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Air Traffic Controller use of Interval Management during Terminal Area Metering

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***Abstract*—A Human-in-the-loop simulation examined the integration of a relative spacing concept (Interval Management [IM]) into a future absolute spacing Terminal Sequencing and Spacing (TSAS) terminal metering environment. Air traffic controllers and flight crews utilized current day automation capabilities with enhancements for terminal metering and IM to test the integration for acceptability and necessary spacing awareness information. Controller results are presented in this paper. Controllers examined different sets of spacing information across several traffic scenarios. The results indicate IM is compatible with terminal metering, but the appropriate tools to support trust of IM should continue to be examined. Concept and operational recommendations are made, including enhancements to IM-related displays.**

Keywords- Absolute spacing, air traffic control, Automatic Dependent Surveillance-Broadcast, Interval Management, metering, relative spacing, NextGen, Terminal Sequencing and Spacing, Time Based Flow Management

I. Introduction

The Federal Aviation Administration (FAA) plans to deploy capabilities and procedures to extend time-based metering into the terminal environment by 2019 via TSAS. The FAA and industry are also developing requirements for IM, in which flight crews space relative to another aircraft based on an Air Traffic Control (ATC) clearance. This improves spacing consistency and predictability by enabling aircraft to be spaced closer to a given separation standard. This increases overall arrival throughput and capacity.

IM and TSAS have been examined in numerous simulations as independent concepts. However, both will need to function together in the future environment. While some past work has examined integrated IM and TSAS operations, this human-in-the-loop simulation builds on that work by examining open questions. It examined how controllers should use the two spacing methods (relative and absolute) to manage arrival aircraft in the terminal area.

II. Background

The FAA expects to see continued traffic growth through 2030 with severe congestion at major airports such as Hartsfield–Jackson Atlanta International Airport (KATL) [1]. To address this growth, the FAA plans to implement Next Generation Air Transportation System (NextGen) enhancements such as Trajectory Based Operations (TBO) to manage future traffic demand and to enable more efficient and environmentally-friendly navigation procedures [2]. TBO operations utilize Performance Based Navigation (PBN) and time-based metering to increase efficiency and predictability.

PBN consists of stringent performance navigation requirements that enable accurate and predictable flight paths. PBN is used to achieve benefits such as optimally-placed routes (e.g., to avoid terrain) with reduced flight path length [3]. Time-based metering manages flow rates of aircraft into constrained airspace by building a sequence and schedule with Scheduled Times of Arrival (STAs) at specified points. Controllers provide instructions (often with the help of automation) to aircraft to meet the schedule. PBN and time-based metering are used together to develop an optimized trajectory that has accurate, predictable crossing times for specific points which leads to more efficient operations for each individual flight (e.g., fewer tactical maneuvers and more time on optimized PBN routes), while predictably managing multiple flights in constrained airspace.

In addition to PBN and time-based metering, new and advanced tools are necessary to enable TBO. Multiple concepts (e.g., relative spacing and absolute spacing) and capabilities (e.g., flight deck and ground metering support and data link) that are being developed somewhat independently will also need to work together. Additionally, different types of tools (e.g., controller decision support tools, Required Time of Arrival [RTA], IM) will be needed to meet the time-based schedule. Not all tools, however, achieve the schedule in the same way or with the same level of accuracy. The appropriate tool(s) needs to be chosen to meet the desired goal and benefit.

A. *Metering and Terminal Sequencing and Spacing*

Time-based metering involves delivering aircraft to a specific point at a specific time. Time-based metering is currently conducted in en route arrival operations with a system called Time Based Flow Management (TBFM). TBFM is used to synchronize multiple traffic flows and to deliver aircraft to the Terminal Radar Approach Control (TRACON) boundary on schedule. Area Navigation (RNAV) route data is used to build four-dimensional trajectories to determine runway assignments, the overall traffic sequence, and STAs for individual aircraft at specified points. Information is presented to the en route controller to meet the sequence and schedule developed by TBFM. While a schedule is built to the runway, metering currently stops at the TRACON boundary. TRACON controllers no longer have the sequence and schedule information once aircraft are in the TRACON, so they must reevaluate the traffic situation and then determine an appropriate sequence and schedule. TRACON controllers must then maneuver the aircraft without the sequence and schedule information, which can lead to inefficiencies. While delivering aircraft metered to the TRACON boundary can reduce fuel burn and increase traffic capacity, further benefits can be realized if metering continues into the TRACON.

Terminal metering is intended to solve the problems associated with tactical control in the terminal airspace (e.g., increased time flown, leading to increased fuel burn). It is intended to keep aircraft on optimized routes longer than would otherwise be possible and to enable shortened traffic patterns such as those enabled by Required Navigation Performance (RNP) Radius-to-Fix (RF) turns.

Time-based terminal metering is enabled by TSAS, which adds more sophisticated scheduling components to TBFM and controller tools to Standard Terminal Automation Replacement System (STARS), the terminal automation platform. On STARS, TSAS displays both scheduling and sequence information to the controller. TSAS also provides decision support tools to help the controller meet the schedule by getting aircraft to the appropriate points by the STA. Key features include the runway assignment and associated sequence number, slot marker (showing where the aircraft should be to reach the control point at the STA), speed advisory (an automation-calculated speed to get the aircraft to the next control point at the STA), and early / late indictor (shown if a speed advisory will not get the aircraft on schedule), and a timeline with the Estimated Time of Arrival (ETA) and STA for each aircraft. TSAS was initially developed by National Aeronautics and Space Administration (NASA) and examined in numerous simulation activities [4]. It was then tech transferred to the FAA and is planned to be implemented at select airports in 2019.

During terminal metering, and while aircraft are still in the en route environment, ETAs are calculated by TBFM at the meter fix (where aircraft cross into terminal airspace), merge points, additional schedule constraints, and the runway threshold. ETAs are used to create a schedule and sequence with STAs to control points to satisfy minimum spacing and wake separation requirements (with an additional buffer). The sequence and schedule are frozen prior to each aircraft's top-of-descent.

Aircraft are sequenced and maneuvered in the en route environment such that only speed control should be required for aircraft to meet the schedule and remain on the PBN procedure in TRACON airspace. En route controllers use TBFM to precondition and deliver aircraft to the TRACON within some error tolerance. TRACON controllers then work to the schedule by primarily using speed instructions to resolve any schedule issues.

B. *Interval Management*

IM is a set of equipment capabilities and procedures for controllers and flight crews to manage inter-aircraft spacing (e.g., achieve an interval on final approach) based on an ATC clearance. Ground tools can be used to support the set-up and monitoring of IM. IM can be used in several environments (e.g., en route miles-in-trail operations and terminal metering), depending on the operational objective and controller needs. Controller responsibilities, including those for separation, do not change.

IM is a relative spacing operation, in which trajectory corrections are made relative to real-time behavior of a lead aircraft. This is in contrast to an absolute spacing operation, such as time-based metering, in which an aircraft is controlled to cross a specific point at a designated time. IM is a tactical tool and the spacing objective can be based on an underlying schedule, separation standard, or other operational need.

IM utilizes Automatic Dependent Surveillance-Broadcast (ADS-B). ADS-B equipment on an aircraft broadcasts position and velocity information, as well as other data such as call sign and weight category. ADS-B transmissions can then be used by receivers on the ground for applications such as ATC separation services, or by aircraft for applications such as IM.

The controller is responsible for appropriately sequencing and spacing aircraft prior to the initiation of IM. Such set-up can be conducted via current controller capabilities, or in more complex environments, with new capabilities. Set-up involves the controller issuing an IM clearance that either invokes speed adjustments alone, or a single turn and then speed adjustments. The IM clearance includes information such as lead aircraft identification, IM clearance type (e.g., achieve-by then-maintain), Assigned Spacing Goal (ASG) units and value (e.g., 90 seconds or 15 miles), and IM special points (e.g., Achieve-By Point [ABP] and Planned Termination Point [PTP]). A sample clearance is: "AAL245 achieve 100 seconds by DERVL behind United 123 on EAGUL6."

Once this information is provided to the flight crew, it is entered into the flight deck IM equipment. The equipment then checks that the initiation criteria are met. If they are, the equipment starts providing information (primarily the speed to fly, termed "IM speed"). Situation awareness information is also provided to assist the flight crew in monitoring the progression of IM.

With the presentation of each new IM speed, the flight crew ensures that the IM speed is compatible with the aircraft's current configuration and environmental conditions. The flight crew is expected to follow the IM speeds in a timely manner consistent with other cockpit duties unless an issue prevents doing so. If any issue arises, the flight crew will maintain their last implemented IM speed and contact the controller to report being unable to conduct IM. Similarly, if the controller has any conditions that prevent continued IM operations, the controller will contact the flight crew and terminate or suspend IM. If the IM is suspended, the controller may choose to resume IM at a later point, should the appropriate conditions exist. If no issues arise for either the controller or the flight crew causing a suspension or termination, the flight crew continues following the IM speeds and the controller continues monitoring the operation until the aircraft reaches the PTP. At this point, the flight deck IM equipment removes the IM speed from the display(s) and IM is terminated.

For additional information on the broader IM concept and preliminary requirements, see [5,6]. These documents describe near-term operations; however, updates are being developed to enable more advanced operational implementations.

IM can be used to improve spacing consistency and predictability by enabling flight crews to make more frequent and efficient speed adjustments than are possible with ground-based metering and pilot-controller voice communications alone. This is because airborne equipment can provide more speeds than the ground to make trajectory corrections. Also, since an aircraft will know its own trajectory more precisely than a ground system, the speeds will be generated using better information and will thus be more efficient. Setting, then achieving, a consistent, low-variance (+/-10 seconds 95% of the time) spacing interval reduces the time interval between aircraft in a traffic flow, which allows each aircraft to be spaced closer to a given separation standard [7,8]. This enables increased arrival throughput and sector or facility capacity. IM is also expected to lead to a reduction in the number of controller interventions [9,10,11,12] and frequency congestion [9,13]. For further details on IM benefits, see [14].

III. Interval Management and Metering

Reference [15] proposed how IM and metering could work together and be mutually beneficial. The authors suggested using a ground-based metering capability to smooth inbound flows and provide accurate spacing at a point like the initial approach fix where IM could be used to achieve further accuracy from there to the Final Approach Fix (FAF). Reference [16] stated that terminal controller metering tools and IM are complementary, and both can be utilized for the overall success of terminal metering operations. The strengths of each capability are used and the weaknesses of each are reduced. The ground tool is used to sequence and merge aircraft (where absolute spacing is important) and the flight deck tool is used when relative spacing becomes more important in the later stages of approach and landing. Simulations have shown that controllers using terminal metering make this switch from absolute spacing to relative spacing when aircraft are close to or on final approach, and some have suggested using relative spacing tools in these cases [16,17,18].

The general acceptance of IM operations has been reported in numerous simulations, including some examining IM during en route and terminal metering [7,16,19,20,21]. A detailed literature review is provided in [14]. A summary is provided here in the context of the following three questions addressed in this simulation.

A. Can IM (relative spacing) work in a TSAS (absolute spacing) environment?

The main question for IM working in an absolute spacing environment is whether or not IM aircraft behavior will look different than non-IM aircraft behavior. This may be most obvious when comparing the IM aircraft position relative to the TSAS slot marker. As discussed previously, the IM aircraft performs spacing adjustments relative to a lead aircraft. In absolute spacing, spacing adjustments are made with respect to crossing a specific location at a designated time, independent of the lead aircraft. IM may also cause some confusion relative to the slot markers because it is working toward achieving the ASG at the ABP, while TSAS may be working toward more constraint points and getting the aircraft into the slot markers more quickly. In the past work, IM aircraft have been reported to be outside of the slot markers more often than aircraft not conducting IM [22,23]. There have been reports of controllers being uncomfortable with IM aircraft behavior relative to slot markers [22], including preparatory activities leading up to the simulation reported in this paper [14]. While slot markers were found useful in general, in some instances they were reported as less so for IM aircraft [22,23]. Proposals to modify slot makers have been mentioned [22] but not reported on. The removal of slot markers for IM aircraft has also been tested but specific results were not provided [16].

B. What are the appropriate Interval Management tools in a terminal metering environment?

Controllers are expected to need information to (1) generate the parameters for and issue the IM clearance, and (2) input and monitor the status of the IM operation, including knowing which aircraft are part of an IM operation.

Previous en route simulations have examined the provisioning of automation-generated clearance information either in a new window [20] or an existing meter list [16,23,24,25] with generally positive results. The TRACON does not currently have a metering list.

To help controllers actively manage and monitor IM operations, IM status information should be provided directly on the surveillance display. Such information will help the controller determine which aircraft are part of an IM operation, what their role is (i.e., trail or lead), and the status of the IM operation (e.g., active and no issues). Past work examined this topic and is reviewed next.

When displaying the IM clearance in a specific area such as a separate window on the surveillance display, the trail and lead aircraft roles are shown out of necessity. However, that information may be as useful, or more useful, when associated with the aircraft symbol because the aircraft symbols are often the primary focus of the controller. When display features in the data block or other locations near the aircraft symbol were used for aircraft role in an IM operation, the feedback was positive (e.g., circles around the trail and lead aircraft symbols [7,11], and information in the data block [20,24]). There have been questions about whether the lead aircraft should be identified. Reference [23] tested identifying and not identifying the lead aircraft in the data block. When the lead aircraft was identified for the controller, IM operations were suspended less often, and controllers confirmed they liked the information. In a simulation of a limited IM implementation with no new controller IM tools / information, pilots reported the initiation of IM [19]. With this information, controllers were reported to use existing display features (e.g., scratchpad, data block position) to flag aircraft that were conducting IM to assist in their determination of which aircraft were conducting IM.

In order to help the controller know / remember the status of an IM operation (e.g., proposed / eligible, active, suspended, terminated), it must be presented. If there is a point where the IM trail aircraft downlinks status information, it can be automated. Until that point, the controller must make an input to change that status of the IM operation. Once that input is made, the information can be shown on the display. It can be shown in a separate IM clearance area, near the aircraft symbol, or in both locations.

References [7,11] used color-coding of the IM features associated with the aircraft symbols to indicate two different states (lead aircraft being identified and IM active). Controllers reported the information to be useful. Reference [20] showed aircraft state (pending versus active) in the data block. IM eligibility was not shown. Controllers reported the pending state to not be useful. Reference [25] also showed status states (capable, pending, active, or terminated) for the trail and lead aircraft in the data block. Controllers reported the different states as being important information. Reference [22] did not include indications in the data block for IM capable, but IM active was shown. The information was rated as helpful and usable. Reference [23] had an indication in the data block to indicate IM capable for the trail aircraft. The IM status indicators were rated as useful, but controllers reported they did not want to have other IM status indicators, such as suspended or terminated, in the data block. In [24], controllers had IM capable and active indications in the data block, and they reported favorably on them.

Controllers may also need information about how well the trail IM aircraft spacing is progressing and whether there are any spacing issues. It remains unclear what information controllers require to monitor the progress of IM and to determine acceptable spacing for the handoff and final spacing at the ABP. In a simulation with no new controller tools / information on IM, reference [13] reported controllers may need to know whether the ASG can be achieved (or an intervention is necessary), and a better understanding of IM aircraft behavior (e.g., relationship between IM speeds flown and the ASG). Reference [20] reported controllers found the predicted interval at the ABP to be useful. Reference [25] included the Meet Time Error parameter that is currently available in en route metering, and controllers reported having this information was useful. However, only a slight majority of controllers reported that it was useful for maintaining awareness of IM. References [7,11] showed a numerical value of the current spacing along a line connecting the lead and trail aircraft. Controllers reported the information to be useful.

The set of necessary IM information and the split of that information between a clearance window (that is likely to be scanned less frequently) and the information associated with the aircraft symbol (that is likely to be scanned more frequently) needed further examination.

C. Do any new IM tools conflict with expected TSAS tools?

Any new IM tools will need to be integrated into existing and planned displays. As mentioned previously, the use of the TSAS slot marker is likely to be affected by IM. IM working toward achieving the ASG at a single point, and TSAS managing to several constraint points, could lead to confusion if speed advisories and early / late indications are shown. The speed advisories could be confusing if the controller sees a speed advisory that does not match the (calculated) airspeed of an aircraft conducting IM. It could appear that IM will not meet the ASG when comparing the speeds. The early / late indication could be confusing for similar reasons. However, the equivalent of the early / late indication should likely be provided for IM if the ground system determines the IM cannot solve the spacing error.

The other TSAS information elements including runway assignment, sequence number for the assigned runway, slot marker airspeed, aircraft airspeed, and the timeline, are likely to be used by controllers in a similar way with or without IM. However, the aircraft airspeed could be useful in helping the controller determine what speed the aircraft is flying for IM.

While IM during terminal metering operations appears feasible, considerations should be given to the appropriate and necessary tools to be utilized by the controllers during mixed IM and non-IM operations.

IV. METHOD

A. Controller Workstation

The ATC interface was hosted on a STARS display with added TSAS and IM functionality. The workstation had a representative 2K display that hosted a STARS interface and a keyboard and trackball, similar to the currently fielded system.

For this simulation, terminal metering was the foundation upon which IM was implemented. The TSAS software and interface design integrated into MITRE's laboratory was heavily based on that used in an Operational Integration Assessment event [26]. The TSAS features implemented included those shown in Figure 1 as well as a timeline. Slot markers had a 15-second radius for the feeder controller and a 5-second radius for the final controller.

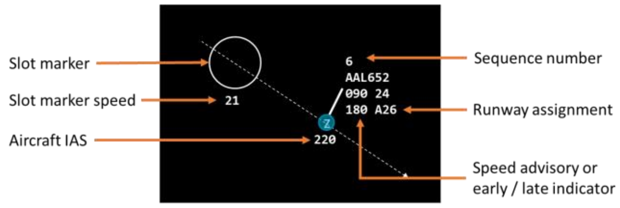

Figure 1. Prototype TSAS Features on STARS

The IM interface was developed in consideration of past work as well as an early draft of a preliminary design document developed within (but not released by) the FAA. The TSAS features were not modified for IM operations. However, the speed advisory and early / late indicator were replaced by IM information for the trail aircraft. The TSAS speed advisories have been reported as less useful for IM operations [23] and removed in other simulations [16].

Three main features were added for IM: an IM clearance window, aircraft role in and status of IM in the aircraft data block, and a slot marker color change.

The clearance window showed the clearance information and the state of the clearance. Four states were shown based on controller input: Eligible, Active, Suspended, and Terminated. If a clearance was determined to be valid and feasible, the clearance information and an "Eligible" status was provided in the IM clearance window to the controller with the trail aircraft. The clearance could be accepted or rejected by the controller. If the clearance was rejected, the status field changed to "Rejected." The text remained for 30 seconds prior to the full IM clearance proposal being removed. This delay allowed for awareness of the rejected operation and to allow for re-activation if the rejection was in error. If the clearance was accepted, instead of rejected, the status field changed to "Active" upon controller input.

The order of the IM clearances in the IM clearance window were based on the runway sequence and consistent with the order of the TSAS timeline. The text in the window was color-coded to indicate different statuses. White indicated activation was possible. Green indicated an IM operation had been accepted by the controller (and likely active). Yellow indicated an action such as termination was required. Dark gray indicated the information was inactive and going to be removed.

The other fields in the IM clearance window are reviewed next. The fields were based on the clearance types used in the simulation which were achieve-by then maintain and capture then maintain. The ASG was calculated by TBFM and was the trail aircraft's STA at the ABP minus the lead aircraft's STA at the ABP. The ASG had an "IM aware" buffer reduction of 0.1 NM based on the expected low spacing variance provided by IM (as compared to metering only operations). The ASG was presented with a 1-second resolution. Next to the ASG (in some scenarios) was a spacing prediction value in seconds to allow the controllers to compare the spacing estimated by TBFM / TSAS (ETA differential) to the ASG and to determine how the IM operation was progressing.

After the lead aircraft identification, the sector of the lead aircraft was included if both aircraft were not in the same sector (for coordination between controllers). The ABP and lead aircraft route were also provided.

IM information was also provided in aircraft data blocks and on the TSAS slot marker (Figure 2). The information for the trail aircraft was shown in the third line of its data block. The field was not time-shared with other information. As mentioned previously, the information for the trail aircraft replaced the TSAS speed advisory and early / late indication because IM was the speed solution, and thus, the TSAS speed advisories become unnecessary. The status states for the trail aircraft were one of the following: "T(E)" / eligible, "T(A)" / active, "T(S)" / suspended, "T(I)" / invalid, or "T(NS)" / No Speed (i.e., no speed solution was found). Termination was not shown. The "no speed" state was only shown in yellow / as alerted for active or suspended operations because controller action was required prior to the operation returning to an active state.

Lead aircraft information was also shown in the aircraft data block. The information for the lead aircraft was shown in the fourth line of its data block and did not replace any TSAS features. The field was not time-shared with other information. The status states were one of the following: "L(A)"/ active and "L(S)"/ suspended. The lead aircraft was shown as active during invalid and "no speed" states so the controller had awareness that the lead aircraft was part of an IM operation that the trail aircraft controller had not yet terminated.

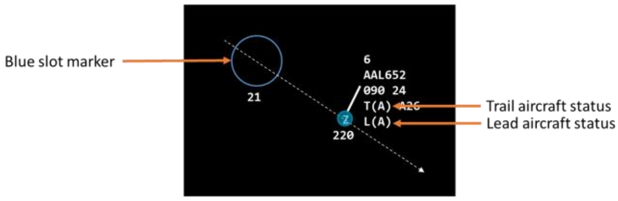

Figure 2. Prototype Interval Management Features on STARS

To allow the controller at a glance to differentiate between aircraft conducting IM and those not conducting IM, the color of the slot marker for the IM trail aircraft noted to be actively conducting IM was changed from white to blue. The controllers could note that any aircraft with a blue slot marker may be off its slot marker and would be working toward that slot marker while conducting IM (and therefore, did not need to be issued a speed). The slot markers for trail aircraft remained blue when an IM trail aircraft was in the suspended state and returned to white when the controller made the keyboard entry to indicate IM was terminated. The slot markers for lead aircraft and all other aircraft remained white.

The following three IM tool sets were developed for the simulation to examine the controller information needs.

- **Basic**: TSAS features, IM clearance window, and IM trail and lead aircraft status fields in the data block
- **Basic+ cue**: The basic tool set plus the slot marker color change (cue)
- **Basic+ cue and prediction**: The basic+ cue tool set plus the spacing prediction value (ETA differential)

B. Traffic and Airspace

The airspace modeled for this simulation was based on Phoenix International Airport (KPHX). North RNAV operations were run. The two RNAV arrival procedures (BRUSR1 and EAGUL6) were heavily based on current arrival procedures. Minor modifications were made to have the arrival connect to the instrument approach procedure and to accommodate the RNP RF turns that joined the final approach. The airspace had a feeder (Apache airspace) and a final (Freeway airspace) position (Figure 3).

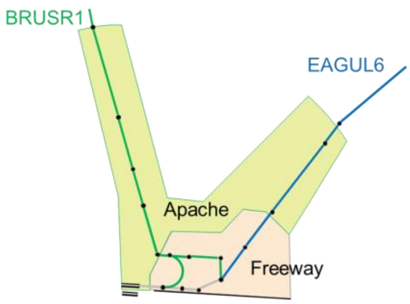

Figure 3. Airspace Overview

The arrival rate was approximately 40 aircraft per hour to Runway 26. The higher workload environment was desirable to keep the controllers engaged, but not so much that disturbances in the traffic flow occurred (and vectoring became necessary). The intent was to examine the integration of IM operations in the terminal metering environment without disturbances. Aircraft were mainly large but also included heavy category aircraft. The percentages of aircraft that were capable of flying the different procedures were: RNAV arrival (100), RNP RF turn (approximately 20), IM as a lead aircraft (100), IM as a trail aircraft (approximately 60).

Aircraft were delivered from the en route environment to the TRACON boundary with a set deviation around the center of the slot markers, which simulated the management of aircraft by an en route controller. Aircraft arrived no earlier than 30 seconds and no later than 15 seconds relative to their STAs, with a distribution between those maximum values. The expected delivery for terminal metering operations is approximately +/- 30 seconds [4]. However, based on aircraft being able to more easily decelerate than accelerate in the TRACON, and the arrival procedures, the 15-second threshold was chosen. This is consistent with a simulation reported in [27] in which en route controllers were asked to deliver aircraft +/- 30 seconds with a preference for the early side.

For IM, aircraft were flown either by the participant flight crew or pseudo-pilots. All aircraft used an IM algorithm defined in [5]. The IM algorithm was a closed-loop speed control algorithm that managed the inter-aircraft spacing error within pairs by estimating arrival and approach dynamics of each aircraft and then providing corrective speeds to the flight crew. It did not have direct access to aircraft performance but used kinematic assumptions to estimate what each aircraft's altitude and speed profiles would be. Aircraft dynamic models were based on industry-standard mathematical descriptions (e.g., Base of Aircraft Data models for non-participant flight crew aircraft and a more complex model for the participant aircraft). The models have been matured over time to more accurately represent real world aircraft behavior.

C. Participants

Controllers were coordinated through the FAA and National Air Traffic Controllers Association (NATCA). Controllers were compensated for their participation through standard FAA processes. Nine controllers acted as final and feeder controllers and were from a variety of busy TRACONs. Controllers had an average experience of 15.4 years. The average age of the controllers was 39 years.

D. Simulation Procedure

Controllers participated for a total of five days. The first two days were training and the last three were data collection. Training days started with a detailed briefing, which was followed by actively controlling traffic in the lab. The training started with a day of terminal metering and TSAS-only training. Terminal metering operations were new to the controllers, so it was introduced before adding IM into those operations. The following day was used to introduce and train IM in the terminal metering environment. On the third day, data collection began. A total of six traffic files were developed for data collection and were derived from real world KPHX operations. Each file was unique but very similar in traffic density, mix of aircraft type and category, aircraft capabilities, and delivery relative to the schedule from the simulated en route controller. Each traffic file lasted approximately 40 minutes. Each participant experienced the same set of data collection scenarios (in a repeated measures design).

Over the course of the three-day data collection, the controllers experienced one traffic file with en route initiation (reported in [14]), while pilots were trained. For the remainder of the day, controllers experienced the other six traffic files with the flight deck participants. The block order of the traffic files was counter-balanced across participant groups.

Off-nominal events were introduced for the controllers through pseudo-pilot action. Each day every controller experienced an event where the termination or suspension of IM was required. The pseudo-pilot was told to acknowledge the IM clearance from the feeder controller but to fly a constant speed without engaging IM. The trail aircraft held its speed and started encroaching upon the lead aircraft (which eventually led to a separation issue) until the controller intervened. The issue started to evolve in the feeder controller's airspace, but the spacing issue may not have been fully realized until the final controller's airspace (based on the slow progression of the overtake).

Four methods of data collection were used: paper questionnaires (one after each scenario and one at the end of the simulation), system recorded data, observations, and final debriefs. Most questions on the questionnaire were response-scale items with 100 hash marks (without numeric labels) and an opportunity for comments. The scale was anchored on the left with the label "Strongly Disagree" and on the right with "Strongly Agree." In the presentation of the results, any mean (M) responses below the midpoint (i.e., lower than 50) on the scale were considered to be on the "disagree" side while any responses above the midpoint (i.e., higher than 50) on the scale were considered to be on the "agree" side. Any responses at the midpoint (i.e., equal to 50) were considered to be "neutral." Responses that have a standard deviation (SD) of greater than approximately 25 and the responses distribution is relatively flat are noted as "variable." If a response was missing, the reply frequency is noted (e.g., 8/8).

V. RESULTS

A. Interval Management in a Metering / TSAS Environment

Of the 1203 IM clearances proposed to the controllers, 97.2% were initiated. Less than 1% were suspended and 3.4% were terminated by the controller for various reasons (e.g., perceived potential for a more efficient operation, spacing concern). Five events occurred where an aircraft was below the applicable separation standard outside the FAF. However, none of the events were for trail aircraft conducting IM.

The majority (89%) of controllers agreed (M=69.9; SD=22.1) IM was compatible with terminal metering. The majority (78%) of controllers agreed IM is acceptable (M=65.0; SD=22.4) and desirable (M=67.3; SD=24.7). When asked about the acceptability of their overall workload, all agreed that it was acceptable (M=88.1; SD=10.2). Some reported issues with workload being too low in this TBO environment. The majority (89%) of controllers agreed their roles and responsibilities were clear for IM aircraft (M=87.0; SD=17.8) and all agreed for non-IM aircraft (M=93.0; SD=7.9)

All controllers agreed their level of traffic awareness was acceptable for IM trail aircraft (M=86.6; SD=10.5) and non-IM aircraft (M=91.8; SD=7.6). Controllers were asked if the spacing of the aircraft would remain outside their separation requirement. The majority (78%) agreed for IM aircraft (M=63.1; SD=27.7) and all agreed for non-IM aircraft (M=80.3; SD=14.6). Participants were asked whether the spacing when conducting IM was acceptable. The majority (78%) agreed for IM aircraft (M=68.7; SD=22.7) and the majority (7/8; 88%) agreed for non-IM aircraft (M=82.1; SD=16.5). When asked whether the necessary monitoring was acceptable, the majority (89%) agreed for IM aircraft (M=77.6; SD=17.4) and all controllers agreed for non-IM aircraft (M=85.2; SD=12.1).

Several comments were made on the questions related to controller confidence in monitoring and predicting spacing and separation. A majority (~78%) of controllers expressed issues with not knowing what speeds would be flown and when. Controllers reported trusting the flight crew and letting IM "play out," but still feeling out-of-the-loop. Similar comments were also made to the research observers. The observers noted that even though IM appeared to perform as expected, controllers did not feel entirely comfortable allowing aircraft to conduct IM, especially when close to the separation standard. Certain geometries appeared to increase that unease. When controllers were asked whether the handed-off aircraft would be accepted with minimal problems, the majority (89%) agreed for IM aircraft (M=84.6; SD=16.6) and all agreed for non-IM aircraft (M=93.4; SD=6.6). All designed-in off-nominal events where a trail aircraft overtook its lead were detected. Participants were asked whether it was clear that IM was driving toward appropriate spacing. Responses were variable, but the majority (78%) agreed for IM aircraft (M=62.9; SD=33.9) and all (8/8; 100%) agreed for non-IM aircraft (M=89.8; SD=12.0).

The majority (89%) of controllers agreed that there were an acceptable number of aircraft (~60%) performing IM (M=77.2; SD=27.6). Controllers reported on average that 78.6% (SD=19.7; 7/7) aircraft performing IM and above was preferred.

IM aircraft (45.9%) were in the slot markers for less time in feeder airspace as compared to non-IM aircraft (54.2%) and both types were ahead of schedule: IM (M=-14.1 seconds; SD=18.2) and non-IM aircraft (M=-14.6 seconds; SD=13.5). IM and non-IM aircraft had similar amounts of time (approximately 18%) spent in their slot markers in the final controller's airspace and both types were ahead of schedule: IM (M=-12.9 seconds; SD=12.6) and non-IM aircraft (M=-11.1 seconds; SD=9.3). Across all the conditions when the lead aircraft was ahead of its slot marker center, the IM trail aircraft was also ahead with similar variance. Controllers expressed interest in landing aircraft as soon as possible. IM pairs and non-IM pairs also looked very similar across all conditions (detailed results in [14]).

IM operations met the performance requirement of +/-10 seconds 95% of the time at the ABP and during maintain operations (met by the operations between 95.8 – 100% of the time). IM aircraft met the spacing goal with an SD of 4.1 seconds (half that of non-IM aircraft). When aircraft were conducting IM, IM aircraft remained on their RNAV procedure 98.2% of the time, while non-IM aircraft remained on their RNAV procedure 93.8% of the time.

B. *Interval Management and TSAS Display Elements*

Controllers were asked whether the TSAS elements were helpful for IM and non-IM aircraft (see Table I).

TABLE I. TSAS ELEMENTS HELPFUL?

Display Element	Aircraft Type	Rating and Frequency	M (SD)
Slot markers (non-blue)	Non-IM	Majority agreed (67%)	**79.8** (22.7)
	IM	Responses variable	**52.8** (35.0)
Speed advisories	Non-IM	Majority agreed (67%)	**69.1** (25.4)
	IM	Variable but majority agreed (67%)	**66.1** (31.2)
Early / late indicator	Non-IM	Responses variable	**30.2** (24.9)
	IM	Responses variable	**35.9** (34.1)
Slot marker speed	Non-IM	Variable but majority agreed (89%)	**80.0** (28.4)
	IM	Variable but majority agreed (89%)	**76.9** (28.0)
Aircraft IAS	Non-IM	Variable but majority agreed (89%)	**78.4** (28.3)
	IM	Variable but majority agreed (89%)	**77.2** (28.2)
Timeline	Non-IM	Responses variable	**34.1** (36.4)
	IM	Responses variable	**40.7** (38.9)
Runway assignment	Non-IM	Responses variable	**70.9** (26.2)
	IM	Responses variable	**71.0** (26.1)
Runway sequence #	Non-IM	Majority agreed (89%)	**82.0** (19.6)
	IM	Majority agreed (89%)	**82.1** (19.6)

For IM display elements, controllers were asked if the information in the IM clearance window was helpful for IM. The majority (78%) agreed for the IM status information (M=71.1; SD=30.8). The majority (78%) agreed for the projected spacing / ETA differential (M=75.1; SD=21.2). The majority (89%) also reported that it was helpful to be informed when there was no speed solution for IM (M=82.4; SD=17.9). Controllers were also asked about the new IM elements and if they were useful for IM (see Table II).

TABLE II. IM ELEMENTS USEFUL?

Display Element	Rating and Frequency	M (SD)
Trail aircraft status	Majority agreed (89%)	**82.1** (16.8)
Lead aircraft status	Majority agreed (89%)	**81.9** (16.9)
Blue slot marker	Responses variable	**66.7** (33.7)

Controllers were asked whether they had the necessary display elements to conduct IM (see Table III). Controllers agreed, on average, regardless of role or tool set. Higher variability existed for both feeder and final replies with the basic and the basic+ cue tool sets. A repeated measures

ANOVA was conducted and did not reveal any significant differences.

TABLE III. NECESSARY IM DISPLAY ELEMENTS AVAILABLE?

Controller Tool Set	Controller role	M (SD)
Basic	Feeder	**76.8** (25.3)
	Final	**71.5** (26.8)
Basic+ cue	Feeder	**75.5** (27.7)
	Final	**80.3** (25.9)
Basic+ cue and prediction	Feeder	**81.1** (21.4)
	Final	**82.3** (15.2)

Controllers were asked whether they could detect spacing or separation issues (see Table IV). Controllers agreed, on average, regardless of role, tool set, or aircraft role. Higher variability was exhibited in feeder replies for IM aircraft with all tool sets and for non-IM aircraft with the basic tool set.

TABLE IV. ABLE TO DETECT SPACING / SEPARATION ISSUES?

Controller Tool Set	Controller role	Aircraft type	M (SD)
Basic	Feeder	Non-IM	**84.5** (25.5)
		IM	**82.5** (25.6)
	Final	Non-IM	**88.2** (12.8)
		IM	**80.2** (22.9)
Basic+ cue	Feeder	Non-IM	**84.0** (21.8)
		IM	**79.8** (25.1)
	Final	Non-IM	**90.0** (10.1)
		IM	**82.3** (21.9)
Basic+ cue and prediction	Feeder	Non-IM	**84.3** (19.6)
		IM	**78.8** (26.0)
	Final	Non-IM	**86.2** (15.9)
		IM	**81.3** (20.8)

VI. SUMMARY AND DISCUSSION

Controllers reported IM during terminal metering was operationally desirable and acceptable. A majority of the IM clearances were initiated by the controllers and few were suspended or terminated. The majority of controllers reported positively on statements related to spacing and separation. However, non-IM aircraft had more positive ratings and / or lower variability. Additionally, observations and comments showed controllers appeared to be comfortable allowing aircraft conduct IM when further from the separation standard and separation was not an issue. However, they appeared to direct more attention to the aircraft (as would be expected) when the pair was near the separation standard and separation monitoring became necessary. Controllers reported some discomfort in not actively managing the aircraft speed and not knowing when aircraft would change speed.

A majority of controllers reported IM was compatible with terminal metering operations, as seen with [7,16,21,25]. At times, the IM / relative spacing operation was very similar to the behavior of controllers who transition from an absolute spacing operation to a relative spacing operation in the later stages of approach and landing during terminal metering operations, as seen with [16].

Aircraft were generally ahead of their slot markers (ahead of schedule) in both feeder and final controller's airspace, and outside of the slot markers for more time in the final controller's airspace. IM aircraft were inside for less time in the feeder controller's airspace than were non-IM aircraft. Reference [28] also found non-IM aircraft conformance with their slot markers decreased over the course of the scenario, though not to the degree seen in this simulation.

Overall, the results show few differences between IM aircraft and non-IM aircraft based on lead aircraft position relative to its slot marker. The majority of the time the trail aircraft (IM or non-IM) had the same relative position to its slot marker as the lead aircraft did to its slot marker. Aircraft in general being out of the slot markers (yet still relatively close to the schedule) in the final controller's airspace, after arriving in the slot markers is logical. The final controllers become more concerned with relative spacing of aircraft at this point, as seen in past simulations. For example, reference [28] stated that final controllers were more focused on relative spacing / separation and that the slot markers changed from a schedule objective to an on-going status indication of whether or not a merge was going to be successful. IM has been conducting relative spacing prior to this point and will continue to do so, thus an IM aircraft's behavior reflects a controller's actions at this point. Final controllers may also be willing to close up spacing if any gaps exist. Several controllers in this simulation expressed an interest in closing gaps and landing aircraft as soon as possible, regardless of the schedule.

Some past work showed controller concerns with IM aircraft being outside their slot markers longer than non-IM aircraft [22]. This was seen in this simulation in the feeder controller's airspace and most likely due to aircraft working toward the ASG, though not as quickly as the controller was getting other aircraft into the slot markers. The majority of controllers in this simulation reported that IM aircraft position and behavior of an aircraft relative to its slot marker was logical. However, this was found to be an issue in past simulations and may continue to be noted as problematic because the controller's task during metering is to get aircraft into their slot markers. The controller may get non-IM aircraft into their slot markers more quickly than IM aircraft that are working to achieve the ASG at a downstream point.

Controllers found mixed IM (~60%) and non-IM equipage acceptable. The percentage of IM aircraft in this simulation was higher than other work done in the past that also found mixed IM and non-IM equipage to be acceptable (e.g., [16]). Therefore, this level as well as lower levels such as those seen in some simulations (e.g., 3 aircraft per scenario [23], 10 – 20%) appear to be acceptable. However, equipage levels higher than 60% appear to be more desirable based on controller feedback from this simulation.

The majority of controllers reported acceptable traffic awareness, and associated monitoring, for IM and non-IM aircraft. However, the majority reported (with some variance) that their monitoring increased with IM aircraft. This may indicate some level of distrust of IM aircraft or a shift from actively controlling to monitoring aircraft.

While IM during terminal metering appears acceptable, an issue was noted about the overall metering environment with IM and structured arrivals that join the final approach course with defined speeds and altitudes. Controllers noted that this environment created a relatively low workload environment and that it could cause controllers to act more as "monitors" and be less engaged.

Controller replies on the helpfulness of the terminal metering tools for IM and non-IM aircraft were similar to past results. The ratings were generally positive for both IM and non-IM aircraft, except for the early / late indicator (which was not available for IM aircraft) and the timeline. Both had lower ratings and a lot of variability. The early / late indicator was not shown for IM aircraft, so this result does not suggest an issue with IM integration. This simulation also did not have any specific events that caused the controller to use the timeline (e.g., schedule disruptions), nor did any results indicate that it caused issues for IM aircraft. Controllers found the slot markers (without the additional IM cue) less useful for IM but the responses had a lot of variability. Overall, the terminal metering tools did not appear to conflict with IM and several seemed to provide as much useful information for IM aircraft as for non-IM aircraft. Past work such as [22] had similar results as controllers reported the terminal metering tools were useful when controlling IM aircraft and that the slot markers were less usable for IM aircraft. Reference [23] also had similar results and reported controllers found the slot markers, timeline, and speed advisories were useful but less so for IM.

When asked about the IM display information in the IM clearance window, the majority of controllers reported the IM status information, the spacing prediction / ETA differential, and the no speed alerting were helpful, as seen in past simulations with several of the elements [23,24,25]. References [20,25] also had controller reports of the spacing prediction / ETA differential being useful, but replies were variable as to whether it should be a minimum feature.

For the data block IM elements, trail aircraft and lead aircraft status indicators were reported as helpful by a majority of controllers, as with past simulations [16,20,22,24]. Presenting the status of the lead aircraft is not only helpful in understanding aircraft roles, it was found by [23] to reduce the chance of suspending an IM operation.

The color change of slot markers to blue (aka "cue") for trail aircraft actively conducting IM received variable responses regarding its usefulness (note these replies are for the same slot markers as noted above but this question was for the color change for IM). However, observations indicate the cue was still important and utilized for IM aircraft (and may help avoid accidentally issuing a speed to an aircraft already conducting IM). The cue may be more useful for controllers who did not initiate IM, and therefore do not have memory of which aircraft had been engaged in IM. The cue is the first visual indication of which aircraft are conducting IM when entering the airspace.

For the different controller tool sets, statistical tests found no significant difference between tool sets (or controller roles) for the question of whether they had the necessary IM display elements. Other data did not reveal clear trends. However, as mentioned previously, the majority of controllers reported that the spacing prediction / ETA differential was useful while the slot marker cue received some mixed responses (although comments and observations indicated they were useful). Additional work is likely necessary to continue to determine the necessary controller tools.

VII. Conclusion and Recommendations

IM during terminal metering was generally found to be acceptable by controllers. However, the following topics warrant additional study.

- The topic of controllers acting as monitors in a TBO environment may require additional study or, at least, continued consideration.
- Initiation geometries different than those examined here (such as opposite corner posts) may be more challenging. The topics examined here could be examined with these more challenging geometries.
- The potential issue of IM aircraft being out of the slot markers for longer periods of time than non-IM aircraft should be further examined to determine whether it really is an issue, including in unusual and complex traffic situations.
- The terminal metering tools tested did not conflict with IM and there were no results indicating any should be removed. The only terminal metering information that was removed, and is suggested to stay removed, is the speed advisory and early / late indicator.
- Additional work should be performed to continue to determine the necessary controller tools and the usefulness of the slot marker IM cue and spacing prediction / ETA differential (to know when separation will be an issue) to support controller trust in and understanding of IM.
- Additional work should be performed to see if a display feature would be helpful in overcoming the concern of controllers about not knowing when aircraft conducting IM will change speeds and by how much.

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