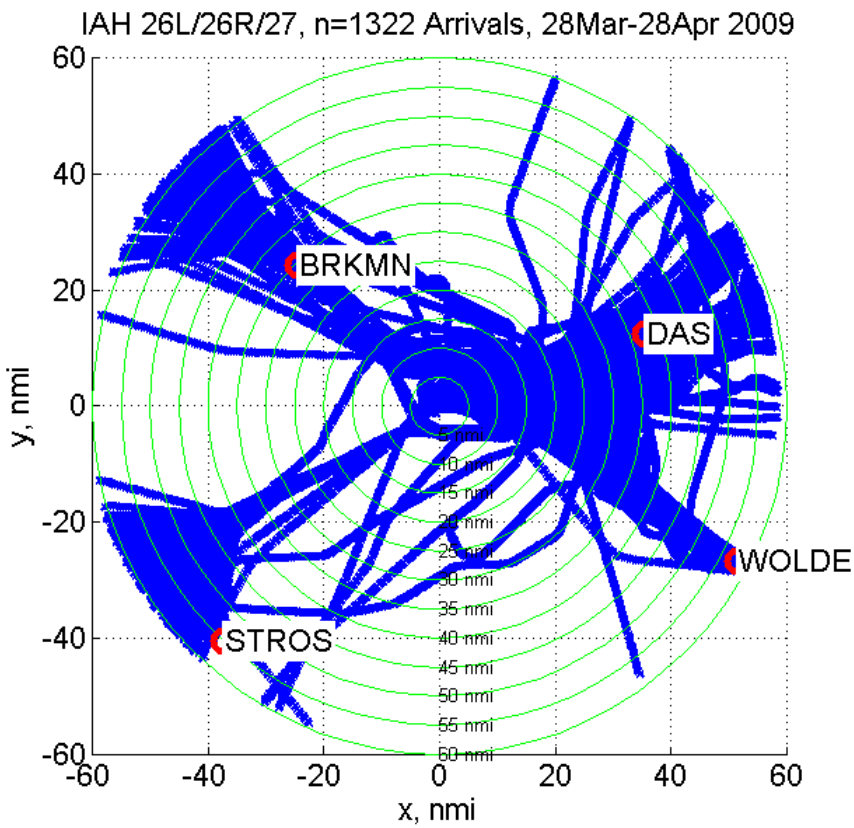

Figure 92. Arrival Flows and Modeled Entry Points for IAH arrival runways 26L, 26R, 27.

Table 278: Meter Fix Separation and route and meter fix usage percentages for IAH 26L, 26R, 27.

Meter Fix	26L%	26R%	27%	Total %	Observed Separation (nmi)
BRKMN	12.52%	5.31%	3.36%	21.19%	7 nmi
DAS	27.96%	3.93%	15.23%	47.13%	5 nmi
STROS	2.53%	0.35%	12.66%	15.54%	10 nmi
WOLDE	2.57%	0.15%	13.43%	16.15%	8 nmi

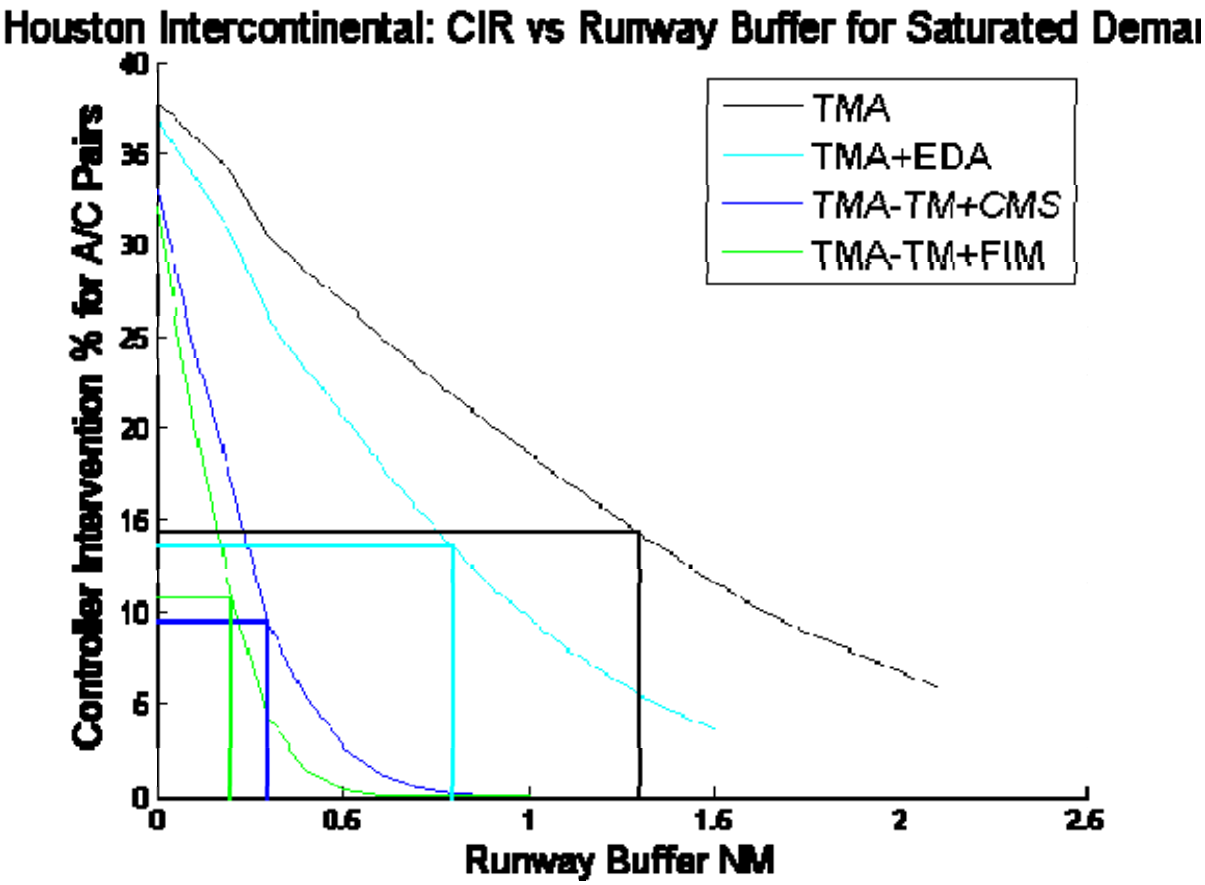

Figure 93: Controller Intervention Rate versus Runway Buffer for every C&T at IAH 26L, 26R, and 27.

Table 279: Potential arrival throughput capacity for IAH 26L, 26R, 27 given the CIR analysis and resulting meter fix and runway buffers.

Concept and Technology	Throughput Capacity (ac/hr)	Percentage of Theoretical Max	Runway Buffer (nmi)	Meter Fix Separation (nmi)
TMA only	107	71%	1.3	(7, 5, 10, 8)
TMA+EDA	120	80%	0.8	(6, 5, 8, 7)
TMA-TM+CMS	139	93%	0.3	(7, 5, 10, 8)
TMA-TM+CMS+EDA	137	91%	0.3	(6, 5, 8, 7)
TMA-TM+FIM	140	93%	0.2	(6, 5, 8, 7)
Theoretical Max	150	100%	0	(5, 5, 5, 5)

B.3.2. Arrival Runways 8L, 8R, 9 Configuration

Table 280: All identified routes for IAH arrival runways 8L, 8R, 9.

Meter Fix	Merge Point	Merge Point	Runway
DAS	-	-	8L/8R
BRKMN	-	-	8L/8R
STROS	-	-	8R
WOLDE	-	-	8R

We estimated IAH arrival routes based on analysis of ASDE-X system-derived arrival flight trajectory data from 28 March to 28 April 2009. None of the analyzed arrival trajectories was estimated to land to IAH runway 9 during this time period, hampering our ability to estimate the coupling of arrival fixes with runway 9, or merge point locations among those traffic flows. Thus, we modeled only IAH arrival runways 8L/8R.

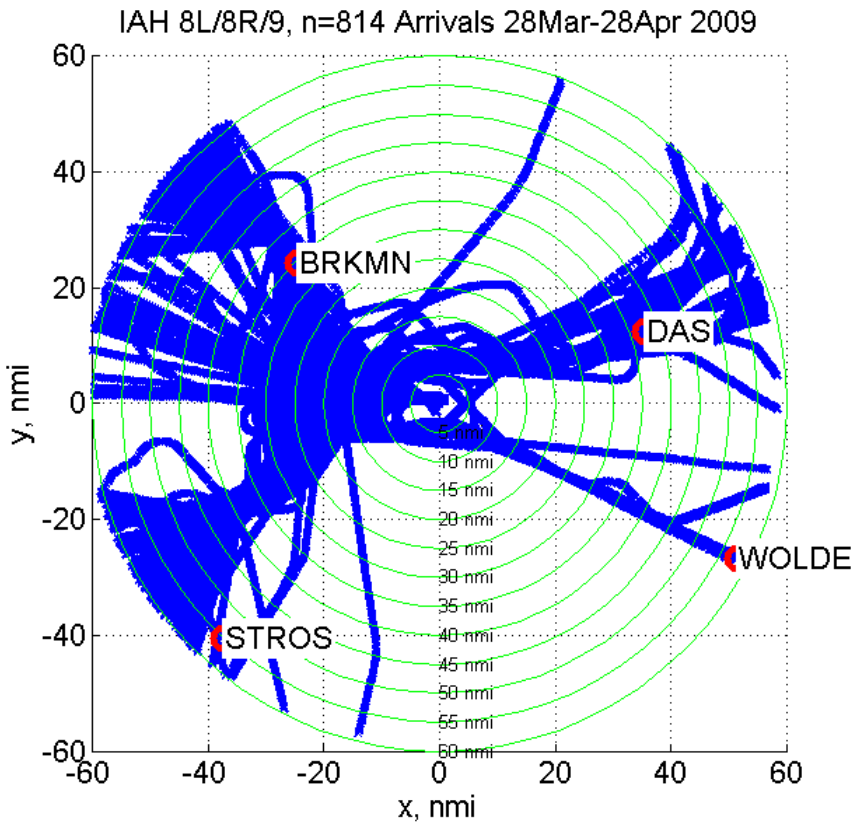

Figure 94. Arrival Flows and Modeled Entry Points for IAH arrival runways 8L, 8R.

Table 281: Meter Fix Separation and route and meter fix usage percentages for IAH 8L, 8R, 9.

Meter Fix	08L%	08R%	9%	Total %	Observed Separation (nmi)
BRKMN	19.49%	27.25%	0.00%	46.74%	5 nmi
DAS	15.01%	7.14%	0.00%	22.15%	5 nmi
STROS	0.36%	17.62%	0.00%	17.99%	10 nmi
WOLDE	0.77%	12.36%	0.00%	13.13%	9 nmi

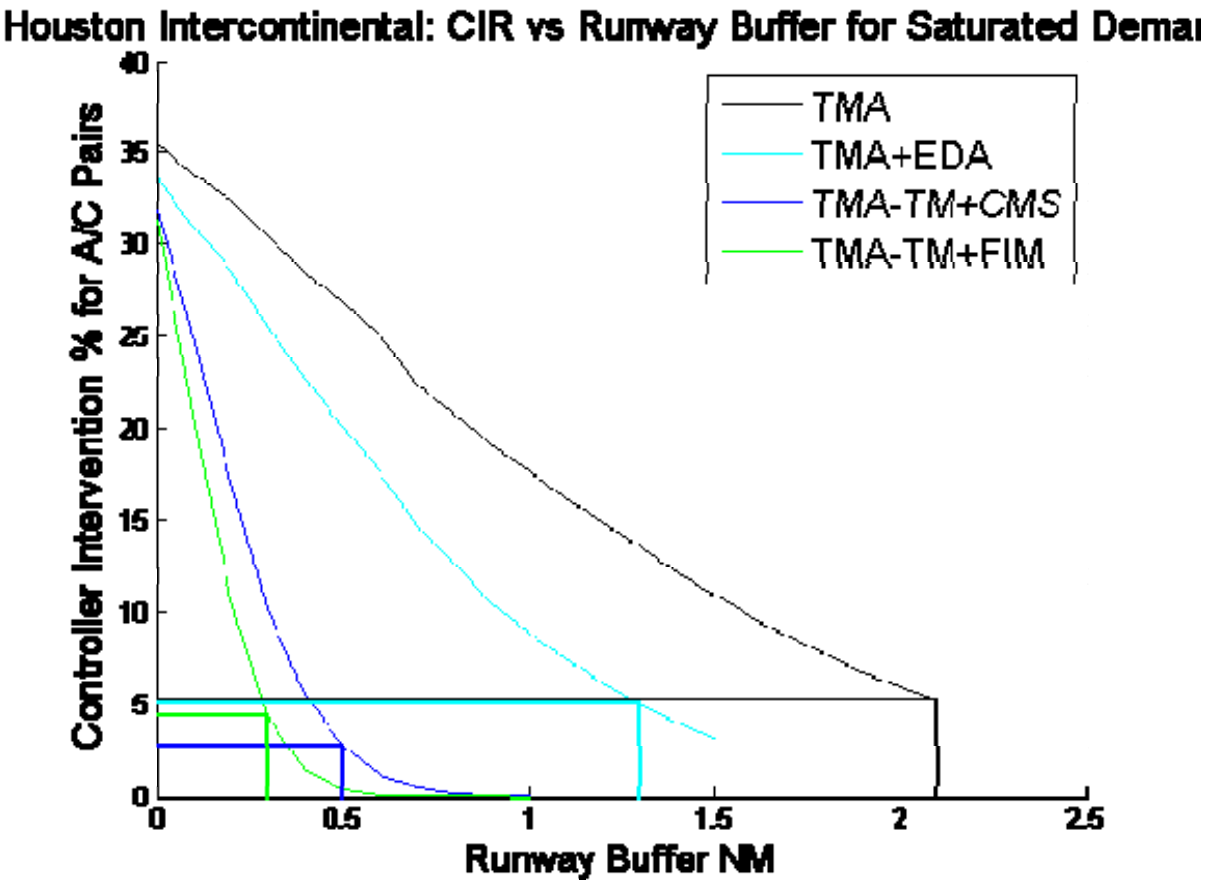

Figure 95: Controller Intervention Rate versus Runway Buffer for every C&T at IAH 8L, and 8R.

Table 282: Potential arrival throughput capacity for IAH 8L, 8R given the CIR analysis and resulting meter fix and runway buffers.

Concept and Technology	Throughput Capacity (ac/hr)	Percentage of Theoretical Max	Runway Buffer (nmi)	Meter Fix Separation (nmi)
TMA only	75	74%	1	(5, 8, 10, 9)
TMA+EDA	80	80%	0.7	(5, 7, 8, 7)
TMA-TM+CMS	92	91%	0.2	(5, 8, 10, 9)
TMA-TM+CMS+EDA	93	92%	0.2	(5, 7, 8, 7)
TMA-TM+FIM	92	91%	0.2	(5, 7, 7, 7)
Theoretical Max	100	100%	0	(5, 5, 5, 5)

B.4. Las Vegas McCarran International Airport (LAS)

B.4.1. Arrival Runways 19R, 25L Configuration

Table 283: All identified routes for LAS arrival runways 19R, 25L.

Meter Fix	Merge Point	Merge Point	Runway
FYTTR	IPUMY	-	19R
FYTTR	-	-	25L
CLARR	-	-	19R
CLARR	IPUMY	-	25L
KADDY	POKRR	-	19R
KADDY	TIFFY	-	25L
LUXOR	-	-	19R
LUXOR	POKRR	TIFFY	25L

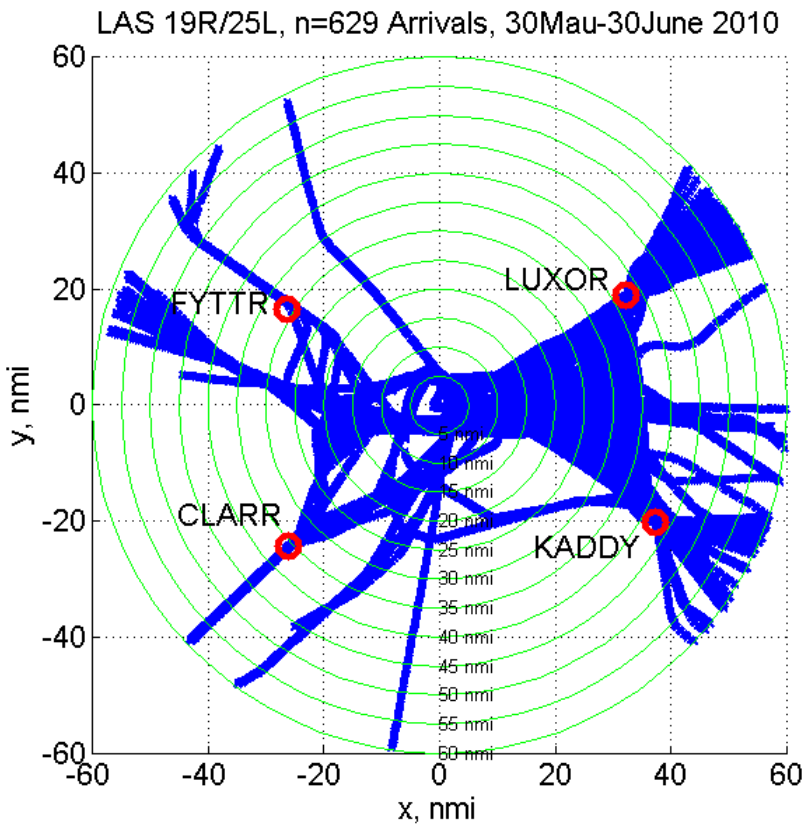

Figure 96. Arrival Flows and Modeled Arrival Fixes for LAS arrival runways 19R, 25L.

As indicated in the figure above, arrival fix FYTTR serves to model two parallel LAS arrival traffic flows via the northeast. This is a limitation in modeling different LAS arrival runway configurations with a common set of arrival fixes.

Table 284: Meter Fix Separation and route and meter fix usage percentages for LAS 19R, 25L.

Meter Fix	19R%	25L%	Total %	Observed Separation (nmi)
CLARR	3.52%	10.91%	14.43%	12 nmi
FYTTR	4.16%	14.11%	18.27%	9 nmi
KADDY	1.95%	28.59%	30.54%	9 nmi
LUXOR	3.29%	33.47%	36.75%	5 nmi

Table 285: Dependent runway timing matrix for LAS 19R leading and 25L trailing.

19R Leading, 25L Trailing				
Time (seconds) (Leading/Trailing)	H	B757	L	S
H	19.02	19.02	19.02	19.02
B757	19.02	19.02	19.02	19.02
L	19.02	19.02	19.03	19.02
S	19.02	19.02	19.02	19.02

Table 286: Dependent runway timing matrix for LAS 25L leading and 19R trailing.

25L Leading, 19R Trailing				
Time (seconds) (Leading/Trailing)	H	B757	L	S
H	20.36	20.36	20.36	20.36
B757	20.36	20.36	20.36	20.36
L	20.36	20.36	19.06	20.36
S	20.36	20.36	20.36	20.36

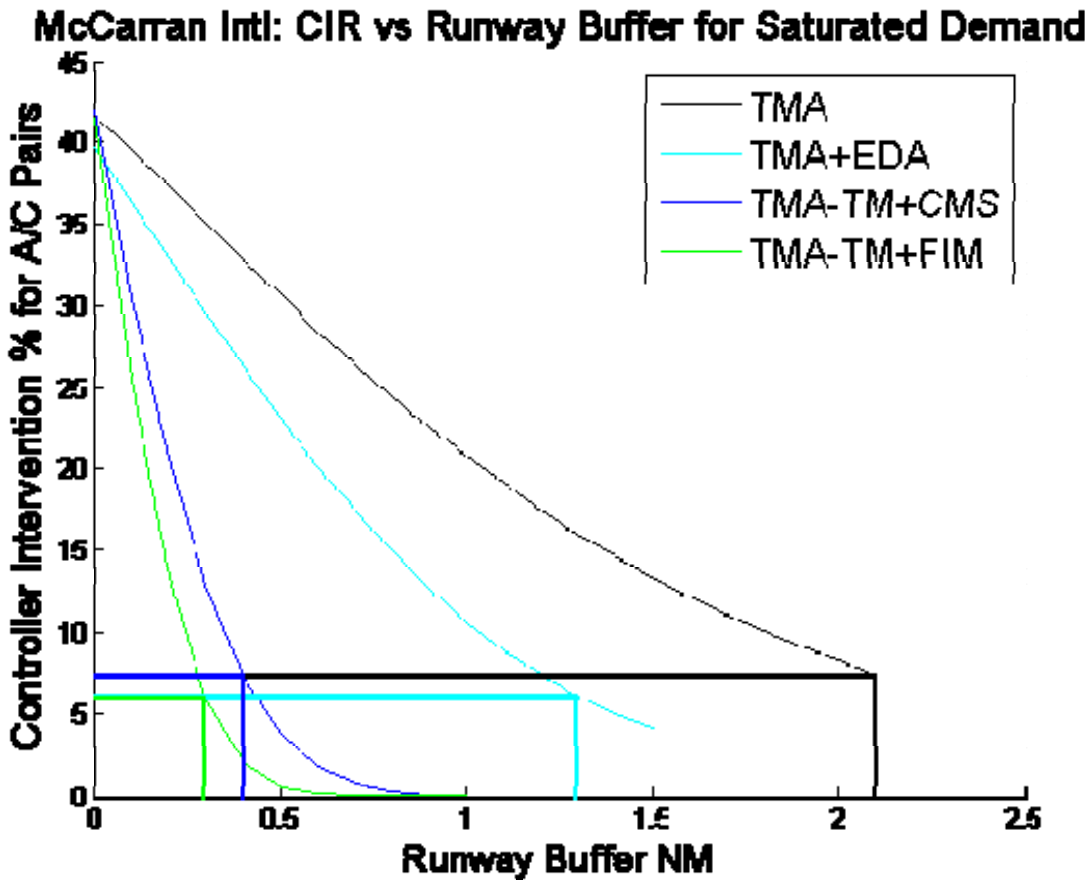

Figure 97: Controller Intervention Rate versus Runway Buffer for every C&T at LAS 19R and 25L.

Table 287: Potential arrival throughput capacity for LAS 19R, 25L given the CIR analysis and resulting meter fix and runway buffers.

Concept and Technology	Throughput Capacity (ac/hr)	Percentage of Theoretical Max	Runway Buffer (nmi)	Meter Fix Separation (nmi)
TMA only	61	58%	2.1	(12, 9, 9, 5)
TMA+EDA	72	68%	1.3	(9, 7, 7, 5)
TMA-TM+CMS	84	80%	0.4	(12, 9, 9, 5)
TMA-TM+CMS+EDA	85	80%	0.4	(9, 7, 7, 5)
TMA-TM+FIM	85	81%	0.3	(8, 7, 7, 5)
Theoretical Max	105	100%	0	(5, 5, 5, 5)

B.4.2. Arrival Runways 1L, 25L Configuration

Table 288: All identified routes for LAS arrival runways 1L, 25L.

Meter Fix	Merge Point	Merge Point	Runway
FYTTR	-	-	1L, 25L
CLARR	DAWNI	-	1L
CLARR	-	-	25L
KADDY	DAWNI	-	1L
KADDY	TIFFY	-	25L
LUXOR	-	-	1L
LUXOR	TIFFY	-	25L

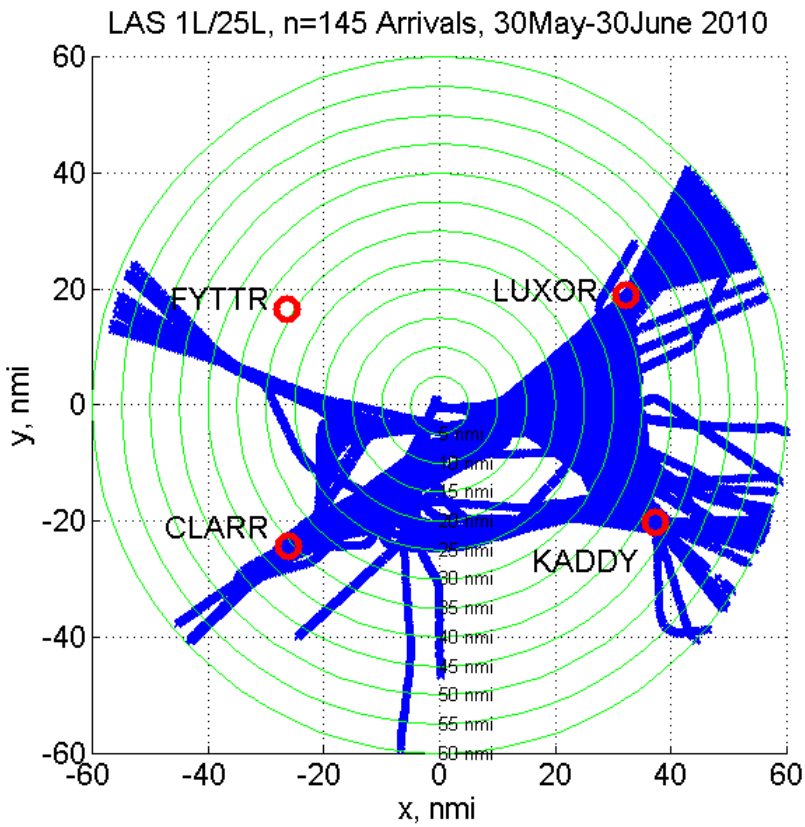

Figure 98. Arrival Flows and Modeled Arrival Fixes for LAS arrival runways 1L, 25L.

As indicated in the figure above, actual LAS arrival traffic flows via the northeast are laterally displaced from modeled arrival fix FYTTR. This is a limitation in modeling different LAS arrival runway configurations with a common set of arrival fixes.

Table 289: Meter Fix Separation and route and meter fix usage percentages for LAS 1L, 25L.

Meter Fix	01L%	25L%	Total %	Observed Separation (nmi)
CLARR	4.79%	11.47%	16.26%	6 nmi
FYTTR	2.24%	14.84%	17.08%	11 nmi
KADDY	1.10%	30.07%	31.17%	9 nmi
LUXOR	0.28%	35.20%	35.48%	5 nmi

Table 290: Dependent runway timing matrix for LAS 1L leading and 25L trailing.

1L Leading, 25L Trailing				
Time (seconds) (Leading/Trailing)	**H**	**B757**	**L**	**S**
H	44.40	44.40	44.40	44.40
B757	44.40	44.40	44.40	44.40
L	44.40	59.59	42.53	44.40
S	44.40	44.40	9.70	44.40

Table 291: Dependent runway timing matrix for LAS 25L leading and 1L trailing.

25L Leading, 1L Trailing				
Time (seconds) (Leading/Trailing)	**H**	**B757**	**L**	**S**
H	21.59	21.59	21.59	21.59
B757	21.59	21.59	21.59	21.59
L	21.59	24.87	6.08	3.87
S	21.59	21.59	26.20	21.59

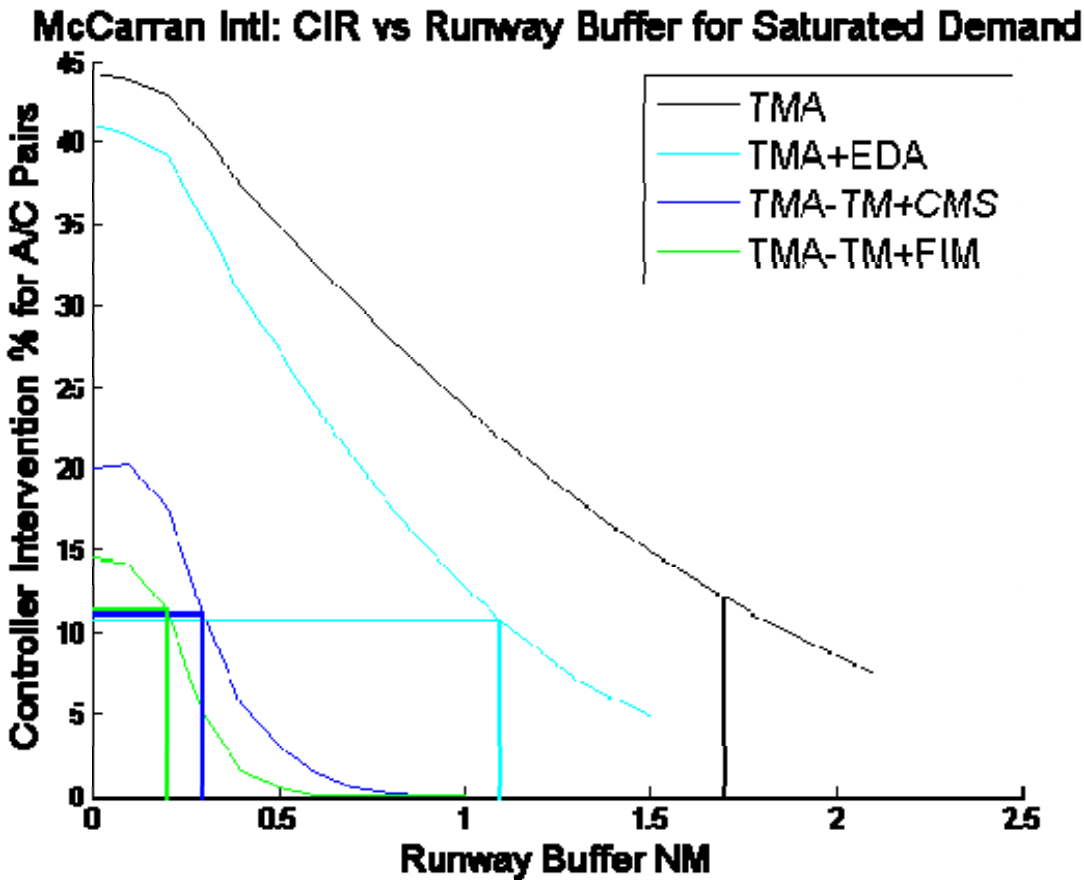

Figure 99: Controller Intervention Rate versus Runway Buffer for every C&T at 1L and 25L.

Table 292: Potential arrival throughput capacity for LAS 1L, 25L given the CIR analysis and resulting meter fix and runway buffers.

Concept and Technology	Throughput Capacity (ac/hr)	Percentage of Theoretical Max	Runway Buffer (nmi)	Meter Fix Separation (nmi)
TMA only	68	68%	1.7	(6, 11, 9, 5)
TMA+EDA	77	77%	1.1	(6, 8, 7, 5)
TMA-TM+CMS	94	94%	0.3	(6, 11, 9, 5)
TMA-TM+CMS+EDA	95	95%	0.3	(6, 8, 7, 5)
TMA-TM+FIM	97	97%	0.2	(5, 8, 7, 5)
Theoretical Max	100	100%	0	(5, 5, 5, 5)

B.4.3. Arrival Runways 7R, 19R Configuration

Table 293: All identified routes for LAS arrival runways 7R, 19R.

Meter Fix	Merge Point	Merge Point	Runway
FYTTR	-	-	07R, 19R
CLARR	-	-	07R
CLARR	-	-	19R
KADDY	-	-	07R
KADDY	-	-	19R
LUXOR	-	-	07R, 19R

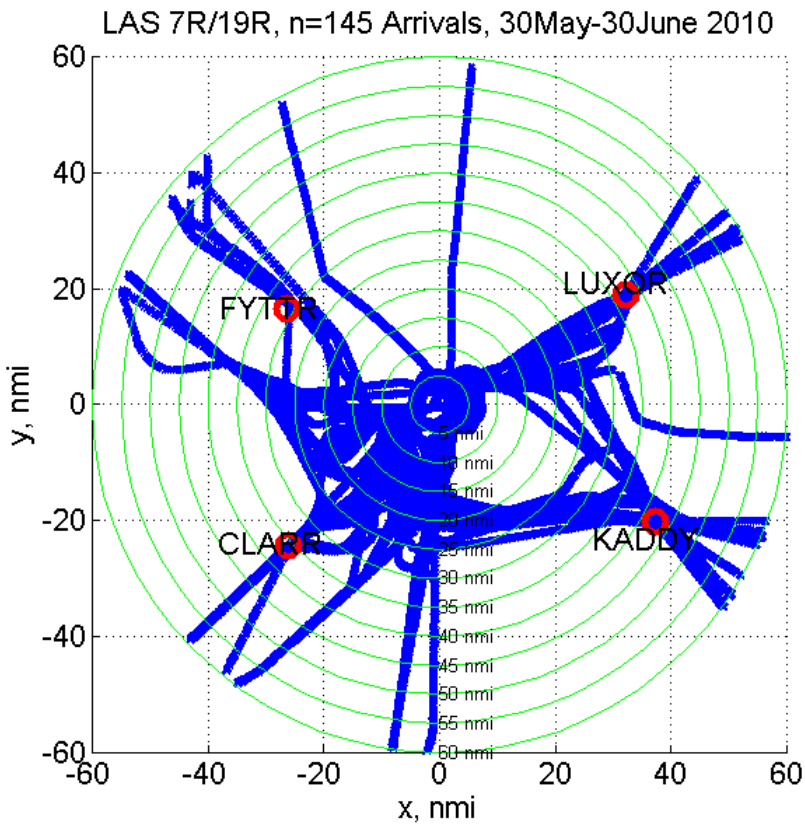

Figure 100. Arrival Flows and Modeled Arrival Fixes for LAS arrival runways 7R, 19R.

Table 294: Meter Fix Separation and route and meter fix usage percentages for LAS 7R, 19R.

Meter Fix	07R%	19R%	Total %	Observed Separation (nmi)
CLARR	8.92%	15.23%	24.14%	11 nmi
FYTTR	17.90%	17.97%	35.87%	5 nmi
KADDY	16.19%	8.44%	24.62%	9 nmi
LUXOR	1.17%	14.20%	15.36%	12 nmi

Table 295: Dependent runway timing matrix for LAS 7R leading and 19R trailing.

7R Leading, 19R Trailing				
Time (seconds) (Leading/Trailing)	**H**	**B757**	**L**	**S**
H	82.72	82.72	82.72	82.72
B757	82.72	82.72	82.72	82.72
L	82.72	82.72	82.72	82.72
S	82.72	82.72	82.72	82.72

Table 296: Dependent runway timing matrix for LAS 19R leading and 7R trailing.

19R Leading, 7R Trailing				
Time (seconds) (Leading/Trailing)	**H**	**B757**	**L**	**S**
H	7.77	7.77	7.77	7.77
B757	7.77	7.77	7.77	7.77
L	7.77	7.77	7.77	7.77
S	7.77	7.77	7.77	7.77

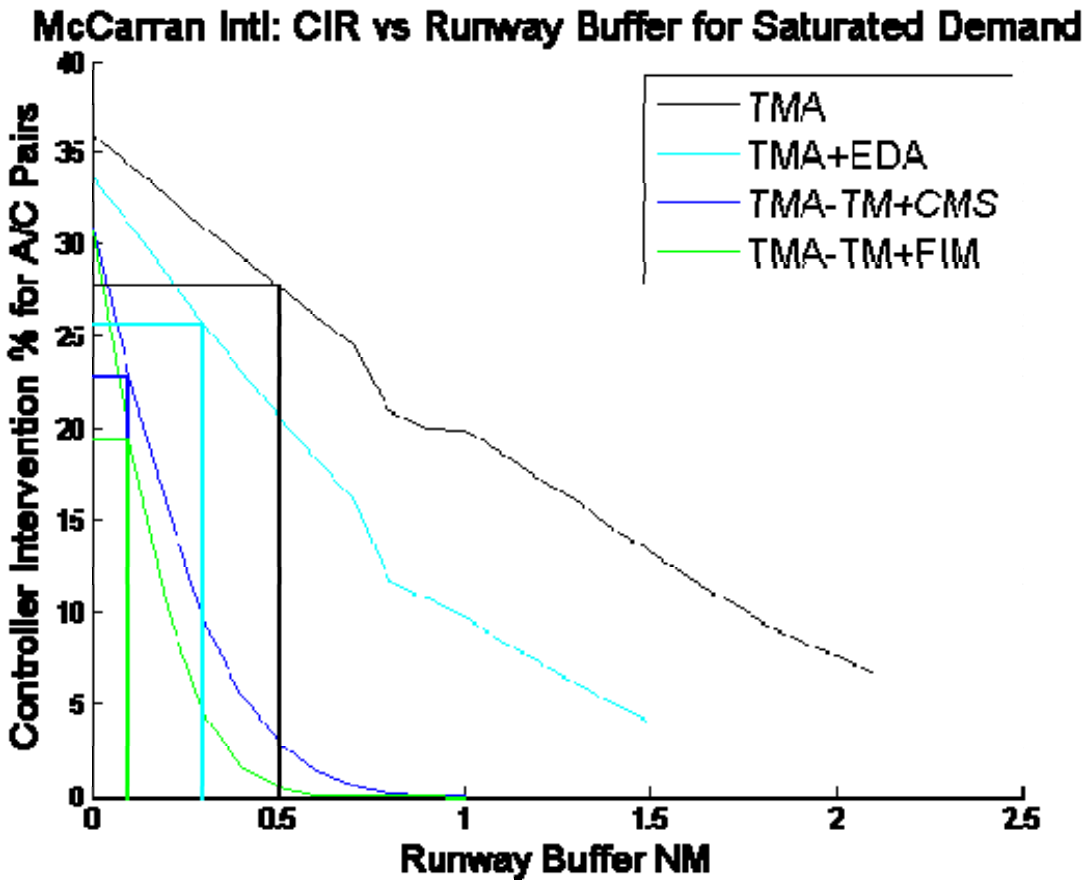

Figure 101: Controller Intervention Rate versus Runway Buffer for every C&T at LAS 7R and 19R.

Table 297: Potential arrival throughput capacity for LAS 7R, 19R given the CIR analysis and resulting meter fix and runway buffers.

Concept and Technology	Throughput Capacity (ac/hr)	Percentage of Theoretical Max	Runway Buffer (nmi)	Meter Fix Separation (nmi)
TMA only	59	91%	0.5	(11, 5, 9, 12)
TMA+EDA	62	96%	0.3	(8, 5, 7, 8)
TMA-TM+CMS	63	98%	0.1	(11, 5, 9, 12)
TMA-TM+CMS+EDA	63	98%	0.1	(8, 5, 7, 8)
TMA-TM+FIM	63	98%	0.1	(8, 5, 7, 8)
Theoretical Max	64	100%	0	(5, 5, 5, 5)

B.5. Phoenix Sky Harbor International Airport (PHX)

B.5.1. Arrival Runways 25L, 26 Configuration

Table 298: All identified routes for PHX arrival runways 25L, 26.

Meter Fix	Merge Point	Merge Point	Runway
DBACK	ZAMEX	-	25L
DBACK	-	-	26
ARLIN	-	-	25L
ARLIN	ZAMEX	-	26
BRUSR	-	-	25L/26
SUNSS	ZAMEX	-	25L
SUNSS	ZAMEX	-	26

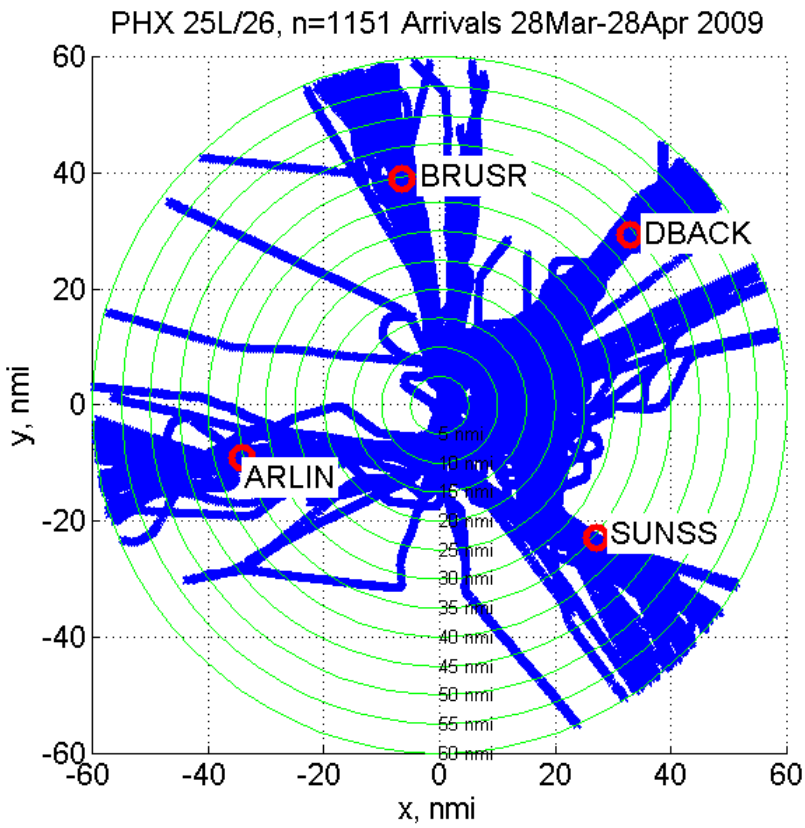

Figure 102. Arrival Flows and Modeled Arrival Fixes for PHX arrival runways 25L, 26.

Table 299: Meter Fix Separation and route and meter fix usage percentages for PHX 25L, 26.

Meter Fix	25L%	26%	Total %	Observed Separation (nmi)
ARLIN	12.87%	2.56%	15.43%	9 nmi
BRUSR	2.45%	15.58%	18.04%	7 nmi
DBACK	3.07%	27.12%	30.19%	8 nmi
SUNSS	21.04%	15.30%	36.35%	5 nmi

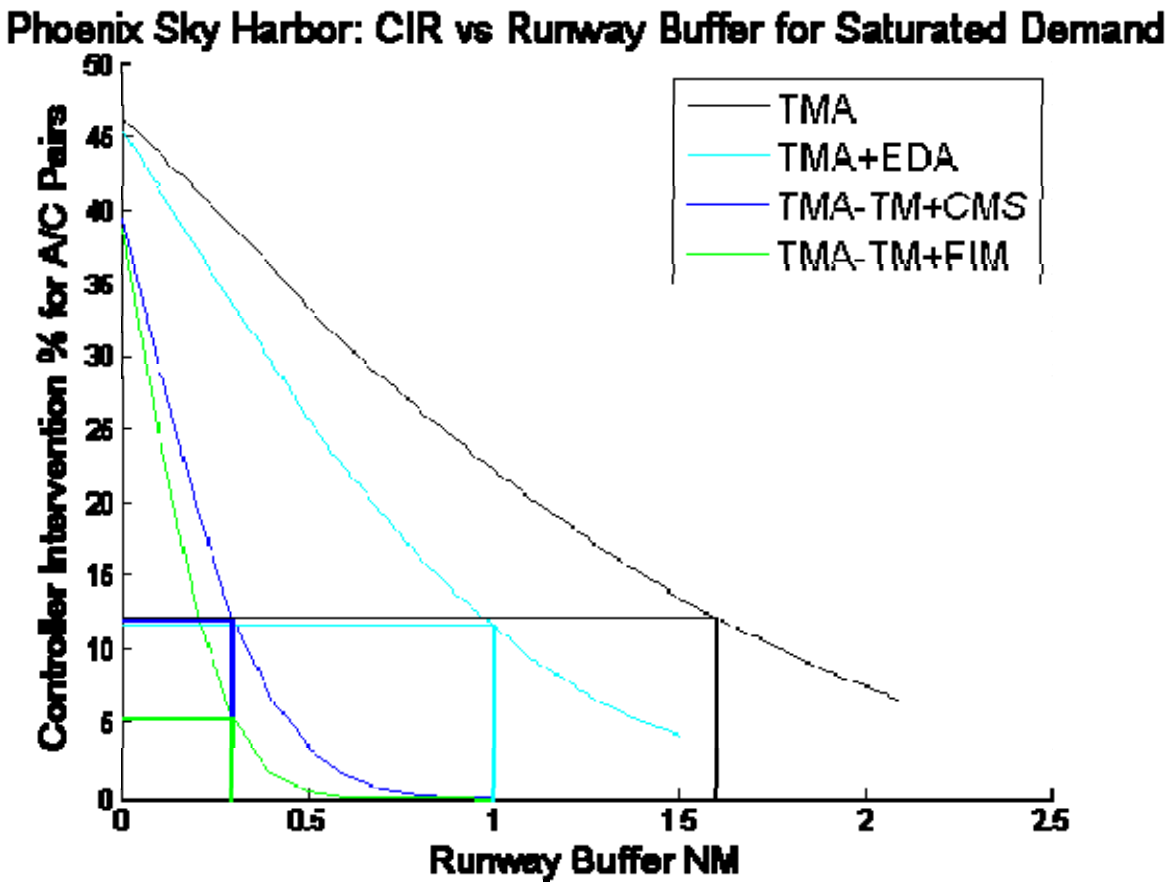

Figure 103: Controller Intervention Rate versus Runway Buffer for every C&T at PHX 25L and 26.

Table 300: Potential arrival throughput capacity for PHX 25L, 26 given the CIR analysis and resulting meter fix and runway buffers.

Concept and Technology	Throughput Capacity (ac/hr)	Percentage of Theoretical Max	Runway Buffer (nmi)	Meter Fix Separation (nmi)
TMA only	76	77%	0.9	(9, 7, 8, 5)
TMA+EDA	82	83%	0.6	(7, 6, 7, 5)
TMA-TM+CMS	92	93%	0.2	(9, 7, 8, 5)
TMA-TM+CMS+EDA	92	93%	0.2	(7, 6, 7, 5)
TMA-TM+FIM	95	96%	0.1	(7, 6, 7, 5)
Theoretical Max	99	100%	0	(5, 5, 5, 5)

B.5.2. Arrival Runways 7R, 8 Configuration

Table 301: All identified routes for PHX arrival runways 7R, 8.

Meter Fix	Merge Point	Merge Point	Runway
ARLIN	-	-	7R
ARLIN	ZINGA	-	8
BRUSR	-	-	7R
BRUSR	ZINGA	-	8
DBACK	ZINGA	-	7R
DBACK	-	-	8
SUNSS	-	-	7R
SUNSS	ZINGA	-	8

Table 302: Meter Fix Separation and route and meter fix usage percentages for PHX 7R, 8.

Meter Fix	07R%	8%	Total %	Observed Separation (nmi)
ARLIN	21.74%	8.12%	29.87%	5 nmi
BRUSR	2.02%	18.98%	21.00%	8 nmi
DBACK	2.76%	31.21%	33.97%	7 nmi
SUNSS	11.44%	3.71%	15.16%	8 nmi

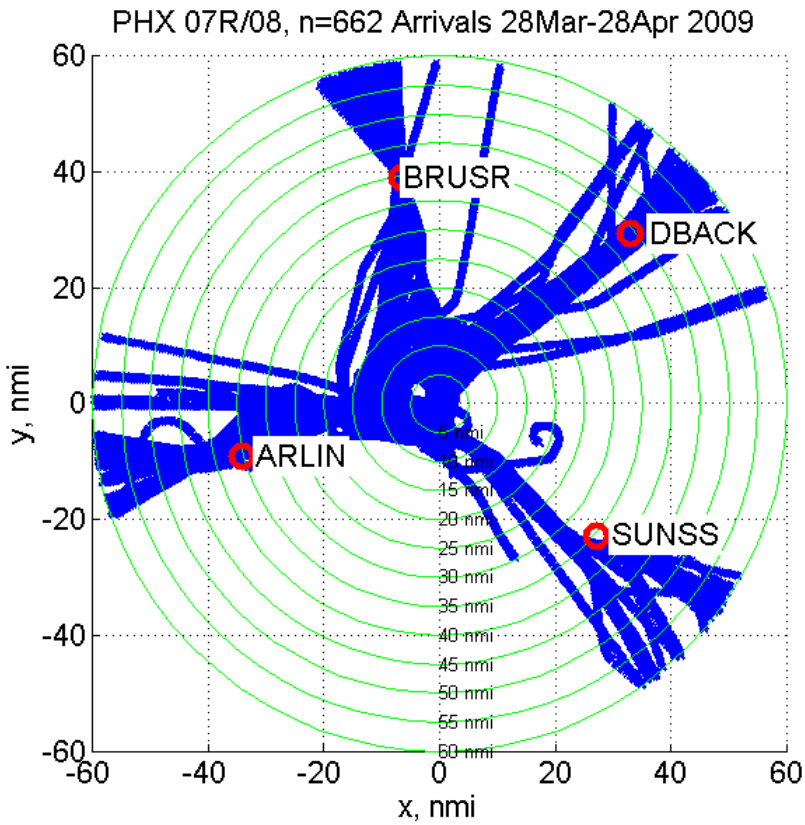

Figure 104. Arrival Flows and Modeled Arrival Fixes for PHX arrival runways 07R, 08.

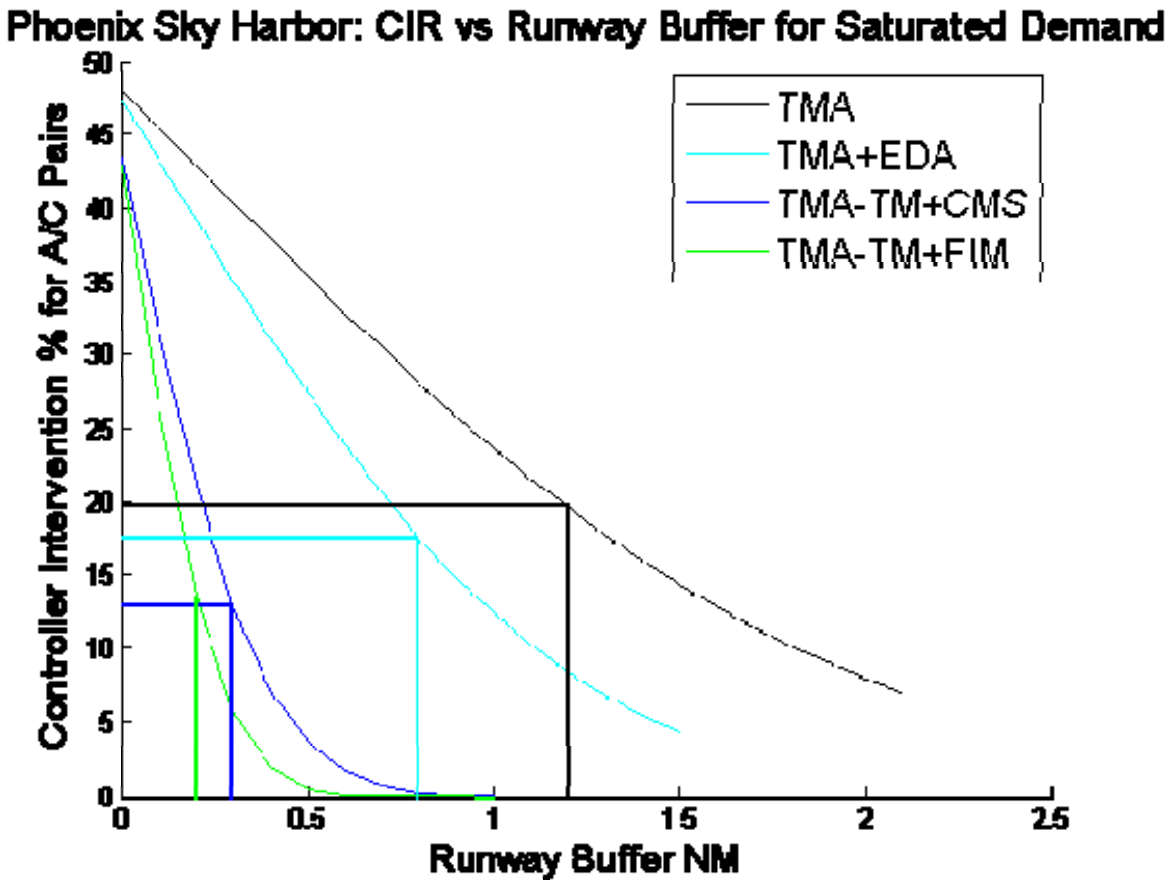

Figure 105: Controller Intervention Rate versus Runway Buffer for every C&T at PHX 7R and 8.

Table 303: Potential arrival throughput capacity for PHX 7R, 8 given the CIR analysis and resulting meter fix and runway buffers.

Concept and Technology	Throughput Capacity (ac/hr)	Percentage of Theoretical Max	Runway Buffer (nmi)	Meter Fix Separation (nmi)
TMA only	72	71%	1.2	(5, 8, 7, 8)
TMA+EDA	79	77%	0.8	(5, 6, 6, 6)
TMA-TM+CMS	93	91%	0.3	(5, 8, 7, 8)
TMA-TM+CMS+EDA	93	91%	0.3	(5, 6, 6, 6)
TMA-TM+FIM	95	93%	0.2	(5, 6, 6, 6)
Theoretical Max	102	100%	0	(5, 5, 5, 5)