Automated Integration of Arrival/Departure Schedules

Paul Diffenderfer, Zheng Tao, and Gaea Payton
Center for Advanced Aviation System Development
The MITRE Corporation
McLean, Virginia, U.S.A.
[diffenderfer, ztao, gpayton]@mitre.org

Abstract— At airports where there is a dependency between arrival and departure operations, existing procedures often result in inefficient coordination between the arriving and departing flights, compromising airport throughput. With two key changes the throughput can be improved without affecting safety: integrating the arrival and departure streams and increasing communication between the Tower and the Terminal Radar Approach Control (TRACON). The airports include those that conduct arrival and departure operations to crossing or converging runways, or conduct same runway operations such as Ronald Reagan Washington National Airport (KDCA) or London's Gatwick Airport (EGKK). Typically at these types of airports, a static interval is set between arriving flights so that the airport's Tower Controller can depart aircraft in the gaps. The static interval is maintained even without any waiting departures and is usually adjusted only with verbal coordination between the Tower and TRACON. At these airports, throughput can be improved by providing dynamic spacing guidance to Approach Controllers that accounts for the departure queue.

The MITRE Corporation's Center for Advanced Aviation System Development (CAASD) is investigating methods to provide automated arrival spacing guidance. A research prototype called the Automated Integration of Arrival/Departure Schedules provides automated arrival spacing guidance for Approach Controllers. The guidance communicates arrival intervals depending on the type and order of departure aircraft queued at or taxiing to the dependent runway. It provides an indication to use minimum arrival spacing when there are no queued departures. MITRE has conducted fast-time and Human-in-the-Loop (HITL) simulations to assess the feasibility of this solution in terms of adherence to spacing guidance and workload impacts. Controllers achieved a high level of conformance to guidance and workload levels were within a safe range. This paper reviews the shortfalls of relevant current operations, the proposed solution and prototype, and presents preliminary results of MITRE's simulation.

Keywords- decision support tools; arrival and departure operations;final approach spacing; slot markers

I. INTRODUCTION

One area of focus for both the Federal Aviation Administration's (FAA) Next Generation Air Transportation System (NextGen) and the European Organisation for the Safety of Air Navigation's (EUROCONTROL) Single European Sky Air Traffic Management (ATM) Research (SESAR) [1] [2] is to improve arrival and departure operations at high density airports. The MITRE Corporation's (MITRE) Center for Advanced Aviation System Development (CAASD) is researching and developing future controller capabilities and concepts to help realize the benefits of NextGen operations in the Terminal Radar Approach Control (TRACON) and Tower. Arrival operations at major airports involve an Approach Controller in the TRACON directing arriving aircraft to a final approach course and a Tower Controller providing landing clearances to these aircraft. At some airports the Tower Controller is required to depart aircraft from the same runway or a crossing runway. Currently, the Approach Controller has little to no information available regarding what is happening on the airport surface such as the length of the departure queue or the number of taxiing aircraft. To address these issues, MITRE is developing an automated tool that aims to increase arrival and departure throughput by providing the Approach Controller relevant information about how the departure situation should affect arrival spacing, without the need for manual coordination.

Section II describes other relevant work designed to manage TRACON arrivals and relevant deficiencies associated within current TRACON spacing operations. Section III identifies the shortfalls in the current system. Section IV discusses the Automated Integration of Arrival/Departure Schedules concept in detail and describes the research prototype. The Human-in-the-Loop (HITL) simulation setup and design are described in Section V, and Section VI presents results from the HITL. The conclusions and future work are discussed in Sections VII and VIII respectively.

II. BACKGROUND

Providing integrated arrival and departure information to controllers has been explored in the past in implementations of Arrival Manager / Departure Manager (AMAN/DMAN). While there are many implementations of AMAN/DMAN [3] [4] [5], they all share the same goals. AMAN implementations try to optimize arrival flows through spacing, sequencing, speed, and altitude recommendations for each aircraft throughout the TRACON airspace. AMAN systems are separate systems and often not integrated into the controller's radar display. They typically require a separate display. A

standalone AMAN system does not account for departure demand. DMAN systems help manage departure flows to optimize throughput at runways and reduce hold times. This is accomplished by assigning runways, take off times, pushback times, sequences, and distributing delays while accounting for various constraints and preferences such as airport configuration and weather. Like AMAN, DMAN systems can operate as standalone systems. There are some implementations that integrate both AMAN and DMAN [4] systems to provide better predictability and more precise advisories.

Controller-Managed Spacing (CMS) was developed by the National Aeronautics and Space Administration (NASA) [6]. This set of tools is designed to integrate with Traffic Management Advisor with Terminal Metering (TMA-TM) [7] to provide precise time-based schedules from the edge of TRACON airspace down to the runways. CMS utilizes target circles called "slot markers" with speed advisories to show the controller where an aircraft should be if it were to fly the nominal arrival routes in order to meet a scheduled time of arrival (STA). Their use of the slot market is similar to this research in that aircraft need to be in the middle of the slot marker and the size of the slot marker shrinks with aircraft speed. However, their slot markets are displayed starting at the edge of TRACON airspace, and represent a sequence for a very specific approach trajectory. The CMS slot markers do not intend to give Approach Controllers the flexibility to perform vectoring or make sequencing decisions. Meeting the CMS slot markers is almost exclusively based on speed advisories, and there are issues with ripple effects when multiple slot markers are not met. The characteristics of CMS are designed to suit TMA-TM and are not applicable to same runway operations that this research focuses on. Because the focus of CMS is to support TMA-TM their slot markers do not factor in departure needs.

NASA's System Oriented Runway Management (SORM) [8] is another concept aimed at improving airport efficiency partly through arrival/departure runway scheduling and strategic assignment of runways based upon traffic demand. SORM is composed of strategic airport capacity planning, airport configuration management, and combined arrival/departure runway planning.

The Final Approach Spacing Tool (FAST) and its variations (Active-FAST (A-FAST) and Passive-FAST (pFAST)) [9] [10] are NASA developed decision support tools for TRACON Approach Controllers. These tools provide heading, speed, runway, turn, and sequence advisories to assist in sequencing and spacing of arrival aircraft down to the runways in order to meet scheduled times. However, the departure situation is not considered when providing guidance. Development on these specific tools has stopped in recent years, but many aspects have been integrated into the CMS research.

III.   CURRENT TRACON ARRIVAL SPACING DEFICIENCIES

Same or crossing runway arrival procedures often dictate a static spacing interval for all arrivals to ensure enough spacing to accommodate departures, even when there are no departures. This strategy is employed due to the practical limitation of the amount of verbal coordination possible between Approach and Tower controllers. For example, typical operations for same runway operations have the Approach Controller providing a static interval between all arriving aircraft (shown in Fig. 1), which is sufficient for most departures. If a departure requires more than the static spacing, the Tower Controller must coordinate with Approach Control and request additional spacing at a defined time. Hence, the requested spacing may not appear for several minutes due to coordination and planning inefficiencies. At airports where there is a dependency between arrival and departure operations, this leads to inefficiencies in two ways:

- Departure capacity may be lost or go unused due to insufficient arrival spacing

- Arrival capacity may be lost when arrival spacing is greater than required by the departure demand

Under current operations, additional arrival spacing is often provided when there are no aircraft waiting to depart. There is typically no attempt to reduce the spacing between arrivals unless there is an extended period without departures.
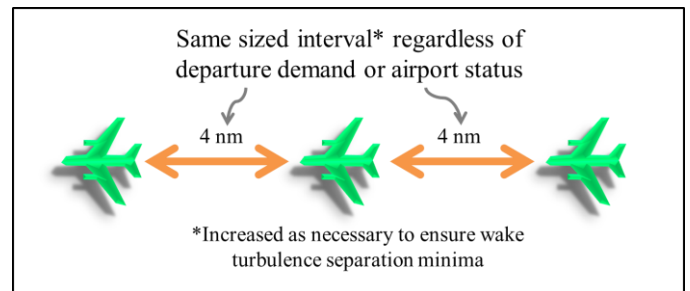

Figure 1. Static arrival spacing does not consider important factors.

A. Insufficient Spacing

A static interval does not account for the specific spacing requirements of each arrival/departure pair. For example, to accommodate a heavy weight class departure, a large weight class arrival should be spaced at least 4.2 nautical miles (NM) behind a previous arrival [11]. Static 4 NM spacing does not provide enough space, but if a slight increase in spacing is provided the heavy departure can depart without significant impact to arrivals. Also, there are situations where a little extra spacing between arrivals would allow for two departures. For example, if there are numerous departures waiting at the runway an incoming arrival pair could be spaced at 6 NM rather than 4 NM so that two aircraft could depart in that 6 NM interval. Manual coordination between the Tower and Approach Controllers is required to request the additional spacing. Sometimes the Approach Control supervisor has to coordinate this request with the Approach Controller. This manual process is inefficient and time consuming, which places a practical limitation on this type of coordination activity.

B. Excess Spacing

A departure requiring less than static 4 NM spacing (such as a Regional Jet (RJ) that only needs 3.7 NM [11]) would generate 0.3 NM of wasted spacing which, over time, accumulates to significant wasted spacing. A static 4 NM interval wastes 0.3 NM in this example, which would be better utilized to increase the spacing of the next arrival pair so that a heavy departure requiring 4.2 NM could depart quicker.

During periods when there are no departures waiting at the runway there is no need to maintain 4 NM arrival intervals, and only minimum spacing between arrivals is required. Regaining this excess spacing is invaluable during periods of high arrival volume to ensure that arrival throughput can be increased and the need to hold or delay arrival traffic is reduced.

IV. AUTOMATED INTEGRATION OF ARRIVAL/DEPARTURE SCHEDULES

Improving arrival and departure operations at high density airports is one focus area for NextGen. The operational improvement (OI) "Improved Management of Arrival/Surface/Departure Flow Operations" (OI-104117) [12] directly correlates with this research. To help address this OI, MITRE is developing a research prototype that provides Approach Controllers with the airport's departure situation using non-verbal methods. This tool has the potential to increase arrival and departure throughput for same runway and crossing runway operations by providing dynamic arrival aircraft spacing guidance to Approach Controllers. The automation enables an increase in throughput by analyzing the departure schedule and providing appropriate inter-arrival spacing guidance. The spacing algorithm employs a unique time-based interval that considers the runway occupancy time of the arrival and departure aircraft as well as the ground speed of the aircraft. This tool is not dependent upon specific weather conditions such as winds from a particular direction, cloud bases above a particular height, or Visual Meteorological Conditions (VMC). It is an all-weather capability.

In general, MITRE research falls in the Strategic Input and Service Analysis phase of the FAA's Idea to In-Service (I2I) process. If this research transitions into the FAA work program its placement in the I2I process is going to depend on the OIs it becomes tied to and where in turn, they are in the Portfolio Allocation process.

A. Concept Overview

The goal of the Automated Integration of Arrival/Departure Schedules is to contribute to the FAA's plan for NextGen by improving an airport's overall arrival and departure throughput. Future capabilities, such as the Terminal Flight Data Manager (TFDM) departure scheduling capabilities, propose a method to accurately model the departure schedule for each runway [13]. The Automated Integration of Arrival/Departure Schedules concept will leverage that knowledge to provide guidance to approach controllers to appropriately space arrival aircraft to maximize the efficiency of both the arrival and departure schedules. This concept analyzes outputs from TFDM's departure scheduling capability, determines the most efficient spacing for arrivals to accommodate the schedule, and provides specific spacing guidance to the Approach Controller for the affected runway.

The concept proposes to integrate the schedules of both the arrivals and departures to achieve an overall throughput gain. The basic goals of the concept revolve around these principles:

- Regain lost departure and arrival capacity by dynamically adjusting spacing guidance between arrivals to take into account the surface departure situation.

- Guidance is never mandatory, and must respond to the controller's actions.

- Safety must not be compromised

In the future, the departure plan will integrate the arrival spacing guidance in a more holistic fashion to facilitate operations such as arrive two, depart one; arrive one, depart two; and other variations.

B. Data Sources

The spacing guidance is based upon departure aircraft information derived from surface-based automation. This will come from a passive tool that uses surface surveillance to observe the position of aircraft in the departure queue and make assumptions as to the departure sequence. It will be enhanced by information entered into an electronic flight data management system such as TFDM, which will be used by tower controllers to sequence and schedule departures. TFDM models departure schedules based upon the movement of aircraft on the surface of the airport, inputs received from controllers via electronic flight data systems, and information from flight operators. The Automated Integration of Arrival/Departure Scheduler would use the surface departure schedule to determine and display the most efficient arrival interval to the Approach Controller.

C. Algorithm

To generate slots markers, the automation needs expected departure times and landing times. The automation analyzes the surface schedule of planned departures (provided by an external system/capability as mentioned in Section IV-B) to retrieve expected departure times. The analysis of arrival aircraft is broken down into two zones. Zone 1 is a large volume of airspace around the airport that the automation uses to sample arrival aircraft. Zone 2 is a much smaller area encompassing the final approach course. Both zones are site adaptable. If an aircraft is in the arrival zone (Zone 1) and its heading is within 120 degrees of the final approach course heading, an expected landing time is calculated using a generic landing speed profile for that weight class. The 120 degree heading implies that the aircraft are turning onto or facing the direction of the final and are intending to land.

The arrival and departure times are then compared. If a departure will be waiting at the runway during the time when an arriving aircraft is expected to land, the automation will convert the departure's time requirement (the time needed after the arrival would land and clear the runway in order to depart) into a spacing distance based on the arrival's current speed along the final. This spacing is used to place a location guidance target (displayed as a circle and hereafter referred to as a "slot marker") behind the arrival along the final approach course. These calculations are repeated for the next scheduled departure, and subsequent slot markers are generated based on the preceding slot marker's expected landing time. Once an arrival aircraft associates with (intercepts) a slot marker, the times and distances needed for the following arriving and departing aircraft are recalculated, and revised slot markers are placed behind the recently associated aircraft. If a departure is not scheduled to depart when an arriving aircraft lands and clears the runway, an indicator to provide minimum spacing is presented and no slot marker is generated.

D. Presentation of Guidance

The Approach Controller receives visual guidance cues on his display providing precise arrival spacing aimed at improving efficiency. The time-based guidance cues consist of slot markers on the final approach course that provide a "goal" location for each arrival. The controller's goal is to vector an aircraft to intercept the slot marker. The slot marker guidance is intended to enable the controller to achieve more precise aircraft spacing (+/- 7 seconds of precision) than current operations. The placement of the slot markers are based on the preceding arrival and represent the computed guidance distance behind that arrival to space the subsequent aircraft. The slot marker tracks along the final approach course maintaining the guidance distance from the lead aircraft and adapts to the lead aircraft's speed using a time-based algorithm. The algorithm accounts for the spacing required to accommodate departures as well as the spacing required behind the lead aircraft based on aircraft type and ground speed, which accounts for compression and factors in wind. If an aircraft successfully intercepts the slot marker, the slot marker is known to be in the *associated* state. If the aircraft moves ahead or behind the slot marker after being associated then the slot marker is in a *disassociated* state. A slot marker remains in an *unassociated* state until it is initially associated. These states drive subsequent slot marker behavior. At any time, if the slot marker intercept solution becomes too complicated or unachievable the controller may "reset" the slot markers to be based on a selected aircraft.

If there are no departures expected after an arrival lands, a minimum spacing indicator is displayed in the leading aircraft's datablock. This indicates to the controller that minimum spacing should be used behind that aircraft. A specific minimum distance is not specified because of variations depending on the weather conditions, traffic management initiatives, and the weight class of the leading and trailing aircraft [11]. Fig. 2 depicts the slot markers and minimum guidance in a scenario where adding a little extra spacing on the second and third arrival would allow two departures to

depart, and hence allow minimum spacing between the last two arrivals since there are no more departures.
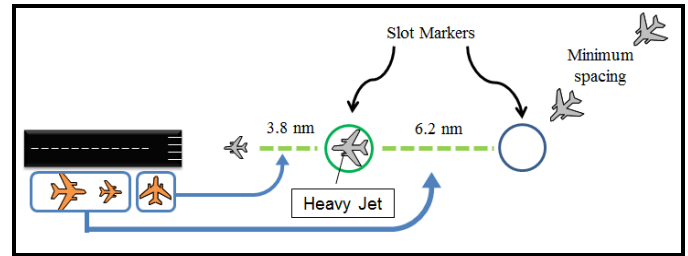

Figure 2. Depiction of concept with automation providing guidance through slot markers and minimum spacing, which allows for efficient departures.

E. Departure List

When the Approach Controller activates the slot marker guidance in the prototype, a "Departure List" is displayed on his radar display. This list provides relevant information about arrivals and departures on the runway and taxiways (Fig. 3). The list consists of three columns: Arrivals, Dep(arture) Queue, and Taxi. This list provides the Approach Controller with valuable situation awareness about aircraft on the surface and provides additional cues to aid the controller in determining when to expect departures and when there will not be aircraft waiting to depart.

Figure 3. Departure list depicting arrivals and departures.

The "Arrival" column indicates the current arrival queue as determined by the automation. This consists of arrival aircraft that are within Zone 1 and within 120 degrees of the final approach course heading. The "Dep Queue" column informs the controller where in the arrival sequence departures are expected to depart. These are the aircraft that will depart between the slot markers. Currently, the "Dep Queue" and "Taxi" columns only shows the aircraft type. The "Dep in Progress" notation indicates that the departure is currently departing and will be removed from the list once it is airborne. The aircraft in the "Taxi" column indicate those that are currently taxiing to the runway (in blue text) and have a blue slot marker generated for it. Aircraft in the "Taxi" column are always listed below the last arrival row to indicate that the exact relationship to the arrival stream is not known. Once an

arrival intercepts a blue slot marker, that associated departure will move into the "Dep Queue" column and be in the row between the arrival that intercepted the circle and the lead aircraft. For example, the first blue aircraft type in the "Taxi" column on the bottom right of Fig. 3 means that the first A319 is taxiing to the runway and has a slot marker representing it on the Approach Controller's display (not shown). Once an arrival (RPA3229) is vectored onto the slot marker, the first A319 in the taxi column would move into the departure column on the row between RPA3229 and AWI4080 to indicate that the first A319 should depart between them.

F. Comparision to Related Research

The Automated Integration of Arrival/Departure Schedules is distinctly different from AMAN/DMAN in several aspects. The focus of this research is only on the final approach course when considering arrivals whereas AMAN manages flights starting from the edge of TRACON airspace. The biggest difference is that the guidance provided by this research is integrated onto the Approach Controller's radar display, and does not require two separate systems to integrate arrival and departure information. The guidance gives the Approach Controller the flexibly to determine their own arrival sequence based upon other factors such as the presence of traffic from nearby airports. The automation provides spacing guidance to fit the controller's sequence and goals. The arrival spacing guidance takes into account the departure schedule to determine the spacing gap required in the arrival stream. Departure throughput is improved by providing spacing gaps in the arrival stream to accommodate scheduled departures. It does not issue any of the advisories to departure aircraft that DMAN does. In fact AMAN/DMAN can work alongside the Automated Integration of Arrival/Departure Schedules guidance.

The Automated Integration of Arrival/Departure Schedules research is complementary to the TMA-TM and CMS concepts. The CMS tools could provide spacing guidance to fixes on the downwinds or straight-in segment and the Automated Integration of Arrival/Departure Schedules could provide guidance from those fixes to the runway. The combination of NASA's and MITRE's research can provide tools to enable time-based operations at airports with a dependency between arrivals and departures.

The arrival/departure planning aspects of SORM are outside the scope of the Automated Integration of Arrival/Departure Schedules concept. The assumption in MITRE's research is that runway assignment is already decided through other means, which may include SORM's arrival/departure runway planning.

The variations of FAST guidance do not take into account the departure situation or the aspects of dependent runways, which is a key differentiator between FAST tools and this MITRE research. FAST tools do not allow much flexibility to control or sequence aircraft. MITRE's approach is to provide the targets (slot markers) and allow the controllers the freedom to meet them (or not) however they deem necessary.

V. HUMAN-IN-THE_LOOP (HITL) SIMULATIONS

A HITL simulation designed to evaluate the Automated Integration of Arrival/Departure Schedules concept was conducted at MITRE's Aviation Integration Demonstration and Experimentation for Aeronautics (IDEA) Laboratory in McLean, Virginia in December of 2012. The goal of the evaluation was to provide an initial validation that Air Traffic Control (ATC) personnel can vector aircraft to the slot markers and minimum spacing guidance, determine efficiency gains, and gauge workload impacts.

A. Research Hypothesis

The HITL simulation was designed to answer the following research questions related to the proposed concept for the application of arrival guidance at airports that conduct same runway operations. The research hypotheses are:

- Participants will vector accurately and "hit" slot markers

- Participants will reduce spacing when minimum spacing guidance is provided

- Presenting participants with slot markers will reduce overall participant workload

While optimizing spacing and throughput are also goals of the concept, the first priority is to determine if the concept of vectoring onto slot markers is feasible and what impacts it has on controller workload. Data from this HITL relating to spacing or throughput is useful, but the HITL's goal was not to optimize spacing or throughput.

B. Experimental Setup and Design

In this HITL simulation, participants included experienced ATC subjects from Potomac Consolidated TRACON (PCT), FAA Headquarters, retired controllers with radar experience, and MITRE subject matter experts with past radar control experience. There were nine participants with an average of 23.11 years of experience (*standard deviation (sd)* = 5.36). Participants were provided with a simulated Standard Terminal Automation Replacement System (STARS) display that simulated a modified version of the Mount Vernon sector in PCT airspace with flights arriving and departing on KDCA Runway 1. The participants were instructed to vector traffic from two downwind streams and one straight-in stream onto the Instrument Landing System (ILS) Runway 1 approach at KDCA. Several simulated pilots were used to manage arriving traffic voice communications through Push-to-talk (PTT) handheld radios. Traffic was scripted for each scenario containing challenging yet realistic amounts of arrival and departure traffic. There were two conditions tested during the HITL simulation:

- Without guidance (slot markers off)

- With guidance (slot markers on)

For each participant the HITL simulation took place over two days. The first day was dedicated to training and introducing the Automated Integration of Arrival/Departure Schedules concept. This included simulation time, wherein

participants completed three 30-minute scenarios without guidance to familiarize participants with the airspace. Each scenario contained aircraft from the three arrival streams to KDCA landing on the same runway as a variable length departure queue taxiing to or departing from the runway. The participants then completed three 30-minute scenarios with the guidance turned on wherein they operated by vectoring aircraft into the slot markers and complying with minimum spacing guidance. Traffic was simulated in all scenarios to provide a direct comparison for each traffic situation. The second day was dedicated to data collection and consisted of four scenarios without the guidance and four scenarios with guidance. All eight scenarios were 30 minutes long.

Heavy weight class aircraft were not included in any scenarios since that type does not operate at KDCA. Visual separation was not used. An automated Tower controller would depart aircraft at set intervals, and only when arrivals were at least 1.75 NM from the runway and 90 seconds had elapsed since the preceding departure. If both conditions were not true the departure would wait until the conditions were met.

All scenarios were counterbalanced in Latin Square format to reduce the effects of learning and fatigue. The scenarios generated followed four different traffic conditions.

- The first scenario (Scenario A) provided under each condition was a build-up scenario. This scenario started off with light downwind traffic then progressed to a high-workload combining double downwind traffic with straight-in traffic.

- The second condition (Scenario B) was randomized and consisted of varying single downwind with occasional straight-in traffic.

- The third condition (Scenario C) was randomized and consisted of double downwind with occasional straight-in traffic.

- The fourth condition (Scenario D) was randomized and consisted of double downwind with occasional straight-in traffic that was slightly more complicated than that of the third condition.

For the purposes of the HITL, the third line of the datablock showed the current distance between that aircraft and the preceding arrival ("4.68" in Fig. 4). This provided the participant improved situation awareness by displaying the current spacing in NM for the purpose of ensuring that the required arrival aircraft separation was maintained. This information was displayed in both modes, with and without slot marker guidance.

The participant also had the ability to turn on a Terminal Proximity Alert (TPA) cone of desired length in front of an aircraft (Fig. 4). The purpose of the TPA cone is to assist the participant in judging set distances. For example, during the *without guidance* condition where the participant was instructed to run a consistent 4 NM interval, they would occasionally opt to place a 4 NM TPA cone on an aircraft to help judge spacing.
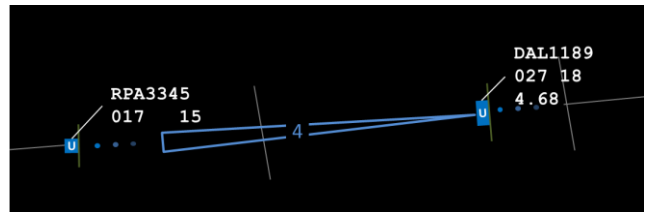

Figure 4. Current distance and TPA cone on aircraft.

An example of slot marker guidance is shown in Fig. 5. In this figure KDCA airport is at the top of the graphic with an aircraft on short final. The controller has successfully associated the next two aircraft with slot markers along the final approach course (green circles). The blue slot marker will turn green (associate) once the aircraft being vectored intercepts the slot marker.

Figure 5. Example of slot marker guidance.

C. Surveys

Before the second day of the HITL simulation, the participants completed a demographics form which indicated the participants' age, work history, and several fatigue factors. After each scenario the participants completed the NASA Task Load Index (NASA-TLX) [14] and the Situation Awareness Rating Technique (SART) [15]. The SART was used to evaluate situation awareness (SA) as it is a non-intrusive SA measure that is commonly used. While there are more effective objective measures of SA it was feared that these measure would too intrusive and impact user performance [16]. After the four scenarios without guidance participants completed a short debrief survey in addition to the NASA-TLX and SART which gauged their understanding of current operations and his/her view on how the system operated. After the four scenarios with guidance, in addition to the NASA-TLX and SART, participants completed an acceptance rating scale to rate their overall views on the use of slot markers, and a long survey with open-ended questions on their views of the slot markers and the functionality of the system. All participant survey data were analyzed.

VI.   HITL RESULTS

This section presents the results of the HITL conducted at MITRE to validate the Automated Integration of Arrival/Departure Schedules concept. This section is broken down into different areas that examine conformance to guidance, workload impacts, separation, and throughput.

A.   Conforming to Slot Marker Guidance

Conforming to slot marker guidance shows how successful the participants were in vectoring to the slot markers, and thus providing the required spacing to depart aircraft. An aircraft conformed to slot marker guidance if it associated with a slot marker at least once anywhere along the final. The aircraft may later disassociate or even re-associate due to compression, but the participant attempted to associate with the slot marker. If the aircraft was still within the slot marker circle as the leading aircraft landed then it was considered a "successful pair". If an aircraft fell behind the slot marker after it was associated, the guidance was still met since the required spacing for a departure was provided. The conformance to slot marker guidance is calculated as the number of aircraft associated at least once (which includes successful pairs) divided by the total number of aircraft presented with slot marker guidance. For the purpose of data analysis one participant's data was not used due to their unwillingness to utilize the guidance software consistently. All performance metrics are calculated with an N=8. The average conformance observed from the HITL ranges from 69% to 88% (Fig. 6). The high percentages show that participants were, on average, able to successfully meet most of the slot marker guidance with only a few hours of training.
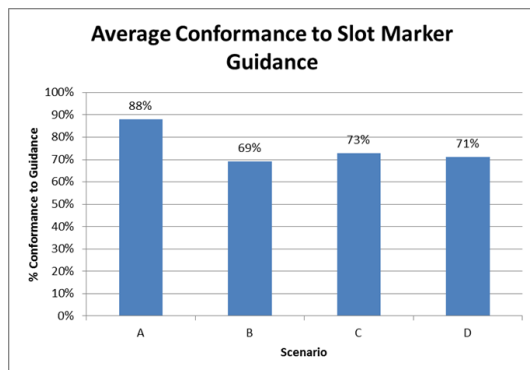

Figure 6. Average conformance to slot marker guidance.

Overall usage ratings were positive in that users felt that they could trust the guidance (*Mean (M)* = 3.60, *sd* =1.36) (see Table I). However, they did not necessarily feel that the guidance was improving their performance (*M* = 2.60, *sd* = 1.28).

TABLE I. USER ACCEPTANCE RATINGS ON A SCALE FROM 1-STRONGLY DISAGREE TO 5-STRONGLY AGREE (N = 9).

Rating	Responses
User Acceptance Rating	M = 3.68, *sd* = 1.23
Trust in guidance	M = 3.60, *sd* = 1.36
Reliance on guidance	M = 4.50, *sd* = 0.50
Confidence in using guidance	M = 4.00, *sd* = 0.63
Belief that guidance improved performance	M = 2.60, *sd* = 1.28

The participants' acceptance of the guidance display of slot markers indicated a moderate to high approval, although they did not feel that the guidance assisted them with vectoring aircraft into the slots (see Table II). The debrief survey indicated that all participants understood the concept and felt that their performance was good or very good. However, most of the participants (90%) did not like the slot markers as an indication of spacing. Participants wanted some type of spacing indicator, but wanted a more stable approach to achieving the required spacing. Currently the guidance indicators and algorithm are still at an early stage of development. These results may be an indication that with further development of the algorithm and slot marker indicators this technology may be beneficial in same runway operations. Participants felt that with further development this system would work well in air traffic facilities (80% agreement).

TABLE II. USER ACCEPTANCE RATINGS ON A SCALE FROM 1-STRONGLY DISAGREE TO 4-STRONGLY AGREE (N = 9).

Rating	Responses
Display Acceptance Rating	M = 3.04, *sd* = 0.66
Display provided enough information	M = 3.10, *sd* = 0.30
Display was easy to use	M = 2.90, *sd* = 0.83
Display was easy to understand	M = 3.20, *sd* = 0.60
Display made it easy to pick out information	M = 3.10, *sd* = 0.54
Made vectoring easy	M = 2.90, *sd* = 0.83

B.   Conformance to Minimum Spacing Guidance

Minimum spacing guidance was issued for arrivals when there were no planned departures. The minimum spacing goal was almost always 2.5 NM unless the leading aircraft was a B757, in which case it would be 4 NM. Participants aimed closer to 3.0-3.5 NM minimum separation on non-B757s in order to provide safety margin and to account for compression effects when nearing the runway. B757s appeared less than 5 times for each participant when guidance was used so it made up a small fraction of arrivals.

Participants found that this guidance allowed them to space the arrivals closer than they do in current operations and allowed them to fit extra arrivals in the arrival stream. When minimum spacing guidance was presented, the controller almost always took advantage of it by turning aircraft towards the final approach course earlier, increasing speed to close a gap, or a combination of both. However, minimum spacing was not always achieved due to the participant or automation resetting the guidance and then having the minimum spacing guidance appearing on an aircraft that had a very large gap between it and the lead aircraft. This gap was the result of the lack of traffic in the scenario design and was most apparent in Scenario A.

Feedback regarding minimum spacing guidance was positive and participants found it valuable to know when they could reduce arrival spacing. However, due to limitations in the algorithm, in most cases this guidance was displayed too late. As participants gained experience with the guidance they found that they could determine the need for minimum spacing before it was displayed in the datablock by examining the departure list. Participants were able to deduce upcoming

lulls in departure demand, and hence plan for minimum spacing earlier.

C. Workload

It is important to examine the consequences on human performance associated with any proposed new system. The NASA-TLX was administered after each scenario; two participants were unable to complete the NASA-TLX due to time constraints. Data analyzed with an N=70 administrations. A graph of the mean values for each component of workload was utilized in evaluating workload between scenarios (see Fig. 7). Fig. 7 shows that the workload was rated highest for scenarios 7 and 11 (shown as Mental, Effort, & Temporal WL). This was expected as scenario 7 and 11 were scenario A, the build-up scenario in which workload started off extremely easy and gradually increased to extreme difficulty by the end.
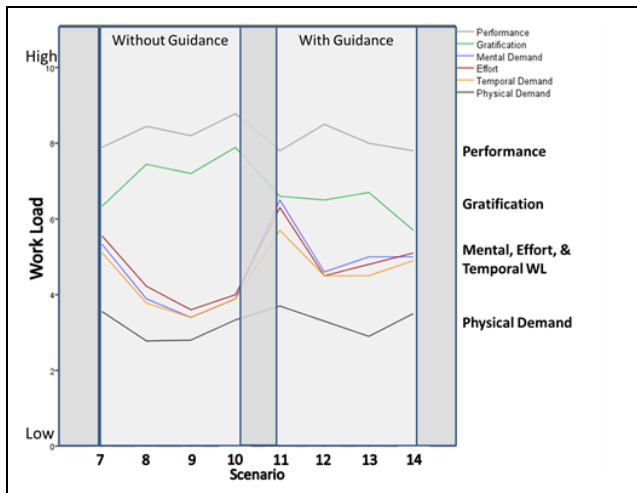

Figure 7. Individual components of workload for each scenario (N = 70).

An independent sample t-test was performed on each level of workload and the overall workload for the two conditions (without/with guidance). The independent t-test for the overall workload indicates that there is a significant difference between the two conditions (t (694.762) = -2.714, p = .007). An independent t-test for the mental demand component of workload indicates that there is a significant difference between the two conditions (t (736) = -8.193, p = .000). An independent t-test for the effort component of workload indicates that there is a significant difference between the two conditions (t (736) = -6.181, p = .000). An independent t-test for the temporal demand component of workload indicates that there is a significant difference between the two conditions (t (736) = -6.934, p = .000). An independent t-test for the performance component of workload indicates that there is a significant difference between the two conditions (t (514.928) = 4.180, p = .000). An independent t-test for the gratification component of workload indicates that there is a significant difference between the two conditions (t (719.202) = 6.659, p = .007). These comparisons showed that the workload for the guidance condition was higher than without guidance. Table III displays the means and standard deviations for each component of workload.

TABLE III. MEAN AND STANDARD DEVIATIONS FOR EACH COMPONENT OF WORKLOAD IN THE NASA-TLX (N=70). *RESULTS SIGNIFICANT AT $P < 0.001$.

Category	Without Guidance	With Guidance
Overall Workload Score	5.24 (sd = 1.20)	5.50 (sd =1.47)
Mental Demand*	4.20 (sd = 1.87)	5.40 (sd = 1.98)
Effort*	4.43 (sd = 1.96)	5.36 (sd = 2.01)
Temporal* Demand	4.15 (sd = 1.73)	5.11 (sd = 1.90)
Physical Demand	3.20 (sd = 2.17)	3.41 (sd = 2.00)
Performance*	8.26 (sd = 1.57)	7.80 (sd = 1.26)
Gratification*	7.80 (sd = 2.13)	5.94 (sd = 2.86)

While the workload was higher with guidance, participants only had approximately two hours of training on the guidance and 2.5 hours of data collection with guidance. It could be expected that this workload difference would decrease over time with practice on the system. Even though workload was higher when using guidance, the workload was still within a safe range for working conditions. Moderate workload can be the most stimulating in short increments (recommendations limit sustained monitoring to 20 minutes) [17].

D. Situation Awareness

The SART evaluates SA in terms of three primary components: the operators understanding of the situation, the supply of operator mental resources, and the demand on the operators' resources. The SART was administered after each scenario. One participant did not complete the SART after one scenario due to time constraints for an N=71. An independent t-test was conducted to compare without guidance to with guidance conditions. There were no significant differences in the scores for without guidance and with guidance for any of the SART components.

E. Separation at Landing

Separation at landing is the distance between the arrival that just crossed the landing threshold and the following arrival. The separation at this moment is important because this is what a real Tower Controller uses to judge if there is enough spacing to depart an aircraft. Although optimizing separation guidance was not the primary purpose of the HITL, it is still worthwhile to examine what separation was obtained. This section examines actual spacing at landing, how close controllers came to the target spacing, and the variance in spacing once the controller intercepted the slot markers. The separation when using minimum spacing translates into saved miles when compared to the baseline (no guidance) scenarios.

The target spacing between the middle of the slot marker and the lead aircraft that landed ranged from 4.81 – 5.81 NM, but averaged out to 5.03 NM (sd = 0.21 NM). Thus, the average landing separation when using slot markers was understandably higher than the without guidance goal (4 NM) when the participant was able to intercept the middle of the slot markers. The radius of the slot marker is 0.75 NM. The data show that being associated at least once (aircraft successfully intercepting the slot marker) helps the aircraft get closer to target spacing (5.03 NM). Successful pairs have lower variation (as expected) and lower separation. As a reminder, successful pairs are subsets of the "Guidance on – Associated at least once" data and are defined as an aircraft

being associated (green) and inside the slot marker when the leading aircraft lands.

When only minimum spacing guidance was presented for an aircraft the average landing separation was usually lower than the baseline with an average of 3.71 NM (sd = 1.49) over all 4 scenarios and ranged from 3.29 – 5.39 NM. As discussed in Section VI-B, participants aimed closer to 3.0-3.5 NM minimum separation on non-B757s. The higher minimum spacing occurred in Scenario A and can be attributed to the scenario setup that led to insufficient traffic. The same scenario setup issue in Scenario A also led to higher standard deviation. If Scenario A was ignored, the average was 3.49 NM (sd = 1.15).
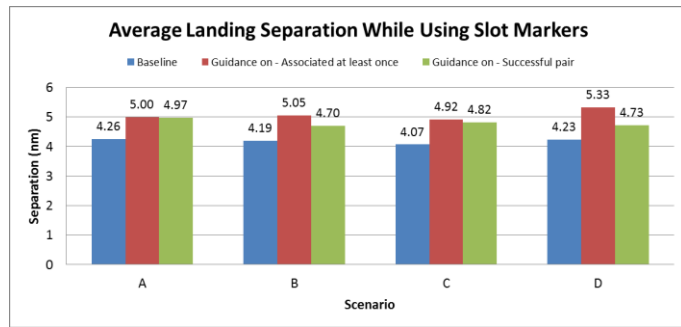

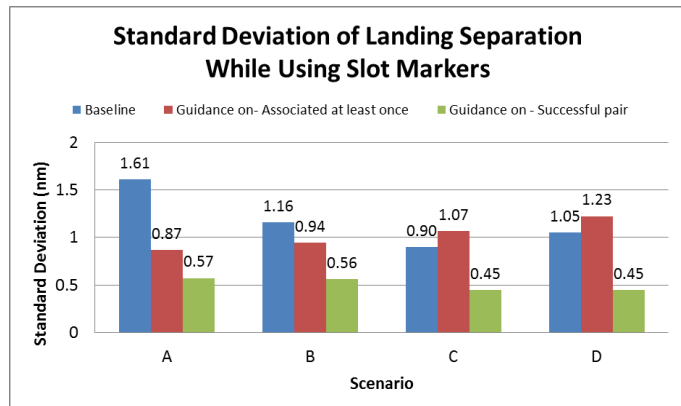Figure 8. Average landing separation while using slot markers (N = 8).

Figure 9. Standard deviation of landing separation while using slot markers (N = 8).

F. Arrival and Departure Throughput

Throughput was not optimized in the guidance algorithm or the focus of the HITL, but it is interesting to see the results. Throughput was greater than the baseline in Scenarios C and D, but less in the other two (Table IV). One has to keep in mind that the slot marker spacing was greater than the standard 4 NM spacing used in the baseline, which influenced throughput. As explained in the previous section, the middle of the circle was closer to 5 NM behind the lead. So the larger arrival throughput using guidance in Scenarios C and D indicates that the use of minimum spacing guidance more than makes up for the extra slot marker spacing in those two scenarios.

TABLE IV. AVERAGE ARRIVAL AND DEPARTURE THROUGHPUT DIFFERENCES (N = 8).

Scenario	Average Arrival Throughput Differences (Guidance – Baseline)	Average Departure Throughput Differences (Guidance – Baseline)
A	-2.00	1.88
B	-1.51	0.88
C	1.44	0.63
D	0.50	0.50

As described in Section V-B, departures always attempted to depart at the same intervals in all scenarios. When using guidance, an increase in departure throughput occurs in all scenarios. Since Scenarios C and D also showed increased arrival throughput, this suggests that the guidance can increase both arrival and departure throughput as shown in Fig. 10. Further refinement of the algorithm can lead to more consistent throughput improvements over the baseline.
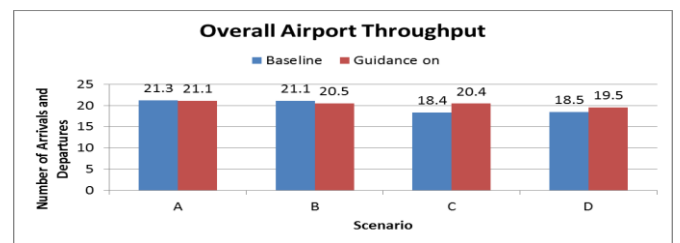

Figure 10. Average overall airport throughput (N = 8). The guidance has shown potential to increase overall airport throughput.

G. Results Summary

In summary, analysis of data from the HITL provided the following results:

- Participants found that it was intuitive to vector onto slot markets (quickly learned).
- Participants hit most of the slot markers. Data showed 69-88% conformance to slot marker guidance.
- Participants successfully reduced spacing when notified early enough to provide minimum spacing.
- Workload was moderate and falls into the range of safe practices. Once the learning effect dissipates, continued usage should reduce user workload.
- There was no difference in situation awareness.
- The departure list was more useful than the datablock indicator to determine when to use minimum spacing.
- Both arrival and departure throughput can potentially be increased by using guidance as evidenced in the throughput data from Scenarios C and D.

VII. CONCLUSIONS

The Automated Integration of Arrival/Departure Schedules concept appears to have merit and is relatively easy to implement in prototype software and explore through HITL evaluations. The HITL described here sought to determine if controllers could successfully meet slot marker and minimum spacing guidance in order to adjust spacing between arrivals to account for the departure queue. The results indicate that this is possible, and could provide benefit if implemented in terminal operations. The HITLs also measured workload

associated with the use of this type of tool. The results show that when presented with slot marker guidance, controllers were able to vector aircraft to achieve that guidance. Feedback from controllers indicates that the workload impacts are minimal and that it was intuitive to learn. Although throughput and calculating optimal separation distance are not the primary focus of this study, the HITL showed that by varying the slot marker guidance based upon scheduled departure demand and providing minimum spacing indications when appropriate, arrival and departure throughput can be improved.

VIII. Continuing Work

Future concept development will investigate: 1) providing guidance to the Tower controller on the most efficient departure plan; 2) devising methods to improve the precision of and stabilize the guidance of the slot marker for the Approach Controller to mitigate the effects of perturbations, which impact the efficiency of the guidance provided to the controllers; 3) prioritizing arrival or departure flows in the algorithm so that the automation provides spacing that allows for two departures in a gap or if earlier minimum spacing guidance can further improve efficiency. There will be a look into other possible applications for the concept such as providing time-based spacing guidance on the final, and applications where occasional gaps are needed for other surface operations such as runway crossing gaps.

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Author Biographies

Paul A. Diffenderfer has a Bachelor of Science degree in Mechanical Engineering and Aviation Technology from LeTourneau University. He served as an air traffic controller, supervisor, and mid-level manager at the Atlanta Tower and TRACON prior to his retirement from the FAA in 2009. He has worked on developing future ATC Tower and TRACON systems.

Zheng Tao has Masters Degrees in Electrical Engineering and Systems Engineering from John Hopkins University and the University of Michigan respectively. He has worked on future terminal air traffic control automation capabilities and roadmaps for the past few years. He is also involved in commercial space research.

Gaea Payton has a Master of Science in Human Factors from Wright State University. She has worked on team communications and coordination, team and individual situation awareness, future systems development, design, and HCI in air traffic control, and fatigue in aviation.