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Flight Deck-Based Interval Management-Spacing During Departures: Flight Crew Human-In-The-Loop Simulation

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Abstract— **An Automatic Dependent Surveillance-Broadcast (ADS-B) concept termed Interval Management-Spacing (IM-S) was evaluated in a human-in-the-loop (HITL) simulation. IM-S is a set of capabilities and procedures supported by ground and Flight deck (FIM) components for controllers and flight crews to use in combination to manage inter-aircraft spacing. Air traffic control (ATC) issues an IM Clearance and flight crews manage spacing through speed adjustments generated by onboard FIM equipment until reaching a planned termination point. Past research on IM-S operational applications applied the concept to the arrival and approach phases of flight using a precise spacing goal. The purpose of this study was to determine if IM-S could support the departure phase of flight when departing aircraft are merging with other aircraft into an en route stream. The environment selected was above 10,000 feet to an en route cruise altitude. Scenarios consisted of a baseline (i.e., no FIM-S), nominal FIM-S, and off-nominal FIM-S. Sixteen airline pilots with advanced Boeing cockpit experience participated, and two pilots participated per day and acted as a flight crew.**

The results of the study generally suggest that FIM-S during departure is a manageable and suitable operation for pilots. Pilots reported their workload, situation awareness, and head-down time as acceptable. Procedures and phraseology were also generally acceptable, although there was some confusion with the appropriate speed to fly after termination. Results also indicate that the necessary display features were available to the flight crews. Pilots reported overall trust in the spacing algorithm, which accurately delivered the assigned spacing goal, when given sufficient time to do so with the implemented algorithm.

The findings from this study provide an initial framework for the application of FIM-S during departure operations. A FIM-S departure operation may be feasible and manageable from a flight deck perspective with promise of crew acceptability and compatibility with current operations. However, in addition to specifically evaluating the benefits of this operation, areas such as the appropriate engagement altitude (or conditions beyond that studied in this simulation), termination procedures, information display, and algorithm design require additional research.

Keywords- Airborne Spacing – Flight deck-based Interval Management (ASPA-FIM), Airborne Surveillance Application (ASA), Automatic Dependent Surveillance-Broadcast (ADS-B), ADS-B Guidance Display (AGD), Cockpit Display of Traffic Information (CDTI), departure, departure procedure, en route, flight crew, Flight deck-based Interval Management – Spacing (FIM-S), Interval Management (IM), IM aircraft, IM Speed, metering, MITRE CAASD, pilot, spacing, spacing algorithm, Target Aircraft, merge

I. INTRODUCTION

Aircraft departing under Instrument Flight Rules (IFR) from airports in close proximity, or from different runways of the same airport, may often share common departure routes. This typically results in a merge operation with other traffic at a terminal or en route waypoint. In order for the merge to be successful, aircraft on the routes to be joined must be synchronized in time and have sufficient spacing to allow for other aircraft to fit into the overall flow, while maintaining no less than the minimum required separation between aircraft [1]. ATC has the responsibility to merge the flows and maintain separation standards while maneuvering aircraft to meet restrictions from other sectors.

Miles-In-Trail (MIT) restrictions that set a predetermined minimum distance between two aircraft, and metering (meter fix times), are two methods often used to absorb delays when the downstream sector is predicted to be or is currently congested [1]. If the desired spacing cannot be achieved early on in the flight, and MIT restrictions are in place, vectors are typically used by ATC to adjust in-trail spacing or to avoid conflicts since speed changes are often inadequate to affect the spacing within the sector [2]. Instead of being able to direct an aircraft to achieve and maintain a specific in-trail spacing interval, controllers must provide specific instructions, or instruction sequences, to achieve their goal. This process can be workload intensive for controllers and can also increase aircraft fuel consumption and flight time. However, new technologies such as Automatic Dependent Surveillance – Broadcast (ADS-B) may allow the flight deck to better support the ATC task of managing intervals.

An ADS-B based concept is being developed to provide operational benefits through the management of spacing intervals between aircraft. Termed Interval Management–Spacing (IM-S), the concept consists of a set of ground (GIM-S) and flight deck (FIM-S) capabilities and procedures for the flight crew and ATC that are used in combination to more efficiently achieve and manage inter-aircraft spacing (e.g., achieve a precise interval on arrival or maintain a closed range interval on departure) based on an ATC clearance. The capabilities can be used in several environments depending on local constraints and traffic characteristics, and expected benefits include reduced need for downstream path-lengthening, and consistent, low variance spacing between paired aircraft. FIM-S is also expected to reduce ATC instructions and workload without an unacceptable increase in flight crew workload.

The FIM-S concept broadly involves capable aircraft first being assigned spacing goals behind target aircraft by ATC. The flight crew enters this information into their on-board FIM-S system and when IM conduct requirements are met, the FIM-S system engages and provides IM Speeds for the flight crew to fly to achieve and (optionally) maintain the assigned spacing goal. A one-time IM Turn option can also be utilized at the point of engagement. After engagement, the flight crew follows the IM Speeds and ATC monitors until termination. Past research on IM-S operational applications applied the concept to the arrival and approach phases of flight using a precise spacing goal (versus a spacing goal type that allows for a range of spacing options). Although this work has built a research foundation for FIM-S, little, if any, work to date has examined an application of FIM-S during departure operations. As an initial step toward examining the feasibility of applying FIM-S to this domain, a HITL simulation was developed and executed that used FIM-S during departure and cruise for nominal and off-nominal departure operations. The findings from this study are intended to provide an initial examination of the feasibility of, and a future research framework for, a FIM-S departure application.

II. BACKGROUND

A. Delay Procedures and ATM Decision Support Tools

There are a variety of factors that contribute to departure delays including weather, traffic density (which leads to longer taxi times), controller workload constraints, downstream flow restrictions, and controller workload [3]. Downstream flow restrictions are used to merge aircraft to departure fixes via metering and play a significant role in overall departure delays. In the event that weather or volume will have an effect on overall throughput, the traffic management coordinator (TMC), terminal radar approach control (TRACON), and the air route traffic control center (ARTCC) traffic management unit (TMU) will make changes as necessary to aircraft departure routes and trajectories (e.g., vectors, new routes) to balance any constraint(s) [4]. Additionally, in many instances a ground delay program (GDP) is established during high traffic volume. GDPs are generally implemented if arrival demand at an aircraft's destination airport exceeds capacity. In this instance, the aircraft departing and flying to the conflict airport will be delayed at the point-of-origin and will be issued a Gate Hold (GH) and an Expected Departure Clearance Time (EDCT), which reflects when the aircraft can be appropriately released into the airspace.

MIT and metering are also used to help controllers manage traffic, although only a limited number of facilities use metering and it is generally restricted to arrival traffic [5]. Since ATC does not always have the information necessary to predict aircraft performance, it may put more conservative MITs in place to account for the uncertainty. Although MIT restrictions are prevalent, they inherently result in bunching or excessive gaps between aircraft which could lead to decreased throughput and increased controller workload [4]. Many of these excessive gaps are the result of workload associated with meeting MIT restrictions, resulting in a decrease in airspace efficiency.

Time-based metering shows potential in mitigating some of the constraints associated with MIT restrictions. MIT restrictions are determined through historic traffic demand patterns while metering is based on specific crossing times or "slots" that a flight crew must achieve over a point to maintain adequate spacing. Metering slots are coordinated through a Center TRACON Automation System (CTAS) tool called Traffic Management Advisor (TMA). TMA is a decision support tool that calculates the number of aircraft a TRACON facility can handle during a period of time. TMA then schedules metering times for the adjacent ARTCC for traffic arriving into the TRACON. A tool known as Multicenter Management Advisor (McTMA), shares TMA data with adjacent air route traffic control centers (ARTCC) so that the delay can be absorbed over multiple centers [6]. Other tools such as the En Route Departure Capability (EDC), Departure Manager (DMAN), and Arrival Manager (AMAN) support TMA by deconflicting aircraft crossing metering points, incorporating aircraft performance characteristics, and meteorological conditions. In addition to these functions, DMAN also incorporates departing aircraft start-up approval time and scheduled take-off time and assigns the aircraft a departure runway. AMAN provides similar functionality by assigning aircraft to destination runways and an optimal time of arrival at a specific TMA entry fix. However, both DMAN and AMAN are not fully integrated with one another which results in degraded efficiency during high arrival volumes as airborne aircraft have priority over those still on the ground.

A prototype system termed Coordination of Arrival and Departure Management (CADM) is under development by EUROCONTROL and utilizes AMAN and DMAN in order to improve mixed mode operations, particularly departure throughput during peak volumes. This is accomplished by extending the flight path of arrival aircraft such that there is enough time for aircraft to depart without adversely affecting throughput. These arrival gaps are known as Arrival-Free Intervals (AFI). Although a prototype, this information is relayed to DMAN where release times are issued based on calculated AFIs [7]. A similar prototype called the Expedite Departure Path (EDP) is a decision support tool that provides climb advisories, transition merge advisories, and time-to-fly estimates for TRACON controllers. Such automation is expected to support controllers in merging aircraft to a departure transition fix. Moreover, EDP merge advisories would lead to precise spacing over a departure transition fix along a conflict free trajectory into the en route traffic stream [8]. If this prototype or similar were to be implemented in the near term, controllers still have to position the aircraft to meet these advisories which could adversely affect throughput.

B. Challenges with Current Delay Procedures

Current delay constraints in the NAS are due in part to procedures and tools that cannot efficiently handle the increase in traffic volume. Much of this is attributed to inefficiencies with current ATM practices such as MIT restrictions. Metering shows potential in mitigating some of these constraints. When Los Angles Center (ZLA) changed from MIT restrictions to time-based metering in 2002, the airspace experienced an 8% increase in arrivals, 12% reduction in airborne holding, and a 23% reduction in delays. However, deficiencies with handling complex airspaces have limited the effectiveness of the metering capability [6].

Another challenge to the system concerns internal departures, which include any departures that require sequencing into an overhead stream within the same or neighboring ARTCC. Internal departures are usually the first to absorb delays and are particularly problematic if the departing aircraft is relatively close to the destination airport. This is predicated on the volume of the arrival stream and the distance of the MIT restrictions. In other words, conservative MIT restrictions make it difficult to manage high traffic volumes. Furthermore, MIT restrictions place a preference to airborne aircraft and penalize internal departures. ATM tools such as EDC mitigate some of the timing associated with releasing departing aircraft at the appropriate time to fit into gaps in the overhead stream. However, the controller still has to monitor this merge and advise aircraft to make speed and vector changes as necessary in order to fit the internal departing aircraft into the overhead stream. This presents another challenge for the controller, namely when an aircraft is merging into an overhead stream, the controller has to stagger the aircraft in such a way that the two merging aircraft do not conflict but still meet the MIT restriction requirements [1]. This can be particularly work intensive for a controller as he or she has to verbally communicate airspeed and heading changes to meet the MIT restrictions and do so without creating a conflict.

C. Cockpit Environment During Departures

Flight deck operations during departure can be workload intensive, especially at lower altitudes. Tasks after take-off and during departure include accelerating, retracting the landing gear and flaps, monitoring aircraft systems, following the published instrument Departure Procedure (DP), conducting pertinent checklists, and complying with ATC instructions / clearances.

The cockpit environment below 10,000 ft can be particularly dynamic. Shortly after takeoff, flaps are retracted based on a flap retraction schedule. The takeoff phase ends with the retraction of landing gear and high-lift devices and the completion of after takeoff duties and checklists. Most aircraft should be in a clean configuration (i.e., flaps and landing gear are all retracted) at the end of the takeoff phase (typically 3,000 ft.) Aircraft also accelerate during flap retraction to an indicated airspeed (IAS) no greater than 250 kts, the maximum speed below 10,000 ft in the United States.

Many modern aircraft type designs allow for the autopilot to be engaged relatively shortly after takeoff, as low as 35 feet above ground level (AGL) in some cases. Many operators encourage the use of automation systems in all phases of flight, including below 10,000 ft, to aid in reducing crew workload as long as the management of the automation systems does not interfere with the flight crew’s ability to maintain adequate situation awareness and effect appropriate control of the aircraft’s flight path. For this reason, operators discourage the re-programming of flight management systems while the aircraft is operating below 10,000 ft.

Upon reaching 10,000 ft, flight crews generally accelerate to a cruise climb airspeed unless prohibited by a DP and / or ATC. Eventually, all aircraft above 10,000 ft will climb at a normal cruise climb airspeed (which is typically faster than 250 knots) and follow the remaining filed route. In addition, above 10,000 ft, there are generally fewer mixed equipment operations, more IFR flights, and typically less communication volume. Also, to maximize fuel economy, there are few to no intermediate altitude restrictions to comply with (except those issued by ATC).

None of the reviewed flight deck workload studies specifically focused on measuring workload during departure using modern automation and procedures in an air carrier environment. However, discussions with experienced air carrier pilots indicate that workload during the takeoff, approach and landing phases of flight is generally more elevated compared to other phases of flight; however workload typically starts decreasing following the takeoff phase and decreases progressively as the aircraft continues its climb to its cruise altitude. The extent of the change in workload depends on several factors, including the complexity of the DP flown, communications workload, environmental factors and the use of aircraft automation systems. These factors would determine whether or not a crew might be able to consider the addition of tasks not required in today’s operations (e.g., FIM-S operations).

D. FIM-S Concept Overview

FIM-S is being developed as an Airborne Spacing Application (ASPA), which requires “flight crews to achieve and maintain a given spacing with a designated aircraft. Although flight crews are given new tasks, separation is still the controller’s responsibility and applicable separation minima are unchanged” [9]. FIM-S is being matured in an international standards body called the Requirements Focus Group (RFG), which is developing a Safety and Performance Requirements (SPR) document for the implementation of ASPA-FIM-S [10].

Prior to the initiation of IM-S, ATC remains responsible for building an appropriate sequence and spacing of aircraft. IM-S does not work in all conditions so the controller uses his or her knowledge, and potentially automation support, to determine desirable and successful conditions. Such set-up can be conducted via current ATC capabilities or with new capabilities in more complex environments. After establishing an appropriate sequence and spacing, a controller makes the determination that a pair of aircraft is suitable for FIM-S. The transition of individual aircraft begins when ATC provides the flight crew with information to conduct the operation including the target aircraft identification, IM clearance type (e.g., achieve-then-maintain, maintain), spacing goal type (e.g., precise value, closed interval, no closer than interval), assigned spacing goal, and special waypoints (e.g., intercept point, achieve-by point, planned termination point). The flight crew enters this information into the on-board FIM-S equipment and once the target aircraft is in surveillance range, is on the expected trajectory, and satisfies the IM conduct requirements, FIM-S is engaged and the system starts providing information such as the IM Speed for the flight crew to follow and IM situation awareness information to assist the flight crew in their understanding of the spacing status. A Cockpit Display of Traffic Information (CDTI) is typically assumed for FIM setup and situation awareness; however some implementations involve secondary displays (such as an ADS-B Guidance Display [AGD]) that present key information in the flight crew's forward field of view.

With the presentation of each new IM Speed, the flight crew ensures that the IM Speed is feasible in the current configuration / conditions. The flight crew is expected to follow the IM Speeds in a timely manner consistent with other cockpit duties unless other conditions prevent it such as safety, operational, FIM equipment, or regulatory issues. If any of these issues arise, the flight crew stops following the IM Speeds and contacts ATC for the termination of IM (e.g. if an IM Speed fell outside of the aircraft flight envelope). Similarly, if ATC has any conditions that prevent continued IM such as safety, operational, or regulatory issues, they will contact the flight crew and terminate or suspend IM. ATC may choose to resume IM at a later point, should the appropriate conditions exit. If no issues arise for either ATC or the flight crew causing a suspension or termination, the flight crew continues following the IM Speeds and ATC continues monitoring the operation until the aircraft reaches the planned termination point. At this point, the flight crew discontinues flying IM Speeds and terminates IM. Additional information on the broader concept and preliminary requirements are available in [10].

III. IM-S IN DEPARTURE OPERATIONS

The current development and / or implementation of ATM tools for departure have shown potential improvements in airspace throughput. Tools such as EDC, DMAN, and AMAN have allowed controllers to sequence departing aircraft into the overhead stream with more efficiency. However, the controller still has to monitor merging aircraft and provide flight crews with instructions to achieve and maintain adequate spacing. FIM-S may help provide a solution for the challenges posed to controllers merging departing aircraft into an overhead stream by allowing flight crews to achieve the assigned spacing goal at a point and then (optionally) maintain that assigned spacing goal using onboard equipment.

Past research [11-18] has shown FIM-S to be feasible in the arrival and approach phases of flight in en route and terminal airspace and can, in some cases, reduce controller workload. General favorability for FIM-S was reported with no deleterious effects on current flight deck workload and mental effort across nominal and off-nominal FIM-S events. Although these simulations and other past work built a research foundation for FIM-S, this study is the first major effort to date to examine the use of FIM-S during departure.

Reference [19] describes an example for how a FIM-S concept could be used during departures for two closely located airports: Chicago O'Hare International (ORD) and Chicago Midway (MDW). Coordination is required between ORD and MDW to allow both airports to run certain departure streams. The ORD departure controller must create, at least, a 14 nm gap between its departures so that a MDW departure can be fit in that gap. The MDW departure controller must then accurately fit its departure aircraft into the middle of the gap using radar vectors and airspeed. The authors note that if the spacing goals for this operation are not met, the impact can be significant and include stopping departures until the situation is resolved. FIM-S could be used in such situations to manage the entire stream, including allowing satellite airport departures to accurately get into position.

Departure IM-S may benefit from a GIM-S capability to determine the aircraft sequence, potential aircraft pairs, and the desired assigned spacing goal. While this may be useful and even required in certain operations, controllers may still be able to use FIM-S as an operational tool; however, in less complex situations. Whether a GIM-S capability is in place or not, however, the controller will need to issue an IM Clearance as part of initiation. For departure operations, it may be desirable to initiate FIM-S after the IM aircraft is in the cruise climb portion of flight, (e.g., above 10,000 ft) due to high communications volume with terminal area ATC, flaps management during initial climb, and the fact that many airlines prefer to limit flight crew inputs into automation below 10,000 ft. Although it is conceivable that a FIM-S operation could be conducted below 10,000 ft., operational suitability may be affected due to workload issues involved with initiation as well as additional operational considerations such as the 250 kt restriction on maximum operating speed below 10,000 ft.

IV. SIMULATION DESCRIPTION

In order to gain an initial understanding of the issues involved with introducing FIM-S during departure operations, a Human-In-The-Loop (HITL) simulation was run to examine the potential impact of adding a FIM-S operation on flight crews. Two types of spacing goal operations were examined: *precise* (i.e., a specific value [e.g., 100 seconds] to achieve or maintain, and *Open With Capture* (OWC) (i.e., IM Speeds are provided to achieve the assigned spacing goal at the achieve-by point only if the IM aircraft is predicted to achieve a spacing interval less than the assigned spacing goal). However, since OWC was recently excluded in [10] due to questions about its operational benefits, and since subjective results were generally consistent for both spacing goal types, this paper focuses primarily on FIM-S overall and scenario descriptions and results specific to OWC are not included. A full description of the research background, method, and results (including OWC) is provided in [20].

The study was designed to address the following primary research questions:

1. What impact does introducing FIM-S during departures have on flight deck operations?
2. What are the human performance impacts on pilots of introducing FIM-S during departures?
3. What are the key flight deck display considerations when performing FIM-S during departures?

Additionally, the experience of designing an algorithm to facilitate the simulation allows some input into a fourth question:

4. What are the key design considerations for a time-history algorithm intended to facilitate FIM-S departure operations?

In particular, the HITL addressed FIM-S impact on current operations, workload, situational awareness, procedures and communication acceptance, head down time, and FIM-S equipment acceptance. Several hypotheses were specified for this simulation, including:

- FIM-S will be manageable and acceptable for both nominal and off-nominal conditions.
- Procedures and clearance phraseology will be operationally acceptable.
- FIM-S crew coordination procedures will be sufficient for departure operations.
- Pilots will show high conformance in following the IM Speeds as presented by the FIM-S system.
- FIM-S may introduce an increase in crew workload and head down time compared to similar operations, but overall levels will still be acceptable under nominal and off-nominal FIM-S conditions.
- Pilots will maintain a sufficient level of situation awareness of the FIM-S operation and the target aircraft.
- The displays used in the simulation will be sufficient to initiate and conduct FIM-S.

A. Flight Deck and Displays

The evaluation took place in MITRE's Aviation-Integration Demonstration and Experimentation for Aeronautics (IDEA) Laboratory. This facility caters to research in flight deck and air traffic control environments and serves as a testing facility for aviation applications development.

1) Flight Deck: A medium fidelity, fixed-base, Boeing-777-like flight deck simulator was used to support the FIM-S departure evaluation. The simulator supports two flight crew members along with space for an observer positioned directly behind the center console. A CDTI and AGD were added to the standard flight deck configuration to facilitate FIM-S operations. The simulator is equipped with two CDTIs, one at the captain's eleven o'clock position and the other located at the first officer's one o'clock position. The AGD was positioned just above the standby attitude indicator on the main instrument panel.

2) CDTI: The CDTI utilizes traffic surveillance information to display traffic and a processing system that utilizes an algorithm to achieve and / or maintain an assigned spacing goal. A recent MITRE research effort developed a CDTI interface that allows for the integration, control, and operation of multiple ADS-B functions in a seamless manner. The MITRE CDTI was developed under the name of Multi-Purpose CDTI (MPCDTI) and its overall design philosophy is described in [21, 22]. The design attempted to conform when possible to existing standards and guidance, but departed when necessary to try to provide flexibility for future functionality enhancements and accommodate the touch-screen as the primary display interface.

Figure 1 shows the CDTI interface used in the study when FIM-S was engaged. Display elements were selected based on a review of past research as well as an examination of other systems used in past research at MITRE. The review yielded that at a minimum, setup elements should include the target aircraft identification and assigned spacing goal. An achieve-by point may or may not need to be specified, depending on the goal of the spacing operation. The review also suggested that the display elements for an engaged spacing operation should include the coupled target aircraft identification and the IM Speed; however, other elements were made available to the user as part of the overall MPCDTI design.

Through the touch-screen interface, pilots were able to select targets by highlighting a particular aircraft of interest wherein additional information is displayed on that target (i.e., aircraft category, flight call sign, range, ground speed, and differential ground speed). After FIM-S was armed and the IM conduct requirements were met, it engaged. At this point, IM Speeds were communicated through the IM Speed indicator and presented relative to an indication of current IAS and the current selected IAS (MCP Speed bug). When these matched on the same value, the three speed indicators horizontally aligned. IM Speeds were displayed in knots IAS (KIAS) and quantized at 10 knots. Additionally, the vertical reference line indicated upper and lower speed limits. Pilots were also able to adjust the view range of the display through the range select feature. A more detailed review of the CDTI features is provided in [20].

Figure 1. MITRE Multi-Purpose CDTI FIM-S Interface

3) AGD: An AGD was implemented to allow for the presentation of the parameters believed to be the most pertinent to FIM-S in the pilot's forward field of view. It included three information fields for the user: speed guidance, target aircraft identification, and current spacing interval (i.e., In-Trail Time [ITT]). When a new IM Speed was calculated, a green box illuminated around the speed command for ten seconds, which alerted the crew to the presentation of a new IM Speed. Due to the functionality of the algorithm (described later), the ITT feature of the AGD showed the IM aircraft's current spacing interval with the target aircraft relative to the first point at which the IM and target aircraft routes join past the merge. Participants were instructed that the ITT would not necessarily show them achieving the assigned spacing goal precisely at the achieve-by point, and that they should use ITT only as a general trend indicator. Figure 2 shows the AGD interface used in the study when FIM-S was engaged.

Figure 2. MITRE AGD Interface

4) Speed Guidance Algorithm: In this study, a time-history algorithm was used to achieve an assigned spacing goal near the achieve-by point. This algorithm was based on the EUROCONTROL CoSpace algorithm [23], but was modified to account for departure and climb profiles that are not known a priori and can prove highly divergent. A full description of design considerations and algorithm functionality used in the study is provided in [20], but key points are summarized later in the disucssion section of this paper.

B. *ATC and Scenarios*

Data collection occurred through seven nominal and two off-nominal scenarios. The nominal scenarios included two north segment departures (using precise) and five south segment departures (one baseline [i.e. no FIM-S], two with precise, and two with OWC). The simulation environment was based Hartsfield-Jackson Atlanta International Airport (KATL) and the surrounding environment, but did not intend to precisely emulate real-world flights or true airspace densities. The scenarios used elements from the KATL DAWGS Four Departure and alternated having the participant aircraft depart via the north or south sequences to a common departure fix: the DAWGS waypoint. In the FIM-S scenarios, the target aircraft flew directly to DAWGS after crossing the ZELAN waypoint for the north sequence, and the ZALLE waypoint for the south sequence. The scenarios ended approximately one minute after crossing the DAWGS waypoint (approximately 25 minutes after the start of the scenario). The basic geography for the South departure scenarios is presented in Figure 3.

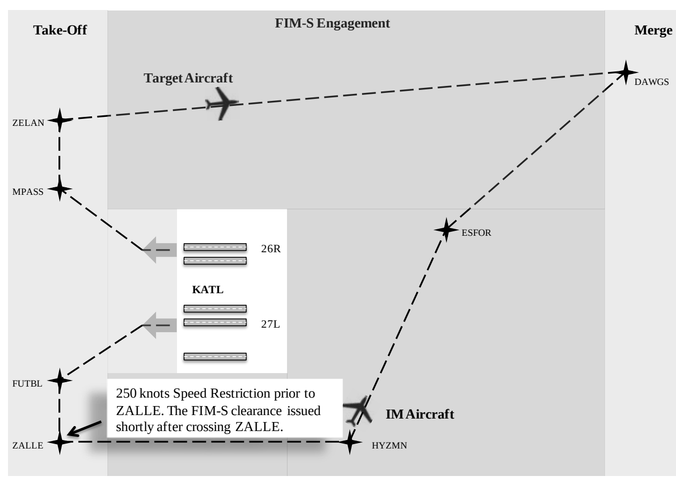

Figure 3. South Departure Sequence

1) FIM-S Scenarios: To support a near term implementation, it may not be suitable to implement FIM-S below 10,000 ft due to workload issues associated with initiation. Therefore, for this HITL, flight crews received the FIM-S clearance shortly after crossing the ZALLE intersection (if departing to the south) or ZELAN (if departing to the north), which was usually between 10,000 and 12,000 ft. After confirming the target aircraft identification and entering the clearance information, the flight crew armed the FIM-S equipment. The FIM-S equipment typically engaged and started providing IM Speeds around 13,000 to 14,000 ft. (although a limited number of crews had difficulty entering the information into the CDTI and did not engage until between 16,000 and 18,000 ft.). The target aircraft at this point was approximately 25 nautical miles (straight line distance) from the IM aircraft. The four nominal FIM-S scenarios allowed the operation to proceed without deliberately introducing any perturbations or controller interventions.

The two off-nominal scenarios included a speed range problem and suspend-and-resume. The speed range problem introduced a situation where FIM-S was initiated, but the distance between the IM aircraft and the target aircraft was too great and could only be reached by following IM Speeds outside the aircraft's operational limitations. This scenario forced the flight crew to decide to terminate FIM-S. The termination in the suspend-and-resume scenario, however, was initiated by ATC. This scenario addresses a situation where the target aircraft is temporarily unavailable for FIM-S, and ATC temporarily suspends, then resumes FIM-S. Here, ATC informed the IM aircraft to suspend spacing and then to expect to resume spacing prior to reaching DAWGS.

2) Baseline Scenario: Pilots flew the south segment of the DAWGS4 Departure as published. Per a typical real-world operation, participants received a speed restriction between ZALLE and HYZMN. It was not necessary for the IM aircraft to receive this restriction when they departed via the South sequence, as participants were using FIM-S to manage their spacing. Additional detail on all the scenarios is provided in [20].

C. Participants and Procedures

1) Participants: Sixteen Air Transport Pilot rated individuals participated in the simulation. Seven were Captains and nine were First Officers (FOs). Participants were required to have experience with Boeing EFIS, autothrottle, and autopilot systems. All pilots received an introduction briefing and initial training, including three training scenarios. Overall participation took approximately eight hours. Two crew members participated each day and acted as pilot flying (PF) or Pilot Monitoring (PM). The role of PF or PM was chosen for each pilot at the beginning of the day based on experience, and the pilots remained in that role throughout the simulation.

A MITRE confederate controller served as ATC, and a pseudopilot was employed to read-back ATC instructions for other traffic in the same area as the IM aircraft. At times the controller issued a FIM-S clearance to surrounding traffic, and the pseudopilot read back the clearance.

2) FIM-S Procedures: Pilots were briefed that with regard to FIM-S, the primary task of the PF is to fly the IM Speeds. The primary task of the PM was to enter the FIM-S clearance into the CDTI and to assist the PF as needed.

Pilots were also briefed on the following points:

- CDTI is for FIM-S initiation, geographic orientation, and a visual confirmation of spacing as required.
- The flight crew does not need to monitor for any spacing or separation issues; ATC will be monitoring and will intervene as necessary.
- Under nominal conditions, the CDTI will automatically disengage FIM-S at the termination point.
- The normal termination procedures include: 1) maintain current speed until ATC instructs otherwise, and 2) not to contact ATC as the normal termination was as cleared and expected.
- If pilots needed to initiate a termination (such as for the speed range problem), they were instructed to communicate this to ATC and await instructions.

3) FIM-S Phraseology: In current operations, controllers typically point out traffic for visual out-the-window acquisition by communicating the bearing, range and direction of flight of the target aircraft. ADS-B In, however, provides traffic call sign for display on a CDTI which FIM-S and other operational applications can take advantage of for target acquistion. Although a standard is not yet in place for communicating target aircraft call sign over the voice frequency, one possible method (used in this HITL), may be by "letter only" for the target aircraft's identification as indicated on the CDTI (e.g., "D-A-L one twenty-three") and not by the target aircraft's company affiliation (e.g., "Delta one twenty-three"). The clearance communication included the target aircraft's identification, assigned spacing goal, spacing goal type, the achieve-by point, and the termination point. Reference [20] includes the complete phraseology used in the simulation, but the following was used for precise FIM-S initiation:

- Atlanta Center: *Delta forty nine, space reference D-A-L one two three, six zero seconds, achieve-and-terminate at DAWGS.*
- Delta 49: *Space reference D-A-L one two three, six zero seconds, achieve-and-terminate at DAWGS, Delta forty nine*.

If pilots needed to initiate a termination message, the suggested phraseology consisted of:

- Delta 49: *Atlanta Center, Delta forty nine is terminating spacing.*

D. Data Collection Methodology

Subjective data was collected via questionnaires. Post-scenario and post simulation questionnaires covered topics such as workload, situational awareness, concept acceptability, pilot roles and responsibilities, and communication requirements. Most questions were on a seven point scale while other questions were yes / no, open ended, or on another scale. Participants were encouraged to add detail in open text fields to justify or clarify their answers. The questionnaires were based on past research on and testing of ADS-B applications [14, 15, 24, 25, 26]. Objective data included spacing performance at the DAWGS waypoint, crew response to IM Speeds, and the number of IM Speeds issued.

V. Results and Discussion

The following sections summarize the results and discussion for the overall FIM-S spacing operation by research question. Complete results and analyses are available in [20].

A. What impact does introducing FIM-S during departures have on flight deck operations?

Pilots generally found FIM-S to be acceptable and operationally suitable under the conditions simulated. They indicated they had a clear understanding of both nominal and off-nominal FIM-S operations and there was strong agreement from most pilots that FIM-S is compatible with current flight deck operations in the departure phase of flight in the en route domain. Flight crews also noted FIM-S had no effect on normal crew interaction and coordination, and had no impact on their prioritization of non-FIM-S flight deck tasks. This is consistent with previous research which also found a favorable pilot perception of FIM-S [14, 15, 18, 26].

Nominal FIM-S initiation communications appeared to be acceptable, and the decision to provide the target identification and FIM-S clearance for initiating FIM-S above 10,000 appeared to be reasonable. It may be possible to initiate at a lower altitude, but below 10,000 may be a more challenging environment. For example, ATC issuing and the flight crew entering the IM Clearance below 10,000 may be difficult as some airlines prefer to limit flight crew inputs into automation below that altitude. Pilots did raise concerns with initiating earlier than they experienced in the simulation; however, they were forced to speculate as they did not get to experience FIM-S at an earlier point.

If it is desirable to initiate FIM-S at a lower altitude, future research should examine the topic, including ways to overcome some of the potential issues. For example, it may be desirable for ATC to notify the flight crew to "expect" an IM clearance and provide all the clearance elements while the aircraft is still on the ground. Once airborne and in the appropriate position, ATC could issue the actual clearance and the flight crew would just need to confirm the already entered information and arm the system. At this point the flight crews would just need to fly the IM Speeds as normal, avoiding entering all the information during a busy period.

The number and rate of IM Speeds provided by the algorithm also seemed to be acceptable to pilots. Flight crews complied with 96% of the issued IM Speeds presented over 10 seconds in length and a 66% conformance rate for cases where there were fewer than 10 seconds between IM Speeds. Such conformance to the IM Speeds was higher than past work in the arrival and approach phases of flight [e.g., 15]. The reason for such high levels of conformance may possibly be due to a strong trust in the algorithm and an acceptable number of IM Speeds provided.

With respect to FIM-S normal termination procedures, some pilots were confused about the correct speed to fly after crossing the achieve-by point. All pilots were told to maintain the last IM Speed after crossing the achieve-by point during the introductory briefing and training, but confusion still persisted. Some thought they were supposed to resume a normal airspeed. One pilot suggested that the use of "terminate" in "achieve and terminate" implied ending the entire FIM-S operation and resume normal operations, including normal speed. Further work should be considered to determine the appropriate phraseology in this situation. In addition, the achieve "only" operation (i.e., no maintain mode) spaces to the achieve-by point and then terminates. If the IM aircraft follows the target aircraft after crossing the achieve-by point (as was done in this simulation), it may be more logical for the IM aircraft to maintain FIM-S after the achieve-by point.

Concerning the procedures for both off-nominal scenarios, most pilots reported that the procedures were acceptable and desirable. In the case of the suspend-and-resume off-nominal scenario, pilots found the resume portion to be acceptable. The flight crews were notified by ATC to suspend the operation and expect to resume prior to DAWGS. Flight crews were also told to maintain current airspeed. However, it was observed that some flight crews did not comply with this instruction and resumed normal airspeed for unknown reasons. Regardless, these operations ended with aircrews successfully reengaging.

For the off-nominal speed range problem, the scenario was designed to calculate an IM Speed that was beyond the aircraft performance envelope requiring an abnormal termination. Flight crews made a decision whether or not to terminate FIM-S if the IM Speed was approaching or exceeded operational limitations. Pilots agreed that abnormal termination was sufficiently detected. However, there was some variability with the time and location during the scenario when flight crews made a decision to terminate, although all eventually did terminate. Some of the variability on the decision to terminate was due to issues related to not knowing the IM Speeds was very close to, at, or beyond V_{MO} due to the speed limitation not yet being visible on the airspeed tape. Past work [15] also reported some pilots experiencing difficulty detecting an IM Speed outside the aircraft envelope.

It may be desirable for the FIM-S equipment to have knowledge of the aircraft speed envelope and only provide IM Speeds within that envelope. If an IM Speed is needed outside that envelope, and the envelope is known, it would be desirable to indicate this to the flight crew. However, certain data may not be available to the FIM-S equipment (e.g., changes in stall speed / buffet boundary with gross weight) and the final determination of whether to implement an IM Speed resides with the flight crew. Flight crew behavior in a situation where FIM-S is providing an IM Speed that is not within the pilots' comfort level is not expected to be different from situations where ATC provides a speed the flight crew does not want to fly. Flight crews would be expected to take into consideration any factors they do today (e.g., individual preferences, meteorological conditions, altitude) in determining whether to follow the IM Speed. In FIM-S, the flight crew would not be expected to fly the IM Speed if they had reasons not to do so, but they would be expected to notify ATC of the termination of FIM-S.

There was some confusion with what to tell ATC during the abnormal termination scenario, regardless of the training received. In addition, as was the case for the nominal termination procedures, some pilots were confused with what airspeed to fly after termination. Per their training, flight crews were told to resume normal speed in this instance. However some were still concerned about their spacing and used the last IM Speed as a substitute for normal speed. However, despite some confusion, pilots agreed that the communications and procedures used during the speed range problem, and abnormal termination, were clear. Such results are consistent with past work where similar non-nominal situations were resolved with some question as the appropriate speed to fly [14, 15]. Future research and any pilot or ATC training should address the issue of what speed to fly following a normal or abnormal termination.

B. What are the human performance impacts on pilots of introducing FIM-S during departures?

As described earlier, the departure phase of flight, specifically after 3,000 ft to cruise, is generally less workload intensive compared to other phases of flight. However, with the addition of FIM-S related tasks during this phase of flight (i.e., initiation, following IM Speeds), it was expected that pilots would report a slight increase in workload as reported through other phases of flight when conducting FIM-S operations: [14, 15, 17]. This is generally supported by the results.

Based on the Bedford workload rating scale, a shift in workload from more ratings of "very easy" to more ratings of "easy" or "fair" was observed in the FIM-S scenarios as compared to baseline. The shift was weak, however, as crews had mixed responses when asked directly whether they felt FIM-S increased or decreased their workload. Pilots reported overall that their workload with FIM-S was "acceptable" and "low," and so any workload shift due to the introduction of FIM-S may be operationally insignificant. Shifts in workload ratings across FIM-S scenarios types were not observed, which suggests that the disruptions of FIM-S such as suspend-and-resume and the speed range problem were not major workload drivers. In these cases, crews felt that that at most, they still had "enough spare capacity for all desirable additional tasks." Some of the past research suggests that reduction in workload may be related to the reduced number of controller interactions during FIM-S operations as compared to current operations. This may also have been a factor for this study, although controller interventions with departing aircraft on DPs are typically already low.

Past FIM-S arrival and approach research has generally shown that pilots reported a better understanding of the traffic situation [26]. In the MITRE studies of FIM-S in the arrival domain, pilots reported improved and acceptable SA with FIM-S under normal and non-normal scenarios [14, 15]. No loss of SA was also indicated by the fact that all pilots detected the non-normal situations. The results of the current study are consistent with past work as pilots subjectively reported that their SA improved with FIM-S. This is further supported by the speed range problem scenario, as pilots always detected a spacing issue when IM Speeds approached V_{MO} and terminated as appropriate.

Furthermore, the intent of the CDTI is to provide the FIM-S situation awareness while the AGD is intended to provide enough information to perform FIM-S. Consistent with past work [14, 15, 26], the results of this study do suggest that the CDTI is important for SA. Although the majority of PFs (who primarily used the AGD to fly the IM Speed) felt they could focus on the AGD as the primary source of information, the majority of PMs did not. Although this could be due in part to the AGD location favoring the PF, it was still visible to the PM. This indicates that PMs felt that the CDTI was important to maintain SA throughout the conduct of the operation.

Overall, participants found FIM-S operations made instrument scanning "somewhat more demanding" but rated this increase as acceptable. This is consistent with previous research which also found an acceptable increase in head down time [14, 15, 28]. The reasons for this likely include the additional information being incorporated into the scan, as well as the displays not being in a position that is incorporated in the pilots primary scan location (although the majority of pilots still found the locations acceptable). For example, one participant noted that the AGD was positioned in an area of the cockpit where standby instruments (e.g., attitude indicator) are located. The pilot noted that standby instruments are rarely, if ever, used. Consequently, pilots may have learned to disregard this location unless necessary and found the AGD location to be awkward. Another participant mentioned the CDTI is far removed from the primary displays. Several participants mentioned the desire of hosting the CDTI on the ND, which is consistent with previous research [15]. Pilots also noted that although their head-down time when conducting FIM-S was increased as compared to similar operations, it was still acceptable.

C. What are the key flight deck display considerations when performing FIM-S during departures?

Crews were observed to have successfully used the CDTI to confirm target aircraft identification and FIM-S initiation. The majority of pilots agreed that the display combination of the CDTI and AGD provided all the necessary information needed for informed and accurate speed implementation decisions. Supporting this, they also indicated they would be willing to conduct FIM-S using these two displays and that they "had a clear understanding of [their] spacing with the aircraft ahead and how well it was being achieved". The information element on the AGD that had the highest usefulness rating was speed guidance (i.e., the IM Speed), followed closely by ITT. The high priority placed on IM Speed is appropriate, as it was the primary element that provided direct information for crews for how to conduct FIM-S.

Despite the adequate salience of the element as suggested by high IM Speed conformance, some participants suggested incorporating an aural alert when a new IM Speed is issued for additional saliency. Reference [15] argued that aural alerts may be challenging to integrate, particularly in busy environments such as arrival. It noted that implementation would need to be considered in light of the functionality of the underlying algorithm, and that it may problematic to have aural alerts in environments where there are frequent IM Speeds.

In past research, pilots have tended to find the usefulness of spacing trend and / or status information to be high [14, 26]. However, this information can take on numerous forms including current interval relative to the achieve-by point, projected interval at the achieve-by point, current or projected interval at the first common point, differential ground speed (DGS), closure rate, straight-line range, etc. Previous research that examined a spacing concept in preparation for a flight event recommended improving the prediction separation tool such that the pilot is better able to judge the underlying functionality of the algorithm [24]. Reference [28] describes an advanced trend tool implementation developed after several simulation activities.

As described earlier, this simulation used a more basic trend tool, which was the ITT. The ITT feature of the AGD used in this study showed the IM aircraft's current spacing interval with the target relative to the first common point. Although pilots were instructed that the ITT indicator would not necessarily show them achieving the assigned spacing goal precisely at the achieve-by point, and that they should use ITT only as a general trend indicator, the majority still rated it as "of considerable use" or "extremely useful". The high rating of usefulness placed on the ITT element may be related to a lack of a graphical display feature that provides status/trend information. As the MITRE MPCDTI design used in the current study did not include a graphical depiction of spacing status or trend information, it is understandable that pilots placed a high usefulness value on ITT.

The information element on the CDTI that had the highest usefulness rating was target aircraft DGS. The information that DGS provides is whether the IM aircraft is opening or closing on the target, and how quickly. In past arrival research [14], the instantaneous DGS provided differences in ground speeds based on current ground speeds, whereas the system was basing the IM Speeds on a past speed of the target aircraft. Therefore, pilots would see the DGS increasing as the lead aircraft slowed with no associated IM Speed (the IM Speed would arrive at the future position where the target aircraft slowed and not before). This seemed to influence some pilots to want to make a speed change and question why the FIM-S system was not correcting. However, this effect was not necessarily observed in the current study. Since the majority of pilots felt that they "had a clear understanding of [their] spacing with the aircraft ahead and how well it was being achieved," they generally seemed to trust the performance of the system. Reference [15] substituted straight-line range to the target aircraft in lieu of DGS, which was also rated highly. However, as seen in this study, when both DGS and target aircraft range were available to pilots, they rated DGS as more useful.

DGS was rated overall as more useful than ITT; however, they were both rated highly which suggests that pilots used them together to obtain spacing trend / performance information. Although the high ratings are consistent with past research, there is still not a clear notion of what the most useful form of this information would be for pilots. This is an area that would benefit from focused study in future research that examined different display implementations.

The other CDTI elements with high ratings mostly consisted of features that improved their SA of their navigation situation and target aircraft, such as the highlight of the target aircraft, target aircraft's ground speed, and the IM aircraft route.

D. What are the key design considerations for a time-history algorithm intended to facilitate FIM-S departure operations?

Time-history based algorithms, such as [23], are typically developed without the assumption that the speed profiles for either aircraft would be known a priori. This is less of an issue in the arrival domain, as aircraft pairs can be constrained to achieve relatively similar speed and vertical profiles during en route merging. However, this study did not place altitude constraints on the departure and climb to cruise as such unrestricted climbs yield the most efficient departure operations. This presents issues for algorithm stability, however, as unrestricted climbs can result in highly divergent vertical profiles between an IM aircraft and its target. This creates difficulties in predicting speed profiles not only for a target aircraft, but for the IM aircraft as well. As a result, the highly dynamic nature of each aircraft's speed profile during departure could cause much more rapid changes in the time remaining than during an arrival merge operation, which would result in a far greater degree of IM Speed fluctuations.

Autoflight modes typically available for climb operations might also influence the stability and predictability of the path flown. During climb, thrust is typically held relatively constant at the climb thrust limit while the pitch attitude is positioned to maintain the target airspeed. When the flight crew or the cockpit automation changes the target speed, a pitch maneuver results. This pitch maneuver can significantly alter the vertical speed of the aircraft, which changes the vertical profile. Rapid changes in the vertical profile alter the relationship between IAS and true airspeed and this can add to the need to change the IM Speed more frequently.

In order to dampen potential fluctuations in IM Speed, the algorithm used in the simulation pursued a strategy of holding constant the time allowed for the algorithm to fix the spacing error, and maintaining that constant time even as the aircraft approached the achieve-by point. So while the error was being reduced, the time remaining to eliminate the remainder of the error was not. As a result, if the algorithm was engaged with the aircraft *inside* of the fixed time window, it began attempting to correct the spacing error at a point *past* the achieve-by point. This approach bears some similarity to elements of the CoSpace algorithm, as documented by [23], which places a lower bound on the time to correct the spacing error. This is needed to ensure stability close to the achieve-by point, and represents a feature for which this class of speed control algorithm likely has an inherent need.

There is inherent error in an algorithmic attempt to achieve spacing at a computed point past the achieve-by point specified by ATC. Pilot and controller expectations would be that the time ownship clears the achieve-by point on their displays (i.e. NAV and Legs page in the Flight Management System) is when they should see their assigned spacing goal being met. In this simulation, however, the algorithm used the first common point past the achieve-by point where the flight paths of each aircraft joined together to determine distance to the merge, and a fixed, but continuously updating, window to determine time to correct the error. Depending on route geometry and aircraft performance, both locations may vary with respect to the achieve-by point expected by pilots and ATC. This suggests that a key consideration for FIM-S using a similar time-history based algorithm is the closest proximity to the achieve-by point that a precise operation can be engaged with a certain likelihood of success.

The precise algorithm performed in the simulation as intended. When it was engaged with sufficient time to correct the spacing error, it generally helped achieve the assigned spacing goal at the achieve-by point within +/- 5 sec, with presentation rates that ranged from one to three IM Speeds every two minutes. The quantization of the IM Speeds may also have played a role in hastening the approach to the assigned spacing goal, as the displayed IM Speed was just as likely to be rounded up as rounded down. Crews were not given an indication of what an acceptable tolerance would be around the assigned spacing goal, but none seemed uncomfortable with the spacing operation overall.

Although the relatively consistent engagement period made selecting a single fixed value for the time to correct the error a convenient approach for the simulation algorithm, time-history algorithms intended to be used during real-world departure merge operations may develop alternate strategies to approach the problem due to the likelihood of highly variable engagement periods. Additional factors that time-history algorithm designers may find important to consider, especially during the dynamic departure environment, include:

1. The predictability of the climb profile of ownship.
2. The predictability of the climb profile of the target aircraft.
3. The reliability and stability / variability of those predictions.
4. The impact of turbulence, in particular wind shears on the climb profile.
5. The available autoflight modes and their impact on the vertical profile during speed changes.
6. The possible need for constraining the climb and/or speed profile of ownship.
7. The possible need for constraining the climb and/or speed profile of the target aircraft.

VI. Conclusion

Relative airborne spacing concepts such as FIM-S may be able to assist controllers in managing inter-aircraft spacing (e.g., achieve a precise interval on arrival or maintain a closed range interval on departure) as aircraft pairs merge at a common departure transition fix and / or into an en route stream. The findings from this study start to provide a framework for the application of FIM-S during departure operations, and suggest that it may be feasible and manageable from a flight deck perspective with promise of crew acceptability and compatibility with current operations. However, in addition to specifically evaluating the benefits of such an operation, areas such as the appropriate engagement altitude (or conditions beyond that studied in this simulation), termination procedures, information display, and algorithm design require additional research.

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Disclaimer

References

[1] Kopardekar, P., Green, S., Roherty, T., & Aston, J. (2003). Miles-in-trail operations: A perspective. *Proceedings of the AIAA 3rd Annual Aviation Technology, Integration, and Operations (ATIO) Conference*. Reston, VA: AIAA, Inc.

[2] Green, S. M., & Grace, M. P. (1999). Conflict-free planning for en route spacing: A concept for integrating conflict probe and miles-in-trail. *AIAA Guidance, Navigation, and Control Conference and Exhibit*. Reston, VA: AIAA, Inc.

[3] Balakrishnan, H. & Chandran, B. (2007). Efficient and equitable departure scheduling in real-time: new approaches to old problems. *USA/Europe Air Traffic Management R&D Seminar*, Barcelona, Spain, June 2007.

[4] Doble, N. A., Timmerman, J., Carniol, T., Klopfenstein, M., Tanino, M., & Sud, V. (2009). Linking traffic management to the airport surface. *Eighth USA/Europe Air Traffic Management Research and Development Seminar (ATM2009).* Napa, CA.

[5] Landry, S. J., Farley, T., and Hoang, T. (2005). Expanding the use of time-based metering: multi-center traffic management advisor. *Proceedings of the 6th USA/Europe ATM 2005 R&D Seminar*, Baltimore, MD, June 2005.

[6] Farley, T. C., Landry, S. J., Hoang, T., Nickelson, M., Levin, K. M., Rowe, D. & Welch, J. D. (2005). Multi-center traffic management advisor: operational test results. *Aviation Technology, Integration & Operations (ATIO) Conference.* Arlington, VA.

[7] Böhme, D., Brucherseifer, R., & Christoffels, L. (2007). Coordinated arrival departure management. *USA/Europe Air Traffic Management Research and Development Seminars*, September 2007. Barcelona, Spain.

[8] Wang, J. J., Datta, K. & Isaacson, D. (2005). Simulation of expedite departure path at Potomac tracon. *Proceedings of the 2005 IEEE / AIAA 24th Digital Avionics Systems Conference*, Oct. 2005, Washington, D.C.: IEEE Press.

[9] FAA / EUROCONTROL Cooperative Research & Development, (2001). *Principles of operation for the use of airborne separation assurance systems, Version 7.1*, 19 June 2001 http://human-factors.arc.nasa.gov/ihh/cdti/DAG_TM_WEB/Documents/ ASAS_report (0601).pdf.

[10] RTCA (2010). Safety, Performance and Interoperability Requirements Document for Airborne Spacing-Flight Deck Interval Management (ASPA-FIM), Interim Draft Version 0.8, Washington, D.C.: RTCA Inc, 9 November, 2010.

[11] Prevot, T., Callantine, T., Kopardekar, P., Smith, N., Palmer, E., and Battiste, B. (2004). Trajectory-oriented operations with limited delegation: an evolutionary path to nas modernization. *Proceedings of the AIAA 4th Aviation Technology, Integration, and Operations (ATIO) Forum,* Chicago, IL, September 2004. Reston, VA: AIAA, Inc.

[12] Barmore, B.E., Abbott, T.S., & Capron, W. (2005). Evaluation of airborne precision spacing in a human-in-the-loop experiment. *Proceedings of the American Institute of Aeronautics and Astronautics (AIAA) 5th Aviation, Technology, Integration, and Operations Conference,* Arlington, VA, September 26-28, 2005. Reston, VA: AIAA, Inc.

[13] Bone, R. S., Penhallegon, W. J., & Stassen, H. P., Simons, E., & DeSenti, C. (2007). *Flight Deck-Based Merging and Spacing (FDMS) Impact on En Route Air Traffic Control Operations: FDMS 1 Simulation. May–June 2006.* (MTR 070071). The MITRE Corporation Center for Advanced Aviation System Development, McLean, VA.

[14] Bone, R. S., Penhallegon, W. J., & Stassen, H. P. (2008). *Flight Deck-Based Merging and Spacing (FDMS) impact on flight deck en route operations: FDMS 2 simulation. August - September 2006*. (MTR 080034). The MITRE Corporation Center for Advanced Aviation System Development, McLean, VA.

[15] Bone, R. S., Penhallegon, W. J., & Stassen, H. P. (2008). *Flight Deck-Based Merging and Spacing (FDMS) impact on flight deck en route operations: FDMS 3 simulation. February - March 2007.* (MTR 080208), The MITRE Corporation Center for Advanced Aviation System Development, McLean, VA.

[16] Penhallegon, W. J., & Bone, R. S., (2008). *Flight Deck-Based Merging and Spacing (FDMS) impact on air traffic control during en route descent: FDMS 4 simulation. May–June 2007.* (MTR 080304). The MITRE Corporation Center for Advanced Aviation System Development, McLean, VA.

[17] Murdoch, J. L., Barmore, B. E., Baxley, B. T., Abbot, T. S., & Capron, W. R. (2009). Evaluation of an airborne spacing concept to support continuous descent arrival operations. *Eighth USA/Europe Air Traffic Management Research and Development Seminar (ATM2009).* Napa, CA.

[18] Oseguera-Lohr, R. M., Lohr, G. W., Abbott, T. S. & Eischeid, T. M. (2002). Evaluation of operational procedures for using a time-based airborne inter-arrival spacing tool—AIAA 2002-5824. *Proceedings of the AIAA's Aircraft Technology, Integration, and Operations (ATIO)* 2002 1-3 October 2002, Los Angeles, California. Reston, VA: AIAA, Inc.

[19] Mundra, A. D., Domino, D. A., Smith, A. P., Bateman, H. L., Stassen, H. P., Lunsford, C. R., & Porter D. J. (2008). Some new potential ASAS Applications in the terminal and en route domains. *Proceedings of 26th Congress of International Council of the Aeronautical Sciences including the 8th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference*, Anchorage, Alaska, USA, 14 - 19 September 2008. Reston, VA: AIAA, Inc

[20] Penhallegon, W. J., Mendolia, A. S., Bone, R. S., Orrell, G.L., & Stassen, H. P. (2010). *Flight Deck-Based Interval Management-Spacing (FIM-S) during Departures: Flight Crew Human-In-The-Loop (HITL) Simulation.* (MTR 100487). The MITRE Corporation Center for Advanced Aviation System Development, McLean, VA.

[21] Stassen, H., Penhallegon, W. & Weitz, L. (2010). *Multi-Purpose Cockpit Display of Traffic Information: Overview and Development of Performance Requirements*. American Institute of Aeronautics and Astronautics, 1-18.

[22] Estes, S., Penhallegon, W. and Stassen, H. P. (2010). A Multi-Purpose Cockpit Display of Traffic Information. *Proceedings of the Human-Computer Interaction Aerospace (HCI-AERO) Crew-Ground Integration Conference.* Nov 3-5, 2010, Cape Canaveral, FL.

[23] EUROCONTROL (2006). CoSpace 2005-ASAS Sequencing and Merging: Flight Deck User Requirements, Version 2.1.

[24] Bone, R., Helleberg, J., & Domino, D. (2003). *Surface moving map and approach spacing preliminary findings: Safe Flight 21 Ohio River Valley 2001 MITRE CAASD flight simulations*. (MTR 03W0000069), The MITRE Corporation Center for Advanced Aviation System Development, McLean, VA.

[25] FAA (2001). *Operational Evaluation-2 final report*. Cargo Airline Association (CAA) ADS-B Program and FAA Safe Flight 21 Program, Washington, DC: DOT FAA.

[26] Hebraud, C., Hoffman, E., Papin, A., Pene, N., Rognin, L., Sheehan, C., and Zeghal, K. (2004). *CoSpace 2002 flight deck experiments assessing the impact of spacing instructions from cruise to initial approach*. EUROCONTROL report No 388, Volumes I and II. Bretigny-sur-Orge, France: EUROCONTROL Experimental Centre.

[27] Lohr, G. W., Oseguera-Lohr, R. M., Abbott, T. S., Capron, W. R., and Howell, C. T. (2005). *Airborne evaluation and demonstration of a time-based airborne inter-arrival spacing tool*. NASA/TM-2005-213772. Hampton, VA: NASA Langley Research Center.

[28] Hoffman, E., Pene, N, and Zeghal, K. (2006). *Flight deck user requirements for airborne spacing (Sequencing and Merging)*. Bretigny-sur-Orge, France: EUROCONTROL Experimental Centre.