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Pilot and Air Traffic Controller use of Interval Management during Terminal Metering Operations

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Abstract

This HITL simulation activity was designed to examine the integration of a relative spacing concept (Interval Management [IM]) into a future absolute spacing terminal metering environment provided by Terminal Sequencing and Spacing (TSAS). 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. Both groups had different sets of spacing information that were examined across several traffic scenarios. The results indicate IM is compatible with terminal metering, but the appropriate controller and flight crew tools to support trust of IM should continue to be examined. Concept and operational recommendations are made, including enhancements to IM-related displays.

Executive Summary

A human-in-the-loop simulation involving air traffic controller and flight crews was conducted to examine the integration of Interval Management (IM) into a time-based, terminal metering environment with Performance Based Navigation procedures. Time-based metering during arrival operations is currently scheduled to the runway, but is only conducted in the en route environment. However, the Federal Aviation Administration (FAA) plans to deploy capabilities and procedures to extend time-based metering into the terminal environment by 2019 via Terminal Sequencing and Spacing (TSAS). IM introduces a new way for the controller to have aircraft meet the terminal schedule, and the goal of the simulation was to test the integration of the concepts for acceptability and the necessary spacing awareness information.

IM is a set of equipment capabilities and procedures for controllers and flight crews. Flight deck capabilities are used to support a range of IM operations with a goal of managed inter-aircraft spacing. Ground tools can be used to support the set-up and monitoring of the IM operation. To initiate IM, the controller issues an IM clearance with the appropriate information such as the Assigned Spacing Goal (ASG) and the lead aircraft identification. The flight crew enters that information into the flight deck IM equipment, which then provides speeds to fly to achieve and, if desired, maintain that ASG. Situation awareness information is also provided to assist the flight crew in monitoring the progression of IM. The controller monitors the operation for spacing or separation issues and intervenes if any unusual spacing issues arise. Under normal conditions, the flight crew continues following the IM speeds and the controller continues monitoring the operation until the aircraft reaches the planned termination point, where the spacing goal is met. At this point, the flight deck IM equipment removes the IM speed from the displays and IM is nominally terminated.

IM improves spacing consistency and predictability by enabling flight crews to make more frequent and efficient speed adjustments than are possible for a controller to provide using only a ground-based metering capability and voice communications. Achieving a consistent, low-variance 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. This enables increased arrival throughput and sector or facility capacity.

During IM / relative spacing, the IM aircraft performs spacing adjustment relative to a lead aircraft. In absolute spacing with TSAS, spacing adjustments are made with respect to crossing a specific location at a designated time, independent of the lead aircraft (once the schedule is frozen). When using the TSAS tools during terminal metering, the controller actively issues speed instructions to aircraft to get them on schedule. During IM operations, flight crews fly speeds generated by the flight deck equipment to achieve the ASG. While the IM aircraft is working toward the ASG, it may not be clear to the controller how well the operation is progressing or whether an aircraft will ultimately achieve the ASG and the underlying schedule. The controller may also find the absolute spacing information provided by TSAS to be confusing for IM operations. This could cause the controller to be concerned about the IM aircraft and potentially not trust or utilize IM, thereby reducing the expected benefits.

For flight crews, IM during terminal metering looks very similar to IM in other environments that has been examined in past simulations. However, additional study of spacing awareness tools for IM in this new environment was deemed necessary to help validate the minimum display requirements being defined by avionics standards organizations such as RTCA. Past work has shown that certain features can support spacing awareness and others can cause confusion. Additional work is necessary to finalize minimum requirements.

Some past work has examined IM and TSAS integration. This HITL builds on it by: increasing the percentage of aircraft conducting IM, examining IM initiation in the terminal environment, integrating the IM algorithm defined in RTCA's technical standards, and continued examination of flight deck and ground human information requirements.

Nine air traffic controllers and 18 pilots conducted IM during terminal metering under different conditions: the independent variables of display information for the controller (a basic implementation with IM clearance information and IM status information, the basic implementation plus an IM status visual cue, or the basic implementation plus an IM status visual cue and a spacing prediction) and pilot (a minimum implementation as specified in standards or a minimum plus enhancements), and role of the controller (feeder or final) and pilot. Controllers also experienced aircraft overtake conditions during IM that required an intervention, as well as conditions where aircraft were conducting IM prior to entering the terminal airspace.

IM operations during terminal metering was found acceptable by controllers and flight crews. A vast majority of IM operations were initiated and only a few were suspended or terminated by controllers. 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.

All aircraft spent a majority of their flying time on the Area Navigation (RNAV) arrivals. However, IM aircraft spent more time on the RNAV arrivals (which indicated less time being vectored) and had reduced spacing variance at the final approach fix when compared to non-IM aircraft. IM and non-IM aircraft met the expected performance baselines and goals.

Controller terminal metering tools did not appear to conflict with IM operations and several appeared to provide useful information for IM aircraft. The basic controller IM tool set was found to be useful and helpful. The additional tools that were evaluated also appeared useful, though no clear trends for benefits were found. For the flight crew displays, the basic IM tool set (based on published minimum requirements) was found acceptable on several measures. However, trends for the enhanced tool set indicate that additional features may be useful and overcome issues if refined and implemented properly. Few to no comments were received about a need for additional display features beyond the min or min+ tool sets.

While IM appeared to work well in this environment, some level of discomfort in IM was observed. Based on controller comments, this seemed to be related to not actively issuing speeds to IM aircraft and thus not knowing what speeds would be flown and when. For flight crews, the distrust seemed to be related uncertainty around the feasibility of the IM operation. Recommendations for addressing topics such as these are included in this report. Suggestions are also made for further work to understand and resolve additional issues. The results and recommendations are intended to be used by the FAA and RTCA in developing IM operational, safety, performance, and interface requirements. The results will also inform the FAA's development of ground requirements to enable IM operations in metering environments.

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1 Introduction

Prior to the introduction of any new operation into the National Airspace System (NAS), Human-in-the-loop (HITL) simulations can be a tool used to reduce technical risk and answer operational and conceptual questions that go beyond expert judgment. These simulations can be especially valuable if new concepts are being introduced that have not yet been examined from a perspective of integration with other systems.

The Federal Aviation Administration (FAA) plans to deploy capabilities and procedures to extend time-based metering into the terminal environment by 2019 via Terminal Sequencing and Spacing (TSAS). This will extend metering operations from en route into the terminal / Terminal Radar Approach Control (TRACON) environment. In the past, TRACON operations have been distance-based and tactical. Terminal metering introduces more structured arrival procedures and time-based spacing. Terminal metering is being designed to solve the problems associated with tactical control in the terminal airspace (e.g., increased time and distance flown, leading to increased fuel burn). It is intended to keep aircraft on optimized routes longer than would otherwise be possible and to enable shorten traffic patterns.

The FAA and industry are also developing flight deck requirements for a concept called IM, in which flight crews space relative to another aircraft based on an Air Traffic Control (ATC) clearance. This improves spacing consistency and predictability in both en route and terminal environments by enabling an aircraft to be spaced closer to a given separation standard. This increases overall arrival throughput and capacity.

Interval Management (IM) and TSAS have been examined in numerous simulations as independent concepts. However, these concepts will need to function together in the future NAS environment. While some past work has examined integrated IM and TSAS operations, this HITL builds on that work by examining several remaining open questions. The simulation will examine how controllers should use the two spacing methods (relative and absolute) to manage arrival aircraft in the terminal. During IM / relative spacing, the IM aircraft performs spacing adjustments relative to the lead aircraft. In absolute spacing with TSAS, spacing adjustments are made with respect to crossing a specific location at a designated time, independent of the lead aircraft (once the schedule is frozen). When using the TSAS tools during terminal metering, the controller actively issues speed instructions to aircraft as necessary to get them on schedule. During IM operations, flight crews fly speeds generated within the flight deck to achieve the Assigned Spacing Goal (ASG). The different spacing methods and the impact on the controller and flight crew acceptability and information requirements required further study.

The document has six main sections, including this one. *Section 2 – Background* introduces the terminal metering and IM concepts and provides a review of past literature. *Section 3 – Methods* describes the simulation environment and how the simulation was conducted. *Section 4—Results* provides the results of the data collection. *Section 5—Discussion* integrates the results into an overall discussion of findings and conclusions. *Section 6—Recommendations* suggests how the results should be considered by conceptual and technical flight deck and ground requirements development activities.

2 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), O'Hare International Airport (KORD), San Francisco International Airport (KSFO), and the New York City area airports (FAA, 2015). As part of the solution to address this growth, the FAA plans to implement NextGen enhancements such as Trajectory Based Operations (TBO) to manage future traffic demands and to enable more efficient and environmentally-friendly navigation procedures (FAA, 2013). 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., avoiding terrain) with reduced flight path length (FAA, 2016). 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 (negotiated between an airline and the FAA) that has accurate, predicted 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 capabilities to support metering and data link) that are being developed somewhat independently will need to work together. Additionally, different types of tools (e.g., controller decision support tools, Required Time of Arrival [RTA] / Time of Arrival Control [TOAC], IM) will need to be utilized 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 needs to be chosen to meet the desired goal and benefit.

2.1 Metering and TSAS

Time-based metering involves delivering aircraft at 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 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 (including points near the TRACON boundary). 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. Once the aircraft are in the TRACON, TRACON controllers no longer have the sequence and schedule information, so they must reevaluate the traffic situation and then determine an appropriate sequence and schedule. TRACON controllers must 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 and distance flown, leading to increased fuel burn). It is intended to keep aircraft on optimized routes longer than would otherwise be possible and to enable shorten traffic patterns such as those enabled by Required Navigation Performance (RNP) Radius-to-Fix (RF) turns.

During terminal metering and while aircraft are still in the en route environment, Estimated Times of Arrival (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 the control points to satisfy minimum spacing and wake separation requirements (with an additional buffer). The sequence and schedule is frozen prior to the top-of-descent of the aircraft.

Aircraft are sequenced and maneuvered in the en route environment such that only speeds 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. Figure 2-1 shows a sample terminal metering operation. It shows multiple routes to the airport including some at the merge. Arriving aircraft are shown with runway and sequence assignments. A table is also shown with STAs that aircraft are expected to meet at the various merge points.

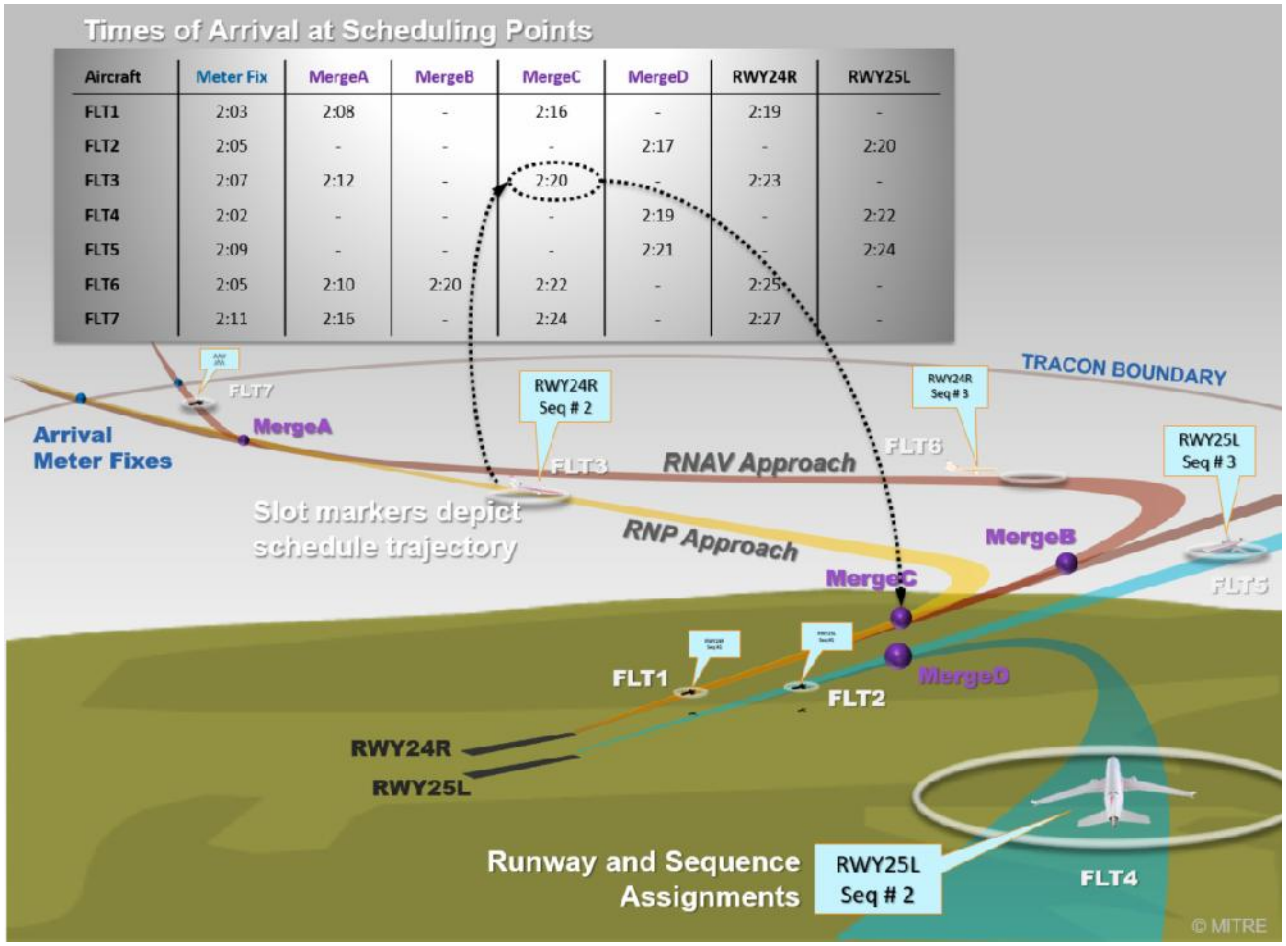

Figure 2-1. Sample Graphical Depiction of Terminal Metering Operations

Time-based terminal metering is enabled by TSAS. TSAS adds more sophisticated scheduling components to TBFM and controller tools to Standard Terminal Automation Replacement System (STARS). 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. Figure 2-2 shows a prototype set of the TSAS tools.

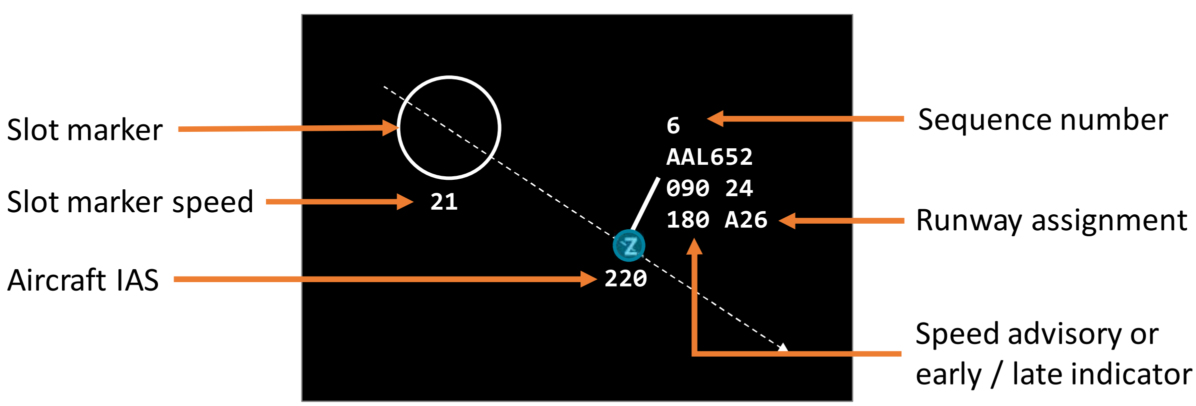

Figure 2-2. Sample TSAS Prototype Tools

The tools shown in Figure 2-2 consist of the following:

- **Runway assignment:** Runway assigned to the aircraft by the scheduler
- **Sequence number:** Order of the aircraft arriving to the assigned runway
- **Slot marker:** Graphical representation of where the aircraft should be to be on schedule
- **Slot marker speed:** Indicated Air Speed (IAS), in knots, at which the slot marker is moving
- Speed advisory or early / late indicator
  - **Speed advisory:** TBFM-calculated IAS, in knots, to get the aircraft to the next control point on schedule
  - **Early / late indicator:** An E or L followed by the amount of time, in minutes:seconds, the aircraft is early or late relative to the schedule (shown if a speed advisory will not resolve the spacing issue)
- **Aircraft IAS:** Estimate of the aircraft's IAS, in knots, calculated by TBFM

A timeline is also provided by TSAS that shows aircraft ETAs and STAs relative to a specified location that can be chosen by the controller.

TSAS was initially developed by National Aeronautics and Space Administration (NASA) and examined in numerous simulation activities (several of which are summarized in Robinson, Thipphavong, and Johnson, 2015) TSAS was tech transferred to the FAA and is planned to be implemented at select airports in 2019.

2.2 IM

2.2.1 IM Operational Overview

IM is a set of equipment capabilities and procedures for controllers and the flight crew. Flight deck capabilities are used to support a range of IM operations with a goal of managed 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 the IM operation. IM can be used in several environments (e.g., en route miles-in-trail and terminal metering operations), depending on the operational objective and controller needs. ATC responsibilities, including separation responsibilities, do not change.

IM is not designed to be implemented in all conditions, so controllers will use their knowledge, and automation support, as needed, to determine when IM operations should be conducted. ATC will still be responsible for appropriately sequencing and spacing aircraft prior to the initiation of IM. Such set-up can be conducted via current ATC capabilities or in more complex environments with new capabilities. Set-up involves ATC issuing an IM clearance that either uses 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), ASG units (i.e., time or distance) and value (e.g., 90 seconds and 15 miles), and IM special points (e.g., Achieve-By Point [ABP] and Planned Termination Point [PTP]).

Once this information is provided to the flight crew, it is entered into the flight deck IM equipment. The equipment checks that the appropriate information has been entered for the operation and that the lead aircraft is in surveillance range. If the lead aircraft is not in surveillance range, the system continues to search. Once the aircraft is in range, is on the expected trajectory, and meets the necessary performance requirements, IM is initiated and 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 other conditions (e.g., safety, operational, equipment, or regulatory issues) prevent doing so. If any of these issues arise, the flight crew will maintain their last implemented IM speed and contact ATC to report being unable to conduct IM. Similarly, if ATC 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 and IM is terminated.

For additional information on the broader IM concept and preliminary requirements, see DO-361 and DO-328A (RTCA, 2015a, 2015b). These documents describe near-term operations; however, updates are being developed to enable more advanced operational implementations such as dependent runway operations. For further details on the IM capabilities utilized in this simulation, see Sections 3.1.1 and 3.1.2.

2.2.2 IM Benefits

IM takes advantage of advances in technology to support current operations, and allows the controller to delegate the low-level, tactical spacing task to IM capable aircraft. Controllers currently try to achieve desired spacings by giving maneuver instructions to aircraft without the flight crews necessarily having an understanding of the goals. Instead of simply being able to assign a specific in-trail spacing goal, the controller has to provide several workload intensive instructions which include trial-and-error to determine the appropriate goal. By allowing flight crews to achieve or maintain an ASG, controllers may be able to more efficiently manage merging aircraft and improve throughput. The remainder of this section will review the benefits mechanism and summarize related results from past IM activities. It will also highlight other expected benefits.

2.2.2.1 Throughput Benefits

IM is a relative spacing operation, in which trajectory corrections are made relative to real-time behavior of a lead aircraft (i.e., the lead aircraft's ATA). 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.

In an absolute spacing operation, the error distribution of both aircraft must be considered when setting the schedule and spacing goals. This is because both aircraft achieve the schedule independently and could contribute to a spacing that encroaches on the minimum separation standard. With IM, however, the error distribution of the lead aircraft does not need to be considered because the IM Aircraft is correcting for it. Therefore, a spacing goal for an IM pair can be closer than would otherwise be possible with absolute spacing alone (e.g., TOAC or terminal metering without IM). Figure 2-3 contrasts the error distributions that must be accounted for in absolute (top diagram) and relative (bottom diagram) spacing operations.

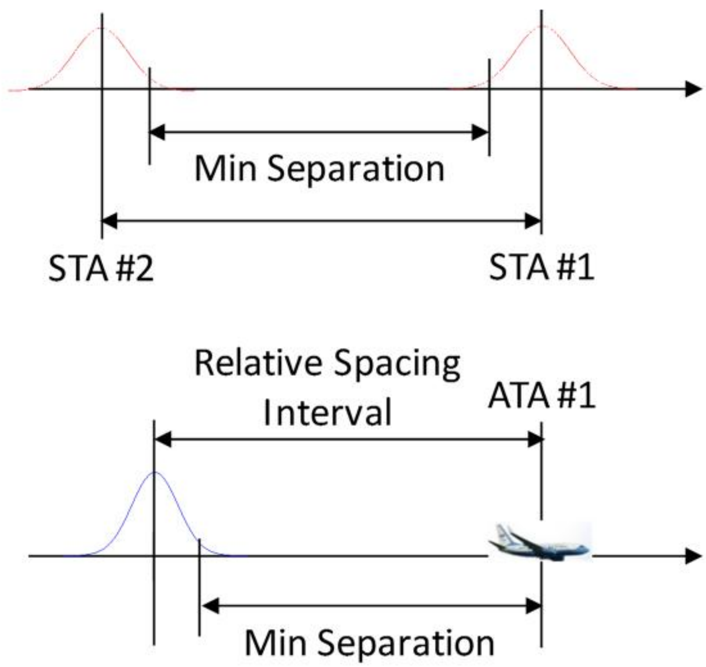

Figure 2-3. Absolute (Top) and Relative (Bottom) Spacing Operations Utilization of Aircraft Spacing Error Distributions

With the spacing goal set, IM can further 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. 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 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. This enables increased arrival throughput and sector or facility capacity.

The performance metric used by the FAA to measure delivery benefits is termed Inter-Arrival Time (IAT). The IAT is defined as the difference in time when two consecutive aircraft cross a common point. For example, if a lead aircraft crosses the runway threshold at 12:30:30 and a trail aircraft crosses the runway threshold at 12:31:50, the IAT is 80 seconds. A population of IATs will have a Standard Deviation (SD) associated with it, which indicates the extent of variations in the IAT. Assuming a normal distribution, one SD will include 68% of the range of IATs in the population. Table 2-1 shows the assumed one IAT SD at the Final Approach Fix (FAF) used to model benefits for different traffic management capabilities.

Table 2-1. Metering Capabilities and the Associated IAT SDs

Capability	IAT SD
No metering (baseline)	18.0[1]
En route metering	16.5[2]
GIM-S and TSAS	12.0[3]
IM	5.0[4]

1. Singha and Haines (1975)
2. Spinoso, Coville, and Roberts (2014)
3. Weitz (2017)
4. DO-361 (RTCA, 2015a)

Ground-based Interval Management-Spacing (GIM-S)

Each added capability in the first column of Table 2-1 reduces the IAT variance, which means that aircraft can be placed closer together relative to a separation standard (i.e., a lower spacing goal can be used), without an increase in the number of controller interventions needed to avoid separation violations.

Figure 2-4 illustrates how IAT SD distributions relate to a separation standard. For example, if the IAT SD is 12 seconds as with GIM-S and TSAS, aircraft will need to be spacing with an IAT of approximately 81 seconds to avoid an unacceptable number of controller interventions (as shown in the magenta distribution[1]). If a controller tries to space aircraft closer together and the IAT SD is limited to 12 seconds, more controller interventions will be needed to prevent separation violations. However, if the IAT SD can be reduced to 5 seconds with IM (as shown in the red distribution), aircraft can be delivered at approximately 65 seconds with the same rate of controller interventions as the 12-second IAT SD distribution.

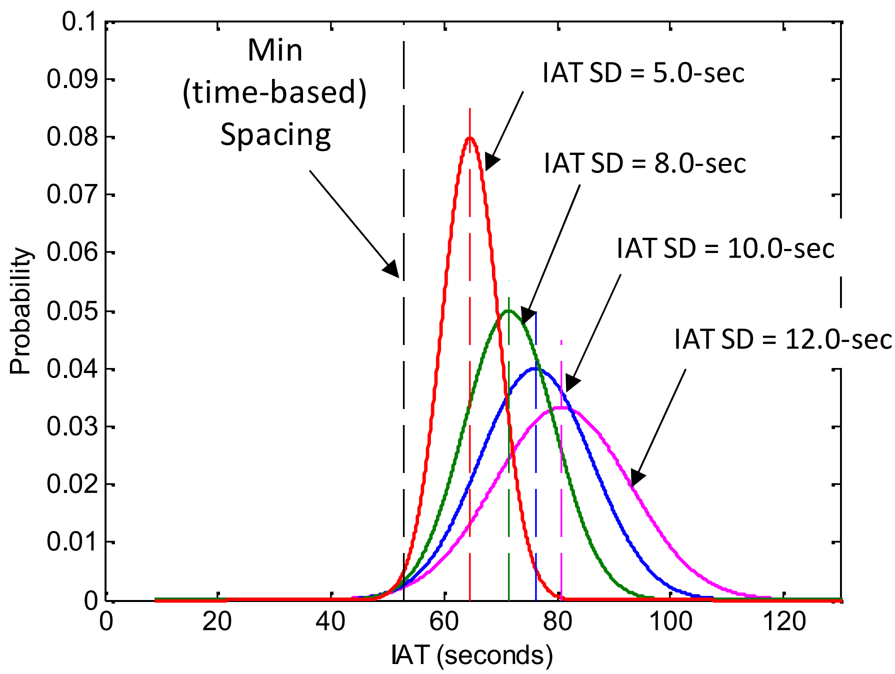

Figure 2-4. Various IAT SD Distributions Relative to the Separation Standard

[Reprinted from Weitz, 2017]

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[1] The 81-second value is derived assuming a uniform flow, a minimum (time-based) separation of 53 seconds at the FAF, and a controller intervention rate of 1 per 100 operations. The 53-second minimum (time-based) separation is derived from a minimum separation distance of 2.5 NM and an assumed groundspeed of 170 knots

Rognin et al. (2005) demonstrated the benefit of accurate and low variance spacing when comparing an en route metering capability only, to one with IM (i.e., all the aircraft were IM capable). In the condition with IM, almost all aircraft were within 5 seconds of the ASG. The en route metering capability alone had a wider and flatter distribution shown in Figure 2-5. The IM distribution translated to an additional two aircraft per hour. Prevot et al (2007) found similar results where IM (70% of the aircraft) had a reduced mean and variance and allowed for an additional aircraft or two per hour (Figure 2-6).

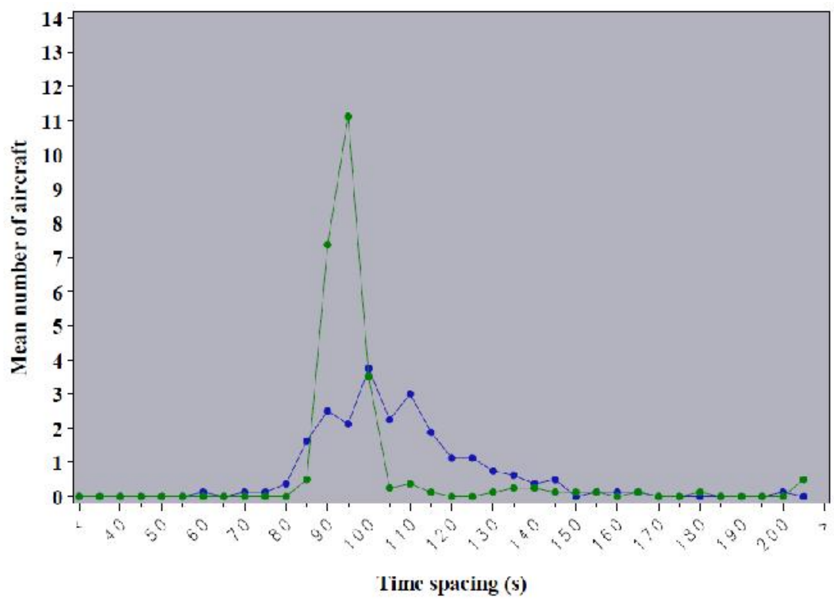

Figure 2-5. Spacing Distribution of Aircraft at the FAF with an En Route Metering Capability Alone (Blue Line) and an En Route Metering Capability with IM (Green Line) [Reprinted from Rognin et al., 2005]

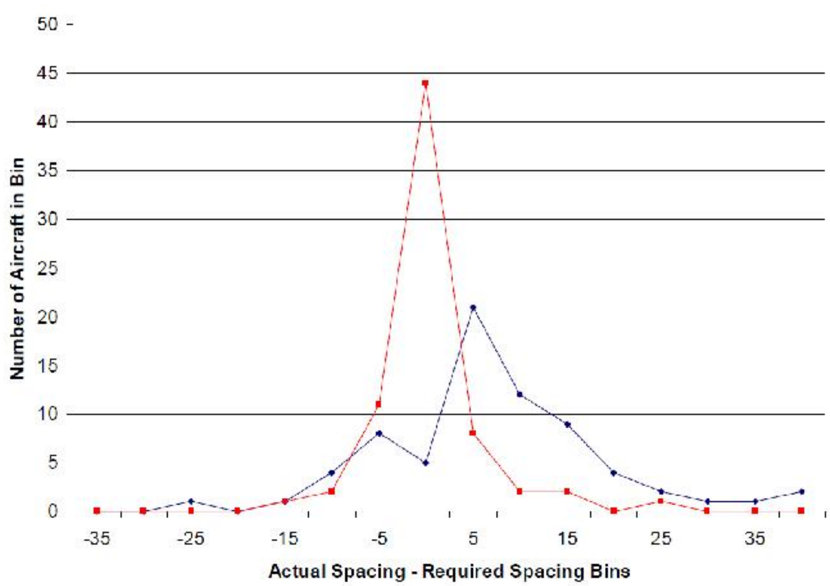

Figure 2-6. Spacing Error at the Runway without IM (Blue Line) and with IM (Red Line) [Reprinted from Prevot et al., 2007]

If IM helps deliver all aircraft with an IAT SD of 5 seconds versus 12 seconds (and the associated IAT of 65 seconds versus 80 seconds), an increase of approximately 11 aircraft per hour can be realized. IM operations 100% of the time may not be possible; however significant benefits are still possible even with partial IM equipage. Figure 2-7 shows throughput increases at different levels of IM equipage and the delivery of aircraft at the 5 second IAT SD, versus a ground system only (GIM-S and TSAS). As shown, the number of aircraft landing per hour increases as the number of IM operations increases and throughput benefits are still realized at lower levels of equipage.

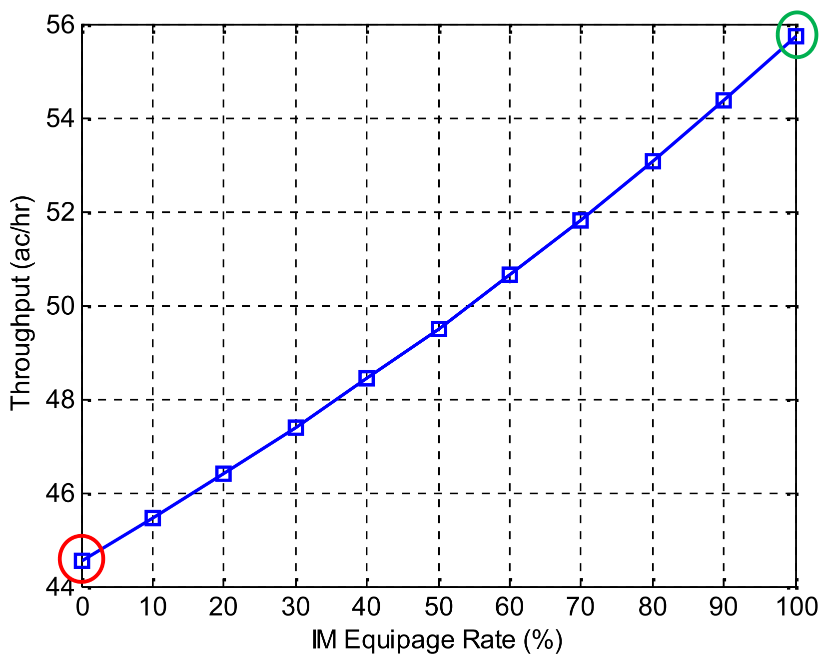

Figure 2-7. Throughput Increase Relative to the IM Equipage / IM Operation Rate

[Reprinted from Weitz, 2017]

HITL simulations (e.g., Baxley et al., 2013; Swieringa, Wilson, and Shay, 2014; Kibler, Wilson, Hubbs, and Smail, 2015) and field tests have shown the 5-second IAT SD to be possible. Lohr, Oseguera-Lohr, Abbott, Capron, and Howell (2005) conducted a flight test where a 90 seconds IM ASG with RNAV procedures was achieved with an average of 89.3 seconds with a standard deviation of 4.9 seconds. Penhallegon, Bone, and Stassen (2016a) reported a field test with a relatively small number of aircraft conducting optimized RNAV routes where flight crews with high speed conformance were within +/- 6 seconds at the ABP and +/- 8 seconds of the ASG as the lead aircraft touched down on the runway (after maintain operations). Swieringa et al. (2017) found similar behavior from a flight test where aircraft were within +/- 2 seconds of the ASG at the PTP with SDs less than 3 seconds (after maintain operations on a RNAV Standard Terminal Arrival Route [STAR]). Achieve-by results from that flight test are still being examined.

Past efforts have shown similar benefits. Grimaud, Hoffman, Rognin, and Zeghal (2003) found that more aircraft were delivered closer to the targeted spacing interval in the extended terminal area with IM (42%) than without (17%). Additionally, fewer aircraft were delivered with too small (or too large) spacing intervals. Overall, they reported a more homogeneous and stable flow at the delivery point with more aircraft achieving the targeted spacing value when aircraft were conducting IM.

2.2.2.2 Other IM Benefits

IM is also expected to reduce the number of controller interventions. Numerous studies have shown a reduction in controller interventions for similar concepts conducted in the en route and terminal areas (e.g., Grimaud, Hoffman, Rognin, Zeghal and Deransy, 2001; Grimaud et al., 2003; Aligne, Grimaud, Hoffman, Rognin, and Zeghal, 2003; and Mercer, Callatin, Lee, Prevot, and Palmer, 2005). A series of studies specifically examining IM in the en route and arrival environments (Bone, Penhallegon, Stassen, Simons, and DeSenti, 2007; Bone, Penhallegon, and Stassen, 2008a; Bone, Penhallegon, and Stassen, 2008b; Penhallegon and Bone, 2008) reported a reduction in controller instructions in IM scenarios (as compared to scenarios without IM) even with spacing disruptions and the introduction of other issues.

Because IM is expected to reduce the number of controller interventions, a reduction in frequency congestion is also expected to result. Grimaud et al. (2001) found a reduction in the number of communications when using IM, though not a reduction in the duration of the communications. In a flight test / demonstration, terminal controllers described a positive effect on communications with pilots (FAA, 2001). A study specifically examining IM in the en route environment (Bone et al., 2007) reported both subjective and objective data indicating a reduction in controller-pilot communications. Controllers reported that their communications were easy and were reduced with IM. Objective data revealed fewer ATC-initiated communications and less total time on the frequency during IM. Although communications during IM operations were generally found to be acceptable, the IM clearance continues to be an area of concern due to the potential length and complexity of the communication. It will continue to be examined in this simulation.

IM is expected to be particularly beneficial during optimized RNAV routes. Optimized RNAV routes allow aircraft to maximize their individual efficiencies; however, this can come at the expense of the efficiency of the overall stream. Past work has found that the vast majority of pilots find optimized RNAV routes to be acceptable (Clarke et al., 2006). However, to avoid the losing their benefits, optimized RNAV routes require no ATC interventions under nominal conditions. Appropriate spacing must be achieved in the en route environment so that terminal controllers are not required to intervene. Achieving the appropriate spacing can be challenging due to uncertainty in the vertical trajectory and arrival time at the FAF (due to winds and aircraft performance differences). Therefore, spacing at the start of the optimized RNAV route is greater than that realized today during high density operations (Erkelens, 2000; Ren, Clarke, and Ho, 2003).

By having aircraft manage their own spacing with IM, aircraft conducting optimized RNAV routes can effectively balance individual and stream efficiency, and operate in a manner beneficial to the overall system. IM is used to set up the appropriate spacing at the entry to the optimized RNAV route and to achieve appropriate spacing on final approach by compensating for uncertainties during the arrival. This should allow for an increased ability to conduct optimized RNAV routes due to consistent, accurate spacing and sustained capacity during optimized RNAV routes. Additionally, if it is possible through IM to achieve a consistent spacing at the entry to the optimized RNAV route and manage the spacing through the optimized RNAV route, the entry spacing may be able to be reduced and the final spacing may be tighter than an unmanaged spacing without IM.

A similar concept of the flight deck managed separation during optimized RNAV routes has been previously proposed (in 't Veld, van Paassen, Mulder, and Clarke, 2003). In that work, it was noted that the ATC task of spacing aircraft during an optimized RNAV route is difficult and that tools such as IM could help.

2.3 PBN and RNP RF Turns

RNAV is a method of navigation that increases efficiency by allowing aircraft to fly direct routes between selected points rather than flying from ground navigation aid to ground navigation aid. RNAV enables PBN operations that specify performance requirements for both RNAV and RNP routes that enable accurate and predictable flight paths. PBN is used to achieve benefits such as ensured deconfliction between defined routes, new routes that would not otherwise be possible due to terrain, lower approach minimums, closer routes, optimally placed route, and reduced flight path length. The benefits are enabled through the stringent, defined performance requirements. PBN procedures and routes are already in place and are helping users realize benefits (FAA, 2016).

PBN RNAV has specified navigation performance standards. PBN RNP is a refinement of RNAV and also has specified navigation performance (in Nautical Miles [NMs]), but it requires on-board performance monitoring and alerting. RNP allows for precise navigation on defined routes. Advanced RNP procedures such as RNP Authorization Required (AR) approach operations are enabled by advanced navigation equipment and have stringent lateral navigation requirements and can include a RNP RF turn (also known as RF leg). A RNP RF turn allows an aircraft to fly a precisely defined arc when transitioning from one leg to another thereby avoiding different turn paths when such a segment is not defined between the legs. RNP RF turns can be used with an instrument approach to reduce track mileage and aircraft can join the final approach course as close as the FAF. RNP RF turns onto final approach can be challenging for controllers but are expected to be supported by TSAS and will be part of arrival and approach procedures in the terminal metering environment (Wynnyk and Kopald, 2013).

2.4 IM and Metering

Ruigrok and Korn (2007) proposed how IM and metering could work together and be mutually beneficial. They 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 the initial approach fix to the FAF. Callantine, Cabrall, Kupfer, Omar, and Prevot (2012) 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 between aircraft becomes more important in the later stages of approach and landing. Previous 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 on final (Callantine, Palmer, and Kupfer, 2010; Kupfer, Callantine, Martin, Mercer, and Palmer, 2011; Callantine et al., 2012). Wynnyk and Kopald (2013) stated that final controllers were more focused on relative spacing / separation and that slot markers changed from a schedule objective to an on-going status indication of whether or not a merge was going to be successful. The following section reviews relevant IM and metering HITL simulation activities.

2.4.1 Past Research on IM and En Route Metering

Benson, Peterson, Orrell, and Penhallegon (2011) examined IM during en route metering. They examined center controller acceptability of IM and different display implementations. They reported general controller acceptance of IM and all the tested interfaces. They also reported that controllers found metering and IM compatible. Most controllers reported being comfortable with flight crew monitoring for conformance and did not want an additional ground tool. However, some said it may help situation awareness.

In a follow-on study, Peterson, Penhallegon, and Moertl (2012) also examined IM during en route metering but with different levels of equipage and new controller display interfaces. They examined center controller acceptability of IM procedures and requirements for ground automation and reported general controller acceptance of IM and the interface. They also reported that controllers could acceptably manage a mix of IM and non-IM aircraft. Controllers also found metering and IM to be compatible, though they reported some workload issues at higher levels of IM equipage due to the communication requirements associated with issuing the IM clearance and with managing off-nominal situations. Overall, controllers reported having all the necessary information to conduct IM operations and that IM information in spacing list and data block locations was acceptable. The authors recommended further examination of IM in the TRACON, including aircraft already conducting IM transitioning into the TRACON.

Rognin et al. (2005) also conducted a simulation examining IM with a en route metering capability. Aircraft transitioned into the TRACON, but there was no terminal metering tool. Controllers were provided new tools to manage IM aircraft. Overall, controllers found IM and en route metering to be compatible and complementary. TRACON controllers reported favorably upon receiving aircraft already conducting IM from the en route environment because the transfer conditions were more stable.

2.4.2 Past Research on IM and Terminal Metering with TSAS

The main body of work to examine IM in a terminal area metering environment was conducted by NASA under the Air Traffic management Demonstration-1 (ATD-1) umbrella of activities. The majority of the HITL simulations are summarized in Robinson et al. (2015). That work will be reviewed next from the perspective of the controller, because from the flight crew perspective, both the metering and non-metering environment look very similar. Flight crew procedures do not change between the environments and the receipt of a time-based ASG may be the only indication to the flight crew that they are in a metering environment.

2.4.2.1 NASA ATD-1 Concept of Operations

NASA's ATD-1 activity started in 2011 to develop, demonstrate, and transfer time-based spacing capabilities to the FAA. The ATD-1 concept is very similar to the time-based metering environment and the IM concept as described in Sections 2.1 and 2.2. In the ATD-1 concept, en route controllers manage and meter aircraft via TBFM to deliver them to the TRACON boundary such that speed alone should achieve the schedule. Aircraft fly PBN arrival procedures with speed and altitude constraints. For aircraft that are equipped, the en route controller can issue an IM clearance (sometimes with an associated STA). If an STA is provided, it is entered in the flight deck and flown until IM can begin. En route controllers hand off aircraft near the terminal boundary with a schedule error of less than 30 – 40 seconds (Robinson et al., 2015). Terminal controllers use TSAS to continue to manage and meter aircraft. They also monitor on-going IM operations. The final controller may also use the Automated Terminal Proximity Alert (ATPA) capability to monitor separation as aircraft join the final approach. ATD-1 activities ended in 2017 with a flight test of the flight deck IM component (Swieringa et al., 2017).

2.4.2.2 NASA ATD-1 Controller HITLs

Between 2012 and 2014, NASA conducted sixteen simulations under the ATD-1 activity with controllers as participants (Robinson et al., 2015). Some simulations included IM and others did not. Of the sixteen simulations, seven had published reports on IM and TSAS integration with controller participants. A report on an additional HITL simulation became available in 2016 (Baxley et al., 2016). Table 2-2 shows the dates and key papers for these simulations.

In these simulations, controller participants were either active or retired controllers. In many cases, the same controllers participated in multiple simulations. Overall, the ATD-1 IM TSAS work with controllers as participants included a low percentage (approximately 10-20%) of IM aircraft. However, some of the simulations appeared to have fewer IM aircraft (e.g., three IM aircraft in a 75 aircraft per hour run in Thipphavong et al. 2013) or did not have IM as part of the main focus (e.g., Wynnyk and Kopald, 2013). Baxley et al. (2016) was a notable exception that had a high level of IM aircraft. High level summaries and results are summarized here and specific, relevant details are discussed in Section 2.5.1.

Table 2-2. NASA ATD-1 TSAS and IM Controller HITL Simulations

HITL Name	Conduct Date	Paper
CA-1	Jan 2012	Cabrall, Callantine, Kupfer, Martin, and Mercer (2012)
CA-2	April 2012	Callantine et al. (2012)
CA-3	June 2012	Callantine et al. (2012)
FIAT-1	Oct 2012	Thipphavong et al. (2013)
CA-4	Dec 2012	Callantine, Kupfer, Martin, and Prevot (2013)
TSS-2	2013	Wynnyk and Kopald (2013)
CA-5.3	2014	Callantine, Kupfer, Martin, and Mercer (2014)
IMAC	2015	Baxley et al. (2016)

CA – Controller Managed Spacing (CMS) Air Traffic management Demonstration (ATD)

FIAT – Fully Integrated ATD-1 Test

TSS – Terminal Sequencing and Spacing

IMAC – IM Alternative Clearances

The first ATD-1 simulation examining TSAS and IM integration was CA-1, as reported in Cabrall et al. (2012). Nine controllers were participants (acting as TRACON and center controllers). Controllers were asked to not interfere with IM operations, even if there was a spacing issue, “to enable close examination of the behavior of the [IM] algorithm in an operational setting” (Cabrall et al., 2012, p. 6). Eight aircraft were equipped with flight deck IM equipment.

Controllers reported acceptable workload, tools, procedures, and phraseology for the integrated operations and that they were able to integrate IM traffic into their operations. The authors did indicate, however, that there were some spacing issues with IM aircraft, which seemed to be due to lack of conditioning aircraft prior to initiating IM operations. When using the TSAS tools (e.g., early / late indicators, slot markers, timeline) as well as the IM data block indicators for IM, feeder controllers indicated that the timeline and data block indicators were both helpful and useful. Their replies also indicated higher helpfulness ratings but lower usability ratings for the slot markers and early / late indicators for IM, even if both showed large schedule errors for IM aircraft. However, controllers seemed to want the tools to help manage IM operations. Final controller ratings were not provided. Controllers reported favorably on manually interacting with the IM status designators and also reported few issues with the IM clearance.

In the follow-on / CA-2 simulation, the focus was on pre-conditioning the traffic (Callantine et al., 2012). Center and TRACON controllers were participants. Eight aircraft were IM-equipped. The same IM status designators and update methods for the TRACON controllers that were used for CA-1 were used for CA-2. Some conditions removed the slot markers and speed advisories for aircraft conducting IM. Results reporting was limited; however, the IM results that were reported indicated that pre-conditioning the IM traffic overcame the IM aircraft delivery problems seen in CA-1. Additionally, center and TRACON controllers reported finding the IM status designators in the data block useful.

The CA-3 HITL built on the previous simulations and examined controller tools, procedures, and phraseology (Callantine et al. 2012), but with different IM status designators. Approximately 11% of the aircraft were IM-equipped. Center and TRACON controllers were participants. Overall, controller replies indicated that the tools, procedures, and phraseology were acceptable and useful. Controllers reported that mixed IM and TSAS operations were not an issue. For this simulation, when controllers were considering terminating IM, they were encouraged to suspend IM instead, so they could resume IM at a later point. Center controllers suspended some IM operations, mostly due to concerns with separation at merge points. The results indicate that IM reduced the inter-arrival spacing variation as compared to aircraft only conducting TSAS operations and that trail aircraft conformed to the underlying schedule when the lead aircraft did. One noted issue was the high number of issues with IM communications. The authors do not provide much detail on the exact nature of the concerns, but acknowledged that it needed to be addressed.

FIAT-1 was conducted to further evaluate the ATD-1 operational concept and its validity (Thipphavong et al. 2013). There were three IM-equipped aircraft per run in a demand of around 75 aircraft per an hour run. In some scenarios, the lead aircraft was not in the same sector as the trail aircraft. Center and TRACON controllers were participants. Overall, IM operations worked with the TSAS operations. The authors again confirmed the need to pre-condition aircraft so that speed changes alone will be sufficient to achieve the desired spacing in the TRACON. When aircraft were on the same route, an IM operation was more likely to be engaged than when the aircraft were not on the same route. All controllers reported manageable workload, though the center controllers reported higher workload than the TRACON controllers and increased communications with IM aircraft (as compared to non-IM aircraft). Both could be attributed to the requirement to issue the IM clearance. TRACON controllers reported lower workload than the center controllers and reported communicating with the IM aircraft the same or less than non-IM aircraft.

For the majority of responses, there were no reported spacing issues for IM aircraft pairs and non-IM aircraft did not need to be maneuvered for IM aircraft pairs. Aircraft in IM pairs spent less time off path than the non-IM pairs. When compared to aircraft not conducing IM, aircraft that were conducting IM showed worse schedule conformance at the meter fixes and meter points in the feeder airspace, but were spaced closer with less variance at the FAF. Controllers reported mismatches between the trail aircraft position and the slot marker. This behavior is expected based on the IM algorithm design. Slot markers, speed advisories, and the timelines were reported as less useful for IM operations.

CA-4 examined the pre-conditioning of traffic, different controller tool sets, and IM integration, among other things (Callantine et al., 2013). There were eight IM aircraft per run in a demand of around 43 aircraft per runway per hour (for a fifteen-minute run). The IM status designators in the data block were also updated. Center and TRACON controllers were participants. Authors reported having some data confounding issues due to winds and system behaviors that negatively affected IM operations (leading to numerous suspensions) and the ability to measure final approach spacing accuracy for IM. However, center controllers found the IM clearance acceptable (in contrast to CA-3), and reported a desire to split the communication into two parts. IM was reported by controllers, on average, to increase task complexity without doing so excessively.

The TSS-2 simulation mainly examined issues related to TSAS operations (Wynnyk and Kopald, 2013). Four TRACON controllers participated. There were three IM aircraft per run in a demand of around 45 aircraft per runway per hour (for a half hour run). Controllers were told IM was not a key part of the simulation, and very little IM-related data was reported. However, from the results that were provided, the TRACON controllers' average rating was neutral for usefulness of the TSAS tools for IM. However, average rating for other tasks such as managing traffic and managing the schedule received a similar rating. The majority of controllers reported that the IM designator (indicator of the status of the IM operation) was an important part of a custom toolset.

The CA-5.3 simulation examined how TSAS can improve efficiency of arrival operations during high demand (Callantine et al., 2014). Center and TRACON controllers were participants. Though the authors did not report specific IM-related result, they did mention that maintaining inter-arrival spacing without IM was an issue and required further examination.

Finally, the IMAC simulation mainly examined acceptability and system performance of different IM operations (Baxley et al., 2016). Eight Center and TRACON controllers were participants (pilots were also participants). Overall, controllers rated the concept, workload, and displays acceptable. The Controller Acceptance Rating Scale ratings also indicated acceptability. The authors recommended a feasibility check prior to initiating IM and during IM conduct so the controller knows when the ASG is invalid.

2.4.2.3 MITRE Concept Evaluation Activities

Three concept evaluations were conducted by MITRE in 2016 to explore IM and TSAS integration issues in the MITRE Integration Demonstration and Experimentation for Aeronautics (IDEA) lab using a team of FAA ground system, flight deck, and ATC domain experts. The goal was to seek input from experts on the integration of the TSAS and IM operations, the prototype displays, and plans for a follow-on HITL simulation (this activity) in all the capabilities being utilized. Each evaluation was a step in the development process as the lab capability matured. Improvements were made over the course of the evaluations as the lab implementation matured and as input was received. Over the course of the three evaluations, sample changes and improvements included: increased traffic density, the reposition of an ABP to the merge of two flows, updated IM information on the STARS display, and the addition of RNP RF turns. These and other relevant changes will be discussed in subsequent sections. Overall, the participants found the operations to have potential to work together, but had questions that would need to be addressed in the HITL simulation.

2.5 Study Purpose and Design

2.5.1 ATC Topics

The understanding of an operation and the information displayed to the controller is key to the successful implementation of an operation. Fundamental to the ATC task is keeping cognizant of current and evolving conditions, i.e., maintaining situation awareness. When aircraft are conducting IM, controllers monitor aircraft speed control instead of actively directing it. Previous studies have indicated that monitoring of aircraft under flight deck spacing operations was increased for non-spacing aircraft in a spacing stream (Mercer et al., 2005), but reduced for aircraft that had been sequenced and were maintaining their spacing (Aligne et al., 2003). Regardless of the impact on monitoring, there did not appear to be an effect on safety or a loss of situation awareness. A summary report of several European IM simulations (Hebraud, Martin, Leone, and Troise, 2006) reported on a study of Italian airspace that found improved controller situation awareness when using IM during metering operations, which also led to improved coordination between controllers.

Related to situation awareness is the controllers trust in the IM operation. They must fully understand the objectives and methods IM uses to achieve and maintain spacing and they must be able to trust that flight crews will properly follow the IM speeds. The degree to which their mental models conform to the reality of IM operations allow them to appropriately calibrate their level of trust as conditions change. For example, if IM usually proceeds in a predictable fashion, but one aircraft starts deviating from the expected procedures, controllers will more likely be able to detect the situation and intervene before it escalates. Mercer, et al. (2005) found that predictability is important for controller acceptance. During IM operations, controllers will need to know what spacing to expect at key points and that the flight crews will operate their aircraft in predictable ways.

Over-trust, resulting in a loss of situation awareness, can also be an issue. If controllers completely trust an operation, they can become complacent and not perform their normal, necessary checks on the traffic. This can result in controllers taking longer to detect a developing situation. Therefore, ways to minimize controller over-trust must be considered by concept developers.

Past work has generally found IM can work in a metering environment with limited issues (e.g., Rognin et al., 2005; Benson et al., 2011; Baxley et al., 2016). However, some key topics remain open. The remainder of this section will review the relevant work related to the open topics.

2.5.1.1 IM Operations Relative to TSAS Slot Markers

In Cabrall et al. (2012), TRACON controllers reported favorably on IM overall and they reported that the slot markers were helpful and usable for IM operations. However, feeder controllers reported the slot markers were very similar in helpfulness but less usable for IM aircraft as compared to non-IM aircraft. They reported confusion regarding IM spacing behavior relative to the slot markers and therefore, the underlying schedule. The controllers expected to have IM aircraft also in the slot markers and were uncomfortable when the IM aircraft were not in the slot markers. Controllers also appeared to be unsure of IM aircraft behavior relative to the slot markers. They reported problems with IM aircraft arriving early relative to the schedule. The authors indicated that follow-on work would look at enhancements to the slot markers to provide controllers information on IM operation progress. However, it was not seen in the subsequent reports.

In the follow-on simulation, Callantine et al. (2012) reported scenarios where the slot markers were removed when aircraft were conducting IM. However, no results were reported. In the third of the series of these simulations, while it is not explicitly stated, a figure seems to indicate that the slot markers were used for IM aircraft in the TRACON (Callantine et al., 2012). TRACON controllers again reported slot markers as being helpful and they reported being confident in their use. However, the reported results did not differentiate between slot marker use for IM and non-IM operations, so it is unclear whether the issue discussed in Cabrall et al. (2012) is still applicable. In the conclusion, the authors point out that the TRACON tool use during IM operations requires controller acceptance as well as consistent understanding and use. When summarizing this third simulation, Callantine et al. (2013) noted that controllers had some misunderstanding of IM aircraft behavior.

In another ATD-1 simulation, Thipphavong et al., (2013) reported that IM trail aircraft had worse schedule conformance at the terminal meter points (indicating slot marker deviations) but better at the FAF, as compared to aircraft not performing IM. TRACON controllers reported that they saw short-term, but less long-term, mismatches between the IM aircraft position and the slot marker position. As the authors note, this is to be expected based on IM algorithm behavior. Finally, controllers reported that the slot markers were less useful for IM aircraft than for non-IM aircraft.

As mentioned previously, after most ATD-1 activities, MITRE concept evaluations were conducted in preparation for the HITL simulation reported here. The participants in the concept evaluations also determined that IM spacing behavior and deviation from slot markers should continue to be examined in the concept evaluations, followed by the HITL simulation. Some options were tested during the concept evaluations that led to the final simulation implementation that will be reviewed in Section 3.1.3.3. One option that was tested at the third evaluation, was a change in slot marker color of an aircraft conducting IM. Differentiating the IM trail aircraft was reported as being helpful and controllers appeared to have a better understanding of IM spacing behavior and reported seeing aircraft closing to their ASG. However, some controllers still expressed concerns about on-going deviations from the slot markers in the feeder's airspace. They reported that their goal was to get all aircraft into their slot markers so that the handoff to the final controller would be acceptable and that they felt uncomfortable when aircraft were not in the slot markers.

2.5.1.2 IM Status Information on ATC Surveillance Displays

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). Past work examined this topic and is reviewed next.

In Bone et al. (2007), a HITL simulation of an achieve-by IM operation is reported that was a transitional implementation that had no active controller involvement in the set-up of IM or in issuing the IM information. The UPS operations center provided the IM information to the trail aircraft based on the arrival sequence and the ASG that was agreed-upon with the TRACON. The controllers monitored IM and intervened when necessary. The simulation was supporting an early field implementation where controller tools would not be available in time. In this simulation, controllers did not know which aircraft were conducting IM, only that some in the stream were capable. Based on the results, the authors noted that controllers may need:

- to know which aircraft are actually (versus potentially) conducting IM,
- a better understanding of IM aircraft behavior (e.g., relationship between IM speeds flown and the ASG),
- to know whether or not the ASG can be achieved, and
- more information to determine when an intervention in the IM operation is necessary.

In a follow-on simulation, during capture then maintain IM operations, Penhallegon and Bone (2008) had pilots report when conducting IM, instead of having the controller assume. While the controllers did not have IM-specific display features, they were reported to use existing display features to flag aircraft that were conducting IM. The controllers did not report the monitoring and intervention needs reported in the previous simulation. However, this difference may be because maintain operations may lend themselves better to monitoring the status of IM than do achieve operations because aircraft are on a common route.

EUROCONTROL IM-related research with controllers (e.g., Aligne et al., 2003) used basically the same tool set (Figure 2-8). Controllers were informed of IM equipage through the flight plan. For the surveillance display IM features, circles were placed around the trail (larger circle) and the lead (smaller circle) aircraft. A line linking the aircraft was also available as an optional display element. The line included a numeric value of the current spacing between the aircraft in distance or time. The features were orange when the lead aircraft was being identified and selected by the trail aircraft flight crew and was green when IM became active. Controllers reported that the tools were useful (Aligne et al., 2003; Rognin et al., 2005).

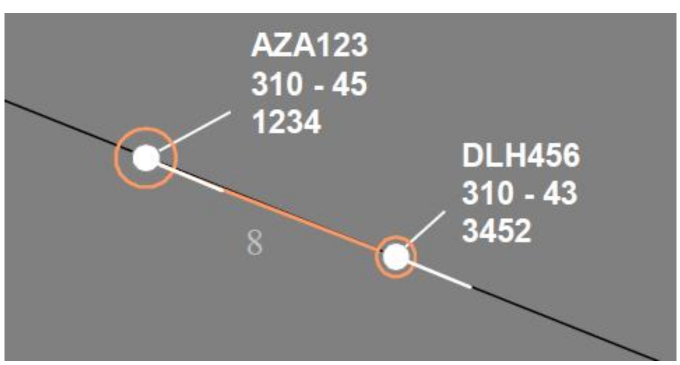

Figure 2-8. EUROCONTROL IM Controller Information [Reprinted from Aligne et al., 2003]

Benson et al. (2011) reported a simulation where center controller data blocks showed trail and lead aircraft role and IM status: pending versus active (in the fourth line). IM eligibility was not shown in the preferred IM window implementation (but was examined in an alternative implementation). A flyout window was also available that allowed controllers to initiate and terminate IM and show the IM operation state and aircraft role in IM. It used color coding to differentiate between the IM pending (clearance issued but not yet accepted by the flight crew) and active states (Figure 2-9). Controllers used the option to initiate and terminate IM with the data block. The data blocks were reported to have provide IM situation awareness benefits. Most controllers wanted the trail and lead identification and lead or trail role in data block and thought it was part of a minimum set of information.

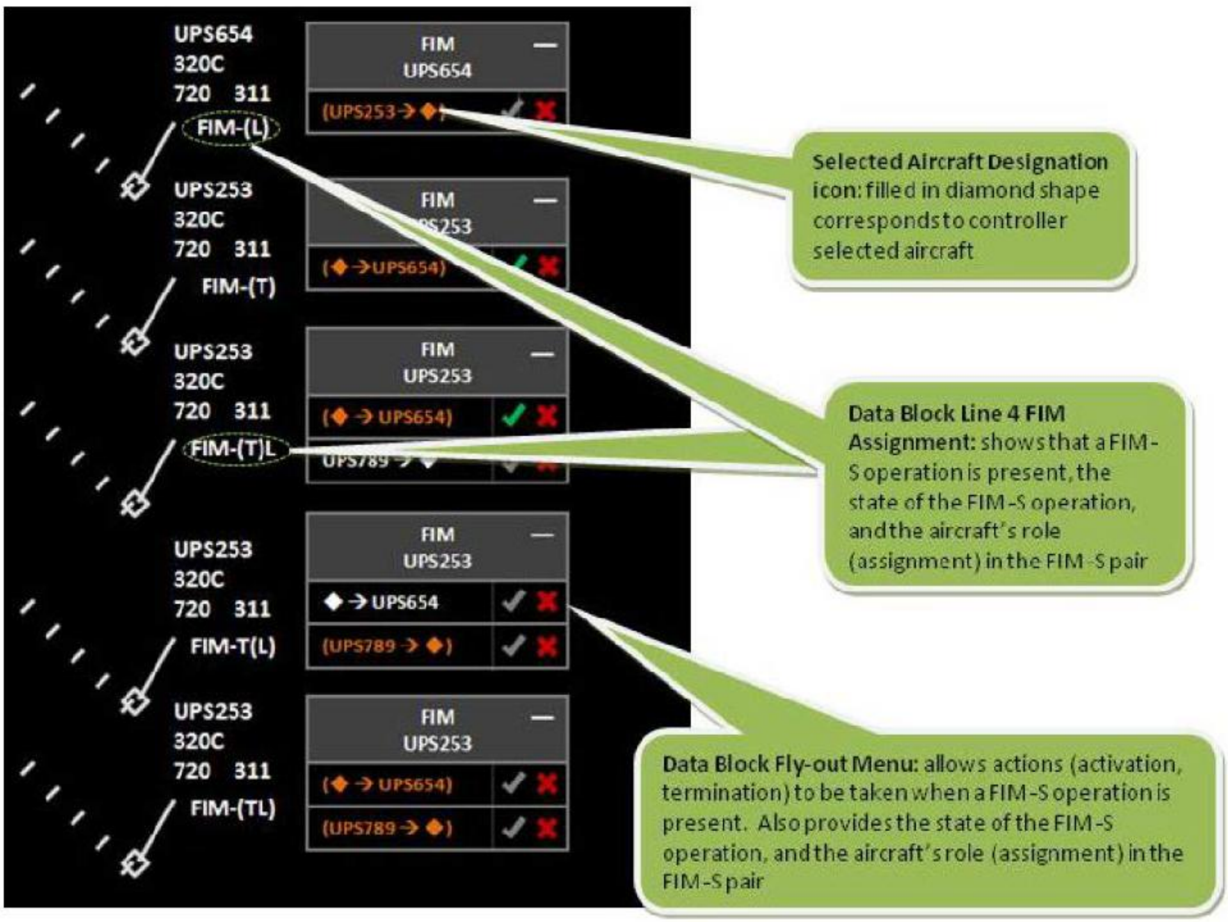

Figure 2-9. MITRE IM Controller Data Block Information [Reprinted from Benson et al., 2011]

Peterson et al. (2012) conducted a follow-on simulation and developed an alternative data block and fly-out menu for IM. In this implementation, the controller could accept or reject a proposed IM operation, as well as change the status states of the IM operations. The status states shown were: capable (FC), pending (FP), active (FA), or terminated (FT). The flyout menu was where the proposal for the IM operation was rejected and where the status states were changed (Figure 2-10). The majority of controllers reported that the data block was their preferred method for conducting IM operations, although controller responses appeared mixed as to the necessity to display IM information in the data block. The majority of controllers agreed that each of the states should be depicted.

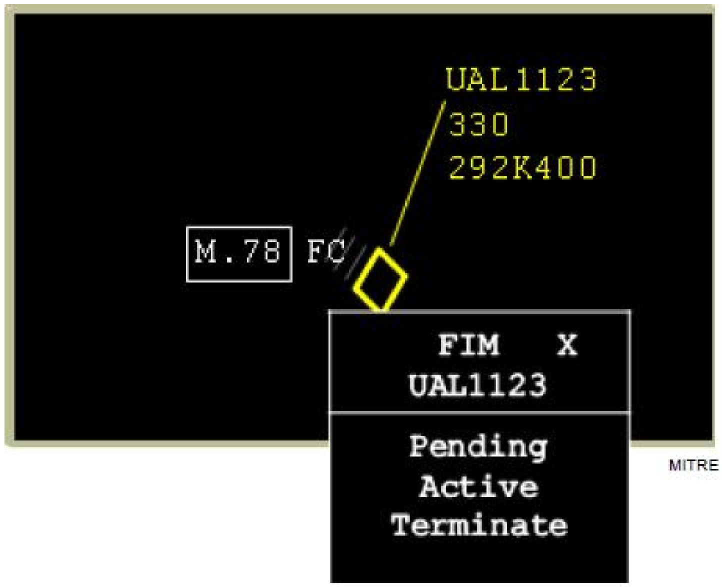

Figure 2-10. MITRE IM Controller Data Block Information [Reprinted from Peterson et al., 2012]

In Cabrall et al. (2012), IM status information for the IM trail aircraft was provided to TRACON controllers in the second line of the data block, after the aircraft type. No IM equipped indicator was shown for the trail aircraft. A "®" was used when aircraft were flying RTAs prior to starting IM and an "S" was used when aircraft were conducting IM. Controllers manually updated the status designators based on flight crew reports. Controllers found the status information itself, as well as the need to manually update the status, acceptable. The information was rated as highly helpful and highly usable. However, controllers reported wanting a single input command to toggle between the status states.

The same method was used in the follow-on simulation reported in Callantine et al. (2012). However, there were also conditions where the TSAS speed advisories were removed during IM for the IM trail aircraft. Both Center and TRACON controllers reported that the status information was useful. In the third simulation of the series, data blocks for the Center controllers had a "/S" indicator in the third line of the data block for the IM trail aircraft. This simulation added an IM equipped indicator for the trail aircraft. A command was used to turn the field magenta when IM started. A "®" was included if the aircraft was flying the RTA prior to IM. A command could be used to toggle between the states. The status information was passed to the TRACON controller where the information was provided in the same field as the previous two simulations (Callantine et al., 2012). The TRACON controllers provided high ratings for the helpfulness and their confidence in the IM status information. Center controller feedback was not reported. The authors note that there were some issues with setting the status, but the reason for the issues was unclear from the report.

In another simulation, Thipphavong et al., (2013) used a similar approach to that reported in Callantine et al. (2012). Data blocks for the Center controllers had a "/S" indicator in the third line of the data block to indicate IM capable for the trail aircraft. A command was used to turn the field magenta when IM started. TRACON controller IM designations in the data block were not described. The lead aircraft was sometimes identified in the data block for the lead aircraft controller when both aircraft were not in the same sector. TRACON controllers reported that the TSAS speed advisories were less useful for IM operations than for non-IM operations, but were still “somewhat useful.” The IM status indicators were rated as more useful than the slot markers by TRACON controllers, but the slot markers were still reported to be used 40% of the time. Controllers reported that they did not want to have other IM status indicators, such as suspended or terminated, 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 the follow-on simulation, the indicators and their location changed for both center and TRACON controllers (Callantine et al., 2013). Center controllers had the following information in the zero line of the data block: “@” for IM-equipped, “R” when the aircraft was flying a RTA prior to IM, and “S” for active IM operations. The “@” symbol changed to magenta when the controller issued the IM clearance and made an entry. The “R” and “S” indicators were shown after controller entry (Figure 2-11). For the TRACON controllers, the IM status was transfer from the center controller systems. In this simulation, the designators were: “FIM” [Flight deck-based IM] for IM clearance issued, “RTA” when the aircraft was flying a RTA prior to IM, and “SPC” for active IM operations. The designators for this simulation were in the third line of the data block replacing the TSAS speed advisories and early / late indicator (Figure 2-12). This simulation had wind-related issues that affected IM operations; however, both center and TRACON controllers reported favorably on the IM status designators and the associated updating.

Figure 2-11. Center Controller Data Block Information from Callantine et al. (2013) [Reprinted from Callantine et al., 2013]

Figure 2-12. TRACON Controller Data Block Information from Callantine et al. (2013) [Reprinted from Callantine et al., 2013]

One of the final NASA simulations is reported in Baxley et al. (2016). As with past simulations, center controllers had IM status information in the data block (top line) which included three status levels: IM capable, IM issued, and IM active / reported "paired." TRACON controllers had IM status information in the data block including: IM issued ("FIM") and ("SPC") IM active / reported "paired." Overall, the controller reported the display elements as acceptable. The authors recommended indicating in the data block of the trail aircraft: (1) whether an aircraft is IM capable, and (2) whether an IM clearance has been issued.

In concept evaluations conducted in preparation for this HITL simulation, the IM information in the data block was examined. The IM information replaced the TSAS speed advisory and early / late indicator. The first concept evaluation included the lead aircraft identification in the data block of the trail aircraft, along with the aircraft role (trail or lead aircraft) and IM state status. Controllers reported the lead aircraft identification in the trail aircraft data block as being unnecessary information (this information was also available in an IM clearance window). In the subsequent concept evaluations, this information was removed but the aircraft role and state status information persisted. Controllers did not report issues with IM information replacing the TSAS speed advisories or the early / late indicator for the trail aircraft.

2.5.1.3 IM Clearance Information on ATC Surveillance Displays

Besides needing information in the data block about the status of the IM operation, similar or different information may be needed in a window that provides the IM clearance information. Previous simulations examined this topic only from the center controller perspective and will be reviewed next.

The information and format provided to the center controller in the first two simulations in Callantine et al. (2012) is unclear. However, the third simulation provided the IM information in the meter list. The IM information provided was the ABP, the ASG, the lead aircraft, and the lead aircraft's Intended Flight Path Information (IFPI). Center controllers reported positively on the overall set of tools available to them, including the meter list. The same information was provided in the meter list in the simulations as was reported in Callantine et al. (2013) and Thipphavong et al., (2013). No display issues were noted. Controllers in Thipphavong et al., (2013) reported that the meter list was "very useful." Baxley et al. (2016) had a similar implementation but reported there may have been unintended consequences in their displayed clearance information because they did not have time to incorporate a capability to only show the controller the relevant IM clearance information for each IM clearance type utilized. This required the controller to know which information was required for which operation and to only issue the necessary information. They suggested fixing this for future implementations. However, controllers generally reported favorably on the display implementation.

Benson et al. (2011) reported a simulation with center controllers that evaluated two different display implementations (i.e., IM window and alert list) for IM clearance information. The IM window will be reviewed as it had more favorable objective results, was the preferred implementation, and is the most relevant implementation. The IM window included four main areas: (1) timeline, (2) a window for the clearance information, (3) a window with IM state and status information as well as an area to initiate or terminate IM, (4) a “trash can” for recently terminated IM operations. The “FIM List” timeline showed when an IM clearance would be available (Figure 2-13). The “FIM information” window showed the lead and trail aircraft identifications, ASG, lead aircraft sector, and predicted spacing at the ABP. It used color coding to differentiate between the IM pending (clearance issued but not yet accepted by the flight crew) and active states. The rest of the clearance (the ASG) was in the “command info” window which is where the clearance was presented.

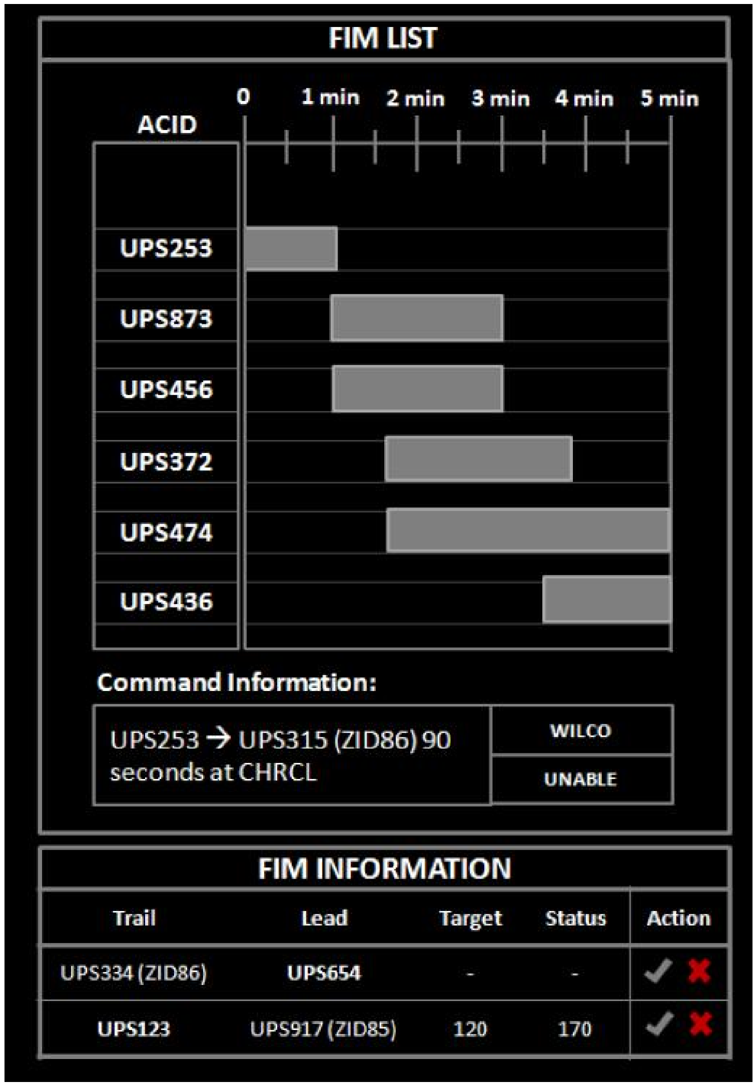

Figure 2-13. MITRE IM Window Controller Information [Reprinted from Benson et al., 2011]

The timeline received favorable feedback. For the information in the window with IM state and status, the controllers reported that the predicted interval at the ABP was useful but were split on whether it was a requirement and just over half thought it was "useful as an indicator of [IM] status." Controllers did not report the sector information for the lead aircraft to be very useful.

In a follow-on simulation, Peterson et al. (2012) used the existing TBFM metering list (which included the Meet Time Error [MTE]) to add IM information. The only IM information that was added was IM status state, the ASG, and an indication of the ability of an aircraft to act as a lead for an IM operation. The trail aircraft was already listed as the first element in the TMA metering list and the lead aircraft was inferred to be the aircraft directly ahead in the schedule. The controller was not able to interact with the list. All interactions were via the data block. The currently available MTE parameter was provided to the controllers as the spacing compliance tool. Controllers reported having this information was useful. However, only a slight majority of controllers reported that the MTE was useful for maintaining awareness of IM operations. More downstream controllers found it useful than did upstream controllers. Controllers reported that the IM status state, the ASG, and the lead aircraft indication were useful.

2.5.1.4 ATC Research Needs

As can be seen from past work, general acceptance of IM operations has been reported in numerous simulations, including some examining IM during metering (e.g., Rognin et al., 2005; Penhallegon and Bone, 2008; Benson et al., 2011; Callantine et al., 2012; Baxley et al., 2016). However, there are still issues that need to be addressed related to the interaction between TSAS (absolute spacing) and IM (relative spacing), as well as controller information needs in the TRACON. The interactions between these two types of spacing behaviors is important to understand since both are expected to be fielded by the FAA to maximize capacity.

As discussed in Sections 2.1 and 2.2, IM and TSAS operations achieve operational spacing goals in different ways. During IM / relative spacing, 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 (once the schedule is frozen). The following issues have been identified in past IM and metering activities.

- Controllers can have difficulty visualizing time-based spacing (as compared to distance-based operations) (e.g., Aligne et al., 2003)
- Under certain conditions, separation can be an issue because the IM algorithm is only considering spacing at a point (the ABP) and not separation along the way. Baxley et al. (2016) recommended examining placing the ABP at the location where the aircraft routes merge to ensure separation at that point. Controllers that participated in the concept evaluation activities also expressed concern about this potential issue.
- IM aircraft can be outside of the slot markers. While slot markers were found useful in general, in some instances, they were reported as less so for IM aircraft. Proposals to modify slot makers have been mentioned (e.g., Cabrall et al., 2012) but not reported or tested.
- Necessary IM information and where it should be displayed to support the controller in IM operations is still an open topic. For example, it remains unclear what information controllers require to monitor the progress of the IM operation and to determine acceptable spacing for the handoff and final spacing at the ABP. Splitting the information between a clearance window and the data block also still needs examination.
- While past simulations did not report issues with TRACON controllers receiving aircraft already conducting IM from the en route environment, concept evaluation activities leading up to this simulation did have some questions from controllers about the acceptability of this. Therefore, the topic should be explored further to see if HITL participants have any concerns.

This simulation will attempt to address these open issues and continue validation of other topics from past efforts.

2.5.2 Flight Deck Topics

2.5.2.1 Flight Deck Display Spacing Information

Displays for IM must include the necessary information to perform IM and must not contain information that conflicts with IM tasks. Any annunciations must also be salient. In order for pilots to trust the IM system, they must be able to develop an appropriate mental model (i.e., abstract functional understanding) of the operation and to fully understand the objectives and methods IM uses to achieve and maintain spacing. For example, they will need to understand that the spacing to be achieved is based on a time interval, and that distance spacing will be variable due to winds and compression. The degree to which their mental models conform to the reality of the IM operations will allow them to appropriately calibrate their level of trust. A good mental model is also important for situation awareness in that it provides a mechanism for integrating and comprehending information and allows for projecting future states (Endsley, 1995).

Over the course of HITL research on IM[2], there has been shown to be general acceptability of IM and the ability to meet the spacing goals (e.g., Hebraud, Hoffman, Pene et al., 2004; Swieringa et al., 2014; Penhallegon, Mendolia, Bone, Orrell, and Stassen, 2011). However, a dominant, re-occurring issue is flight crew understanding and trust in the IM algorithm's behavior and the related ability to monitor the progress of the spacing task. Past simulations have attempted to support the flight crews and through examination of different display features. The past work has shown that certain features can lead to confusion, additional workload and head-down time, or simply may not be utilized. The past work also shows that an ideal, or even reasonable, implementation has been challenging to achieve. The remainder of this section will review this past work.

2.5.2.1.1 EUROCONTROL Research

The first IM simulations conducted by EUROCONTROL included a limited number of pilots, and only a basic Cockpit Display of Traffic Information (CDTI) capability (Zeghal, Hoffman, Cloerec, Grimaud, and Nicolaon, 1999). Only qualitative feedback was received as the main effort was to determine the feasibility of IM. Results revealed some issues that the authors speculated were due to the rudimentary CDTI (e.g., no IM speeds).

The second set of flight deck experiments was conducted in 2002 and is reported in Hebraud, Hoffman, Papin et al. (2004). These two evaluations (May and December) were conducted after the initial small-scale experiment examining feasibility of spacing and the requirements for the CDTI. The setup for the spacing was conducted through the Control and Display Unit (CDU), and a CDTI traffic display was placed on the navigation display. In both experiments, pilots reported favorably on their situation awareness and their active participation in the maintenance of

[2] "IM" is used generically in this section. Not all simulation examined the full capabilities now being defined in new versions of DO-361 and DO-328A (RTCA, 2015a, 2015b). Most examined only a subset of those capabilities or an early implementation of those capabilities, under different concept names.

spacing. Flight crews were found to be able to maintain spacing within the tolerances, with few exceptions.

For spacing information in the May experiment, the CDTI traffic display included lead aircraft ground speed, closure rate to lead aircraft (difference between lead aircraft and ownship groundspeed), a required spacing arc and a predicted spacing cue (position on trajectory where spacing will be acquired) (Figure 2-14). The predicted spacing cue changed to amber if the spacing was predicted to be outside tolerances. IM speeds were not provided to the flight crew. Pilots reporting desiring spacing trend information and IM speeds.

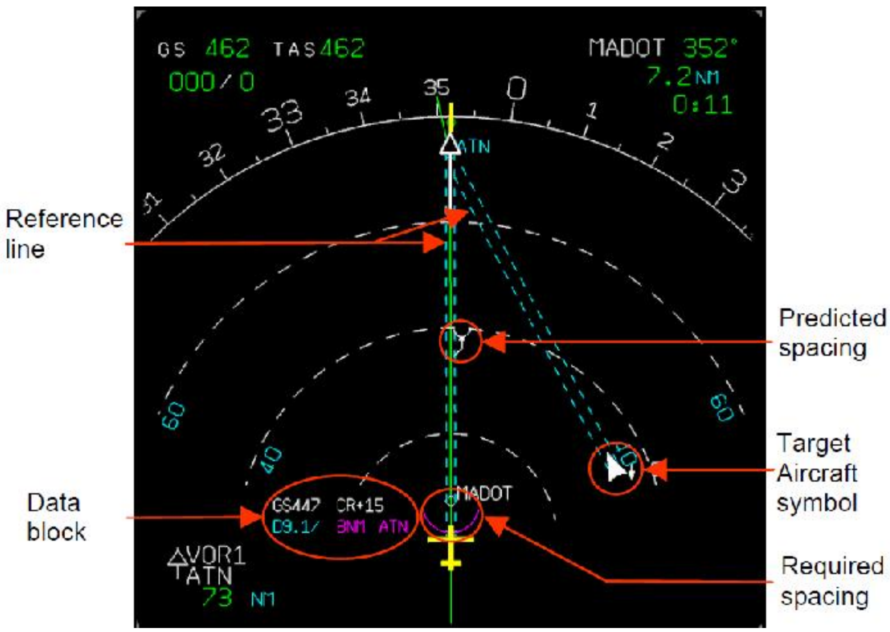

Figure 2-14. Navigation Display with IM Information from Hebraud, Hoffman, Papin et al. (2004) First Evaluation [Reprinted from Hebraud, Hoffman, Papin et al., 2004]

Based on the findings from the May evaluation, changes were made for the December evaluation. The required spacing arc and the data block information were removed. The CDTI traffic display now included an IM speed and spacing scale (Figure 2-15). The spacing scale showed current spacing, required spacing, spacing trend, closure rate, and tolerance margins (Figure 2-16). When current spacing was out of tolerances, the flight crew was alerted. Flight crews were also prompted with the visual advisory “losing spacing” when spacing was an issue.

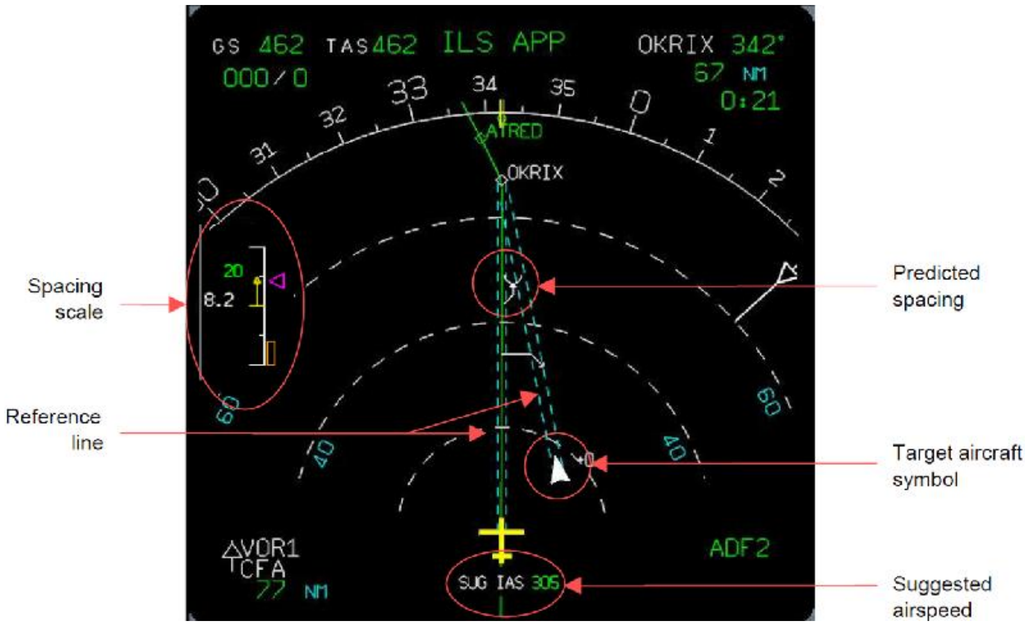

Figure 2-15. Navigation Display with IM Information from Hebraud, Hoffman, Papin et al. (2004) Second Evaluation [Reprinted from Hebraud, Hoffman, Papin et al., 2004]

Figure 2-16. Spacing Scale from Hebraud, Hoffman, Papin et al. (2004) Second Evaluation and Hebraud, Hoffman, Pene et al. (2004) [Reprinted from Hebraud, Hoffman, Pene et al., 2004]

The majority of pilots reporting that the spacing task could be conducted with the displayed information and that the new features were helpful. Pilots reported the new spacing scale was intuitive and useful, though the closure rate information was of little use. Some pilots also thought they focused too much on the new spacing scale while others felt it was well integrated into their scan. Pilots also reported liking the IM speeds and questioned the relevance of the predicted spacing cue. Finally, pilots reported a worry about focusing on the spacing task requirements too much when busy or forgetting when no action is needed during a long period of time.

A third flight deck evaluation was conducted in 2003 and was reported in Hebraud, Hoffman, Pene et al. (2004). The display implementation was very similar to the December 2002 evaluation (Hebraud, Hoffman, Papin et al., 2004). This experiment added flashing for the IM speeds when there was a difference of 7 knots between the IM speed and the current IAS.

While the December 2002 evaluation prompted the flight crews with the visual advisory "losing spacing" when spacing was an issue, this experiment changed the visual advisory to either "ASAS ACCELERATE" or "ASAS SLOW DOWN."

The 2003 evaluation found the spacing task to be acceptable and all pilots reported the spacing as easy. They reported favorably on their active participation in the maintenance of spacing and were found to be able to maintain spacing within the tolerances with no loss of spacing with the displayed information. They again reported that spacing scale may have too much information and that the closure rate information was of little use. However, pilots reported the trend information was useful. They noted the flashing of the IM speed was good but that there should be more alerting. Pilots reported potential fixations on the spacing scale and a possible reduction in monitoring other flight information.

After this set of evaluations, the final flight deck requirements were defined by EUROCONTROL (Hoffman, Pene, and Zeghal, 2006). The requirements relevant to the spacing cues are noted below.

The flight deck implementation shall include the following:

- Advisory if IM is infeasible (visual alert only during the feasibility check)
- Advisory if spacing is drifting and may exceed tolerances (visual alert) with message for corrective action
- Caution if tolerances are exceeded (visual and aural alerts) with message for corrective action
- Warning if the clearance cannot be complied with (visual and aural alerts) with reason why the clearance cannot be complied with
- Spacing indicator with current spacing, required spacing, spacing trend, and tolerance margins in the main field of view (preferably analog representation). Information on where the ASG will be reached
    - Note closure rate is excluded
- Guidance indicator / IM speed in the main field of view

2.5.2.1.2 NASA Research

Much of the early work on in-trail following, spacing, and merging applications was conducted by NASA Langley and was from the flight crew perspective in the terminal environment during approach (e.g., Abbott and Moen, 1981; Williams and Wells, 1986). The work continued under different names and programs. The most relevant recent work is reviewed here.

Oseguera-Lohr, Lohr, Abbott, and Eischeid (2002) conducted an IM pilot evaluation in a high-fidelity simulator with active airline pilots. The CDU was used to enter the IM information and provided relevant information (i.e., lead aircraft identification and groundspeed, current spacing, ASG, as well as current distance to the lead aircraft). The IM speed was provided on the Electronic Attitude Direction Indicator in association with the standard fast / slow bug (left side of Figure 2-17). New IM speeds were annunciated with a box flashing for 5 seconds around the IM speed value. On the Electronic Attitude Direction Indicator, the IM speed was shown immediately numerically but the fast / slow bug for the IM speed followed a scheduled speed reduction (though the exact method is not described in detail). The IM speed was also shown on the airspeed indicator. The navigation display included a highlighted target aircraft along with its associated flight identification and range in NM, spacing position indicator (aka "picnic table"), and history data from the target aircraft (right side of Figure 2-17). It also showed the ASG ("PDA" field) and IM Speed ("CMD" field). The spacing position indicator showed the predicted spacing relative to the ASG. When the predicted spacing was the same as the ASG, the apex of ownship fit into the "v" of the indicator.

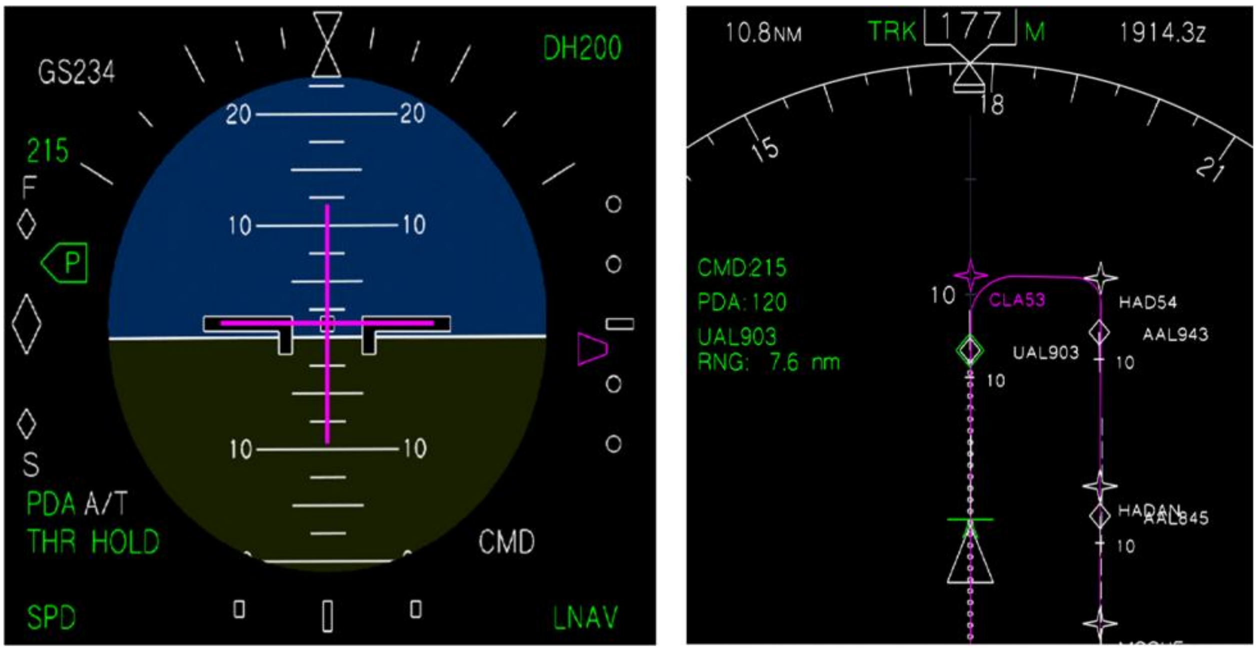

Figure 2-17. Primary Flight Display (PFD) and Navigation Display with IM Features from Oseguera-Lohr et al. (2002) [Reprinted from Baxley et al., 2014]

Pilots reported the tools were acceptable. Head-down time was found to be higher than current operations, but acceptable. No major changes were proposed for the display implementations. In a summary of this work, however, Baxley, Shay, and Swieringa (2014) stated the fast / slow symbology was found to be borderline effective, the speed change notification should be longer than 5 seconds, and the spacing position indicator received varying reports of usefulness.

As a follow on to Oseguera-Lohr et al. (2002), Lohr et al. (2005) made minor updates to the IM display information (e.g., the IM speed location on the fast / slow indicator was moved to be alongside the bug) and algorithm to conduct a flight test. Information was provided to indicate to the flight crew that the current IM speed was limited due to configuration or procedural reasons. As with the previous activity, the pilots reported the tools were acceptable. Head-down time was found to be higher than current operations, but acceptable. The authors noted an issue with the spacing position indicator. Although pilots had been told to follow the IM speeds and only use the spacing position indicator for spacing awareness, they had a desire to quickly drive the aircraft symbol into the spacing position indicator versus following the IM speeds, which would progressively get them in the proper position over time. This, unnecessarily, led to additional workload and unnecessary speed inputs. The authors recommended additional work to refine the IM tools.

Prevot et al. (2004) describes a CDTI used by flight crews in their work on trajectory-oriented operations with limited delegation. It is described and shown in greater detail in NASA (2004). Figure 2-18 shows the implementation. The CDTI included lead aircraft identification, ASG, spacing box, and a line between the trail and lead aircraft showing the ASG and 30-second markers. The spacing box was green if the trail aircraft was within tolerance but changed to yellow when the aircraft was greater than 10 seconds ahead of the ASG and changed to white when greater than 20 seconds behind the ASG. Limited results were found related to the use of this implementation for IM.

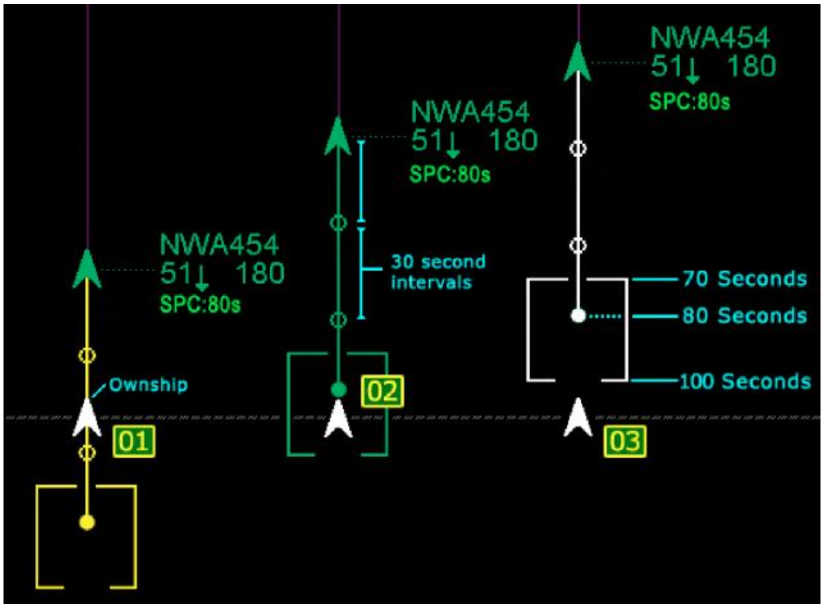

Figure 2-18. IM Features on the CDTI from NASA (2004). [Reprinted from NASA, 2004]

Barmore, Abbott, and Capron (2005) examined IM with pilots flying a desktop simulator. This simulation used displays very similar to those used in previous simulations, with a few modifications (e.g., no fast / slow indicator) and the use of PFDs and navigation displays (Figure 2-19). Crews were alerted if the current speed was not within 5 knots and closing on the IM speed. The IM speeds were coupled to the autothrottle so the flight crew did not enter the IM speeds through the Mode Control Panel (MCP). The Multifunction Control and Display Unit (MCDU) was used for set-up and provided the same information as that in Oseguera-Lohr et al. (2002). In a summary of this work, Baxley et al. (2014) stated the spacing position indicator was again problematic (e.g., low usefulness ratings, over-control issues) and that it should be removed or improved.

Figure 2-19. PFD and Navigation Display with IM Features from Barmore et al. (2005) [Reprinted from Baxley et al., 2014 (Highlights Added)]

Murdoch, Barmore, Baxley, Abbott, and Capron (2009) conducted an IM HITL simulation during optimized RNAV routes. The objectives of the HITL were to assess pilot ability and acceptability of IM procedures during nominal and off-nominal situations and to evaluate human and system performance in terms of aircraft spacing and system performance. Two separate simulation platforms were used and the displays are shown in Figure 2-20 and Figure 2-21. It can be seen in the PFD and navigation display in Figure 2-20 that elements have been removed (relative to the previous simulation) and only the IM speed and mode are shown on the PFD. Also, only the target aircraft highlighting is shown on the navigation display. The same is true with Figure 2-21, except the spacing position indicator also appears to have been used. The MCDU was used for set-up and provided IM information during conduct. Using subjective measures of acceptability, completeness of procedures, and workload, Murdoch et al. (2009) found overall favorability of IM and the tools across nominal and off-nominal events.

Figure 2-20. PFD and Navigation Display with IM Features Implementation 1 from Murdoch et al. (2009) [Reprinted from Baxley et al., 2014]

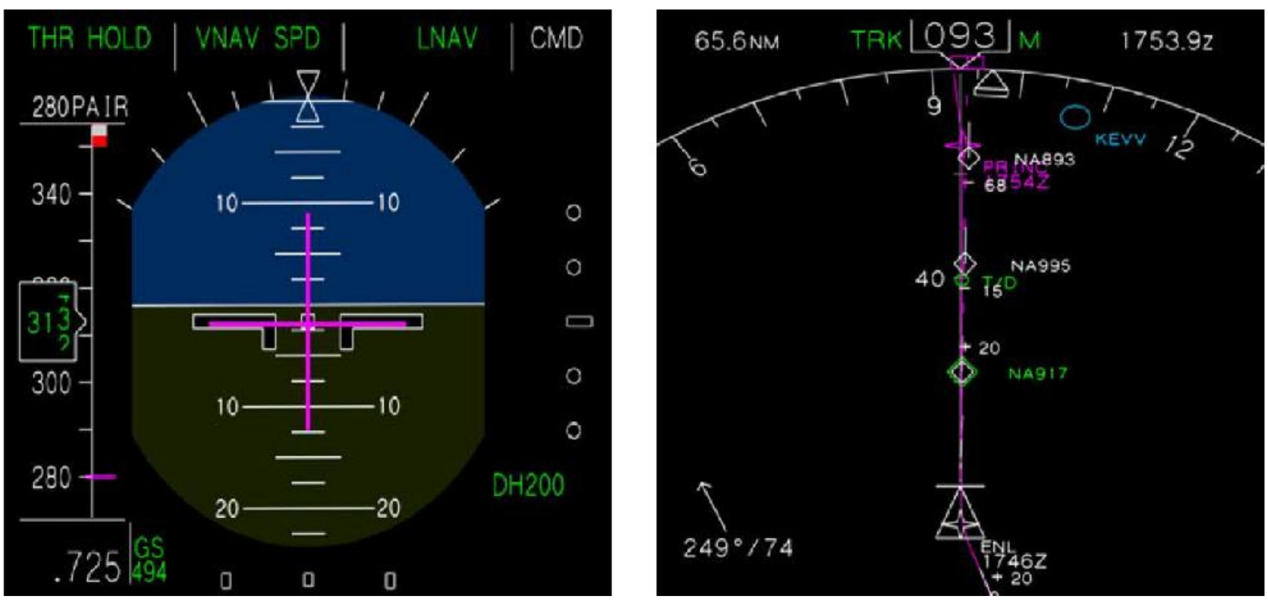

Figure 2-21. PFD and Navigation Display with IM Features Implementation 2 from Murdoch et al. (2009) [Reprinted from Baxley et al., 2014]

Baxley et al. (2013) conducted an IM HITL simulation during dependent runway operations. Controller Pilot Data Link Communications (CPDLC) was used to convey and load the IM clearance information into the flight deck IM equipment. The MCDU was used for set-up and provided IM information during conduct. Three separate simulation platforms were used. The PFDs are shown in Figure 2-22. As can be seen, the IM speeds were shown above the airspeed tape and as a bug alongside the airspeed tape. A green box was placed around a new IM speed for 10 seconds. Pilots were also notified if the IM speed was limited due to procedural speeds. Pilots were notified if they were greater than 6 knots above the IM speed (by an Engine-Indicating and Crew-Alerting System [EICAS] message). No early / late (progress) indicator or fast / slow indicator was present. For the navigation displays, the only IM feature included was the highlighting of the target aircraft, except for one exploratory run where a conformance box was shown (Figure 2-23). The conformance box showed the band within which it was still possible to reach the ASG by the ABP. The goal of the box was to provide better spacing predictability. Spacing error was presented on the MCDU.

Figure 2-22. PFDs with IM Features from Baxley et al. (2013) [Reprinted from Baxley et al., 2013]

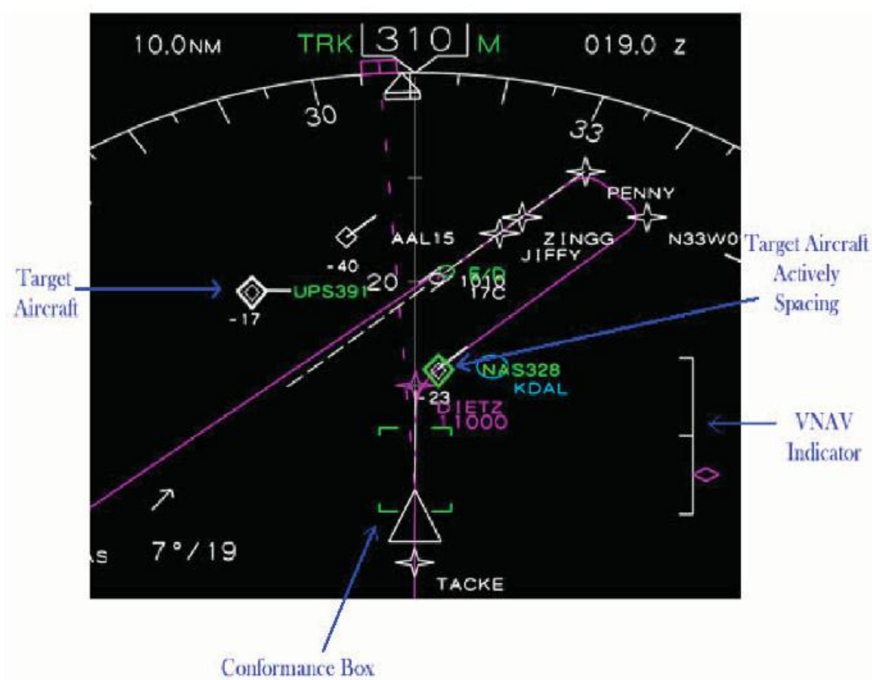

Figure 2-23. Navigation Display with IM Features from Baxley et al. (2013) [Reprinted from Baxley et al., 2013]

Pilots reported general acceptance of the display elements but the majority reported wanting a more salient speed change notification such as flashing or an associated aural alert. Pilots also reported a strong preference for a progress indicator and the ability to predict new IM speeds. Some comments indicated that the pilots may have had a poor mental model of the relationship between the spacing error and the IM speeds and the conformance box did not help much with the issue or pilot comfort in IM. However, the conformance box did provide useful information for IM operations about the current time error relative to the tolerance boundary. Pilot reported it should be a tool available for IM. The authors recommended examining tools that provide a clear indication of the relationship between the time error and the arrival of new IM speeds and a tool similar to the conformance box showing the current status and trend of IM. Spacing error was only shown on the first IM page on the MCDU and the authors were concerned about the amount of time the crews would spend viewing the MCDU page for this key piece of information. Flight crews were reported to use the spacing error information but not spending excessive amounts of time referencing the MCDU.

NASA continued the IM work under its ATD-1 activity. Kibler et al. (2015) examined IM operations in a HITL simulation that used an auxiliary / Electronic Flight Bag (EFB) display location and an Automatic Dependent Surveillance-Broadcast (ADS-B) Guidance Display (AGD). In this simulation, the EFB was used to enter the IM information. The AGD had a fast / slow indicator and the IM speed (Figure 2-24). New IM speeds were annunciated with a Light-Emitting Diode (LED) light on the AGD. The EFB display hosted the CDTI traffic display (Figure 2-25). The traffic display included spacing information such the IM speed, a fast / slow indicator, and the ASG.

The fast / slow indicator provided trend and acceleration and deceleration information and was not simply an indication of whether the aircraft's current IAS or MCP speed matched the IM speed. It was designed to assist the flight crew with matching the acceleration / deceleration profile expected by the IM algorithm. The NASA algorithm attempts to keep the number of IM speeds low (i.e., display one large speed command versus several smaller ones). By giving fewer IM speeds, the deviation from the expected speed profile can be greater so NASA provides the fast / slow indicator to help the flight crew follow the expected profile. The fast / slow indicator shows the flight crew whether the aircraft is on the expected speed profile, which is otherwise unknown to the flight crew. The flight crew is expected to set the IM speed in the MCP but is also expected to use the fast / slow indicator to manage pitch / drag to decelerate (for example) to match the profile (and to avoid poor performance when off-profile). Based on the design, there could be a situation where an IM speed is given that the flight crew quickly decelerates to, which takes them off the expected profile. In this situation, the IAS / MCP speed would match the IM speed but the fast / slow indicator would show the aircraft slow (because the aircraft has decelerated too quickly relative to the assumed profile).

Figure 2-24. AGD with IM Features from Kibler et al. (2015) [Reprinted from Kibler et al., 2015]

Figure 2-25. CDTI Traffic Display with IM Features from Kibler et al. (2015) [Reprinted from Kibler et al., 2015]

Pilots found the display implementation usable, but there were some concerns with the limited amount of information in the forward field of view. Baxley et al. (2014) also noted that pilots expressed some concerns about the LED indication of a new IM speed not being salient enough.

Latorella (2015) examined IM operations with different display combinations and locations (as a within subjects variable) and alerting schemes (as a between subjects variable). The display combinations included: (1) an EFB in an aft location; (2) an EFB in an aft location with an AGD in the forward field of view; (3) an EFB in a forward location; and (4) an implementation integrated into existing PFDs and navigation displays. The integrated displays were similar to

Baxley et al. (2013) except for the addition of a flashing box around new IM speeds and the lack of the conformance box (Figure 2-26). The EFB and AGD implementations are shown in Figure 2-27. Fast / slow indications were also provided in a manner similar to previous simulations. Either the EFB or the MCDU were used for set-up. As with previous simulations, the MCDU provided IM information during the conduct of IM.

The alerting triggers included: (1) new IM speeds; (2) deviations from IM speeds; and (3) reminders if the IM speeds were not entered into the MCP. The triggers were alerted either visually or visually and aurally. The three alerting methods were: (1) all visual only; (2) all visual and aural alerting; and (3) visual only for new IM speeds and reminders with visual and aural alerting for deviations from the IM speed.

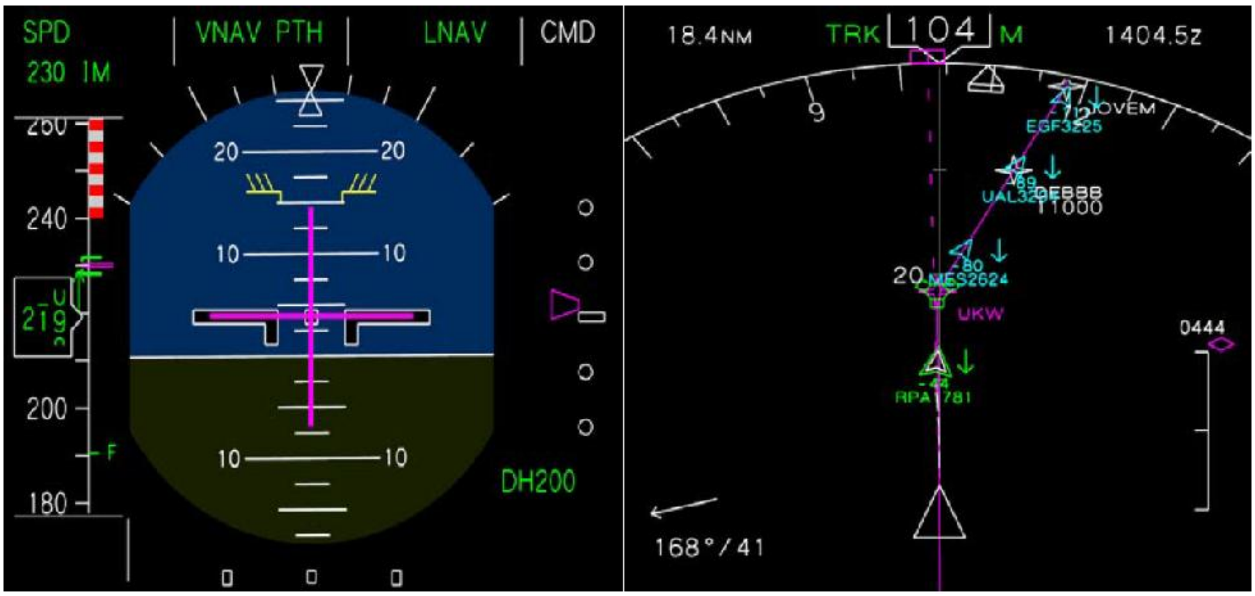

Figure 2-26. PFD and Navigation Display with IM Features from Latorella (2015) [Reprinted from Baxley et al., 2014]

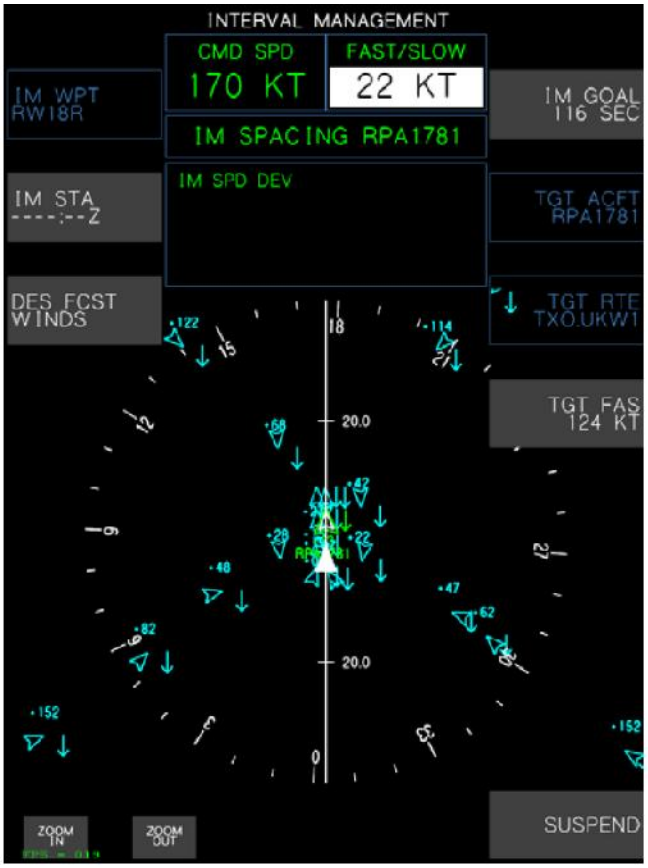

Figure 2-27. CDTI Traffic Display and AGD with IM Features from Latorella (2015) [Reprinted from Baxley et al., 2014]

Relevant results here are those related to the alerting. The all visual and aural alerting method generally did better than the all visual only alerting, and sometimes better than the visual / visual and aural combination. There were also results that had interactions between the display combination and the alerting scheme (as well as Pilot Flying [PF] seat position). However, though most are less relevant to this work, they are important when considering the display and alert combination. The author recommended additional work to optimize the IM displays and the associated alerting schemes with a strong consideration for the use of visual and aural notifications.

Swieringa et al. (2014) conducted a HITL simulation examining IM in nominal conditions and a condition where the lead aircraft slowed more than expected causing a potential issue with spacing. The simulation utilized a retrofit display implementation that included an EFB traffic display (also used for set-up) and either a numeric (Figure 2-28) or graphical (Figure 2-29) primary field of view AGDs.

Figure 2-28. Numeric AGD with IM Features from Swieringa et al. (2014) [Reprinted from Baxley et al., 2014]

Figure 2-29. Graphic AGD with IM Features from Swieringa et al. (2014) [Reprinted from Baxley et al., 2014]

The flight deck platform was a desktop personal computer simulator. The numerical AGD was similar to Latorella (2015) in that it had the IM speed, a fast / slow numerical value. However, a time error (predicted spacing error at the FAF/ABP) was added. The graphical AGD had fast / slow graphic (with trend), IM speed, IM mode, trail aircraft ID, and an early / late (progress) indicator graphic. The early / late (progress) indicator depicted the spacing error relative to feasibility bounds (field 5 in Figure 2-29). The boundaries of the indicator were approximately 10% of the trail aircraft's time to go to the ABP. The green bug was the difference between the lead aircraft's ETA and the trail aircraft's ETA at the ABP subtracted by the ASG. If the green bug reached the boundary, the ASG could not be achieved at the ABP. The flight crew was presented with a visual notification on the CDTI traffic display that the operation was no longer feasible. The fast / slow field and indicator functioned as previously described.

For the numerical AGD, new IM speeds would be indicated by a green LED light (field 4 in Figure 2-28). For the graphical AGD, new IM speeds would be indicated by reverse video. Both indications would extinguish when the IM speed was set in the MCP. Flight crews were notified if they were greater than 10 knots above and diverging from the IM speed.

Several tests were conducted comparing the numerical and graphical AGDs during no perturbation conditions and a perturbation condition (lead aircraft slowed below profile speed). Graphical AGD use during a perturbation was found to provide better situation awareness than the numerical AGD with no perturbations, but both had positive ratings. Graphical AGD use during a perturbation was found to be more intuitive than the numerical AGD with or without perturbations. There were no differences found between the displays and conditions when pilots were asked if the IM speeds made sense, but both had positive ratings. Related to this finding (as the early / late [progress] indicator was attempting to support this understanding), pilots reported that they did not use the early / late (progress) indicator often and did not find it very useful. The fast / slow indicator was reported it to be moderately useful but comments indicated pilots did not use it and did not think it should be a requirement for display.

Pilots were faster to implement the IM speeds with the graphical AGD, which the authors attributed to the more salient method of alerting to the new IM speeds (versus something better in the graphical elements). No significance for the deviation from the IM speeds.

Overall, the graphical AGD was found to be better than the numerical AGD. However, the numerical AGD was reported to be sufficient but not ideal. The authors stated reasons why the specific implementation of the early / late (progress) indicator could be problematic and why other algorithms may have different outcomes. They also stated variations in the system can cause the spacing error to increase, but be nulled out later in the operation, leading to difficulty in understanding and interpreting the displayed information and how it relates to the possibility of getting a new IM speed. The authors suggest that a future simulation could examine the progress indicator with a different algorithm and a different representation to increase the usefulness. In a summary of this simulation, Baxley et al. (2014) recommend removing the early / late (progress) indicator if it cannot be improved. They also recommend adding an aural chime or flashing indicator to improve the saliency of new IM speed notifications.

Baxley et al. (2016) reported the final HITL simulation of the ATD-1 activity. It included nominal and off-nominal events (e.g., separation issue). The simulation used an auxiliary / EFB display (Figure 2-30) and a graphical AGD (Figure 2-31) in the primary field of view. The EFB was used for set-up. New IM speeds were annunciated by the IM speed being shown in reverse video until the IM speed was set in the MCP. If that was not done within 10 seconds, the field flashed. As can be seen both an early / late indicator and a fast / slow (progress) indicator were used (features D and H in Figure 2-30). The early / late indicator was only shown on the auxiliary / EFB display (feature A in Figure 2-31).

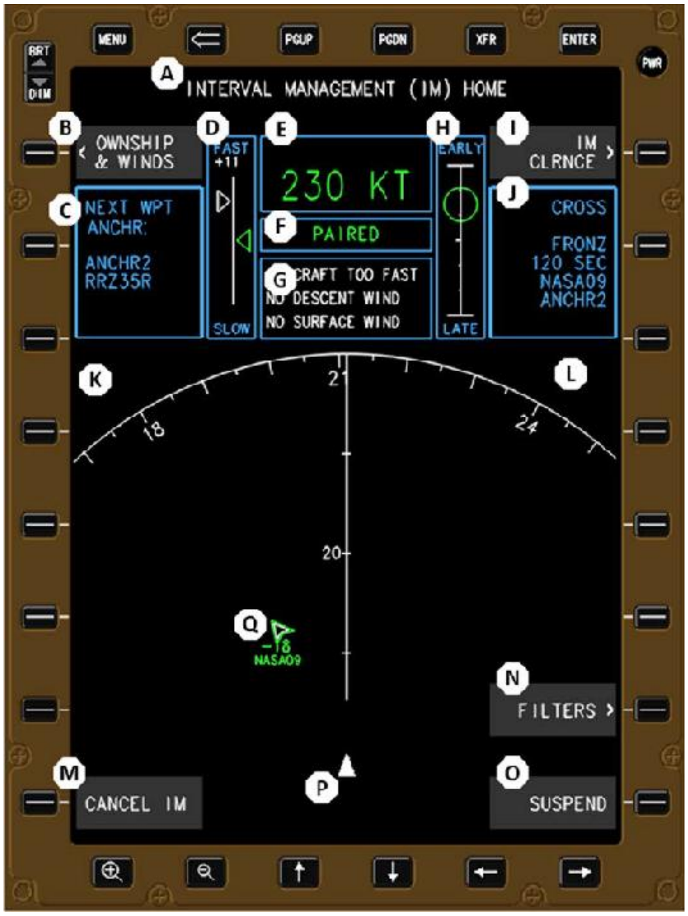

Figure 2-30. CDTI Traffic Display with IM Features from Baxley et al. (2016) [Reprinted from Baxley et al., 2016]

Figure 2-31. Graphic AGD with IM Features from Baxley et al. (2016) [Reprinted from Baxley et al., 2016]

As with previous work, the early / late indicator was intended to assist the flight crew in determining whether the ASG could be achieved, within tolerances, by the ABP. It was modified from previous simulations and displayed to the flight crew when specified by DO-361 (RTCA, 2015a). Two scales were shown. One when the aircraft was greater than greater than 210 seconds from ABP and within 210 seconds of the ABP (Figure 2-32). When greater than 210 seconds, the scale was +/- 120 seconds and the circle had a diameter of 20 seconds centered on the spacing error. When within 210 seconds, the scale was +/- 45 seconds, and the circle had a diameter of 20 seconds centered on the spacing error.

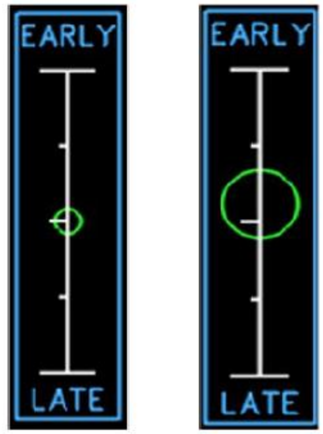

Figure 2-32. Early / Late (Progress) Indicator When Greater than 210 Seconds from ABP (Left) and within 210 Seconds from ABP (Right) [Reprinted from Baxley et al., 2016]

The fast / slow indicator was intended to allow the pilot to determine current IAS and IM speed mismatches and what action to take. As mentioned previously, it is not simply an indication of whether the aircraft's current IAS matched the IM speed. In this simulation, the green triangle on the indicator considered the IM speed, delay due to pilot behavior, and aircraft deceleration rate. It stayed fixed at the center of the display. The solid white triangle was the aircraft's current IAS. The two triangles could have been aligned when an IM speed change occurred, but then started to diverge when the aircraft should have been changing speed to match the IM speed and the expected speed profile.

Pilots reported that the fast / slow indicator was not very useful, confusing, and many were reported to have ignored it. The authors reported pilot confusion when the aircraft's current IAS matched the IM speed but the fast / slow indicator displayed a "too slow" alert because the aircraft decelerated faster than the algorithm expected. A redesign and move to the speed tape on the PFD was recommended by the authors.

Pilots also reported that the early / late (progress) indicator was not very useful and could be confusing. However, results were mixed and variable. The authors also stated that the pilot action when reaching the boundary were unclear, as it was not an indicator of infeasible operations. Again, the authors stated a need to improve the design, including showing the infeasible limits. The authors also recommend defining pilot procedures to notify ATC when the operation becomes infeasible.

The IM speed limit notifications were reported as confusing to pilots since there was no action to take based on the information. Finally, based on pilot attention concerns, the authors recommended keeping the alerting scheme associated with IM speeds but to add an additional aural alert at 15 seconds if the flight crew had not yet implemented the IM speed.

2.5.2.1.3 MITRE Research

The MITRE Corporation has been conducting simulations and participating in field and flight tests of IM over the course of many years to support concept and requirements definitions. Several were in conjunction with community activities where NASA also participated and supported through the previously reported activities. The following paragraphs review the most relevant MITRE activities.

An early effort supporting a flight event examined IM (Bone, Helleberg, and Domino, 2003). Two IM algorithms were used. In one, the symbology on the navigation display and algorithm were very similar to Oseguera-Lohr et al. (2002), as the organizations were working together on the capability. The navigation display included the lead aircraft identification, weight category, ground speed, and distance from the trail aircraft. The navigation display also provided the IM speed and the speed set in the MCP, as well as the spacing position indicator and history trail. For this implementation, a flashing box was provided around the IM speed when a new one was displayed. An IM speed bug was also presented on the airspeed tape of the PFD.

For the other algorithm, the navigation display had the same features except for the spacing position indictor and history trail. This algorithm included an aural alert (e.g., “Reduce speed 180”) for new IM speed notifications. Based on previous feedback, a graphical prediction tool was provided that attempted to provide the flight crew an independent check of the functioning of the underlying algorithm and supported the prediction of the new IM speeds. It showed a zone where getting a new IM speed was likely and a zone where getting a new IM speed was unlikely.

Pilots in this activity reported wanting to be able to monitor the progress of the spacing operation in relation to the ASG, including being able to predict when new IM speeds would be issued. Pilots reported wanting to know when to abandon IM due to spacing issues. Pilot feedback was mixed as to whether an aural alert was necessary for new IM speeds. However, pilots reported that flashing box for new IM speeds was insufficient.

The authors recommended improving the spacing prediction tool such that the flight crew is better able to judge the underlying functionality of the algorithm and to explore making it clear to the flight crew when the speeds available and the existing spacing do not allow for IM to be conducted successfully (i.e., when to report “unable”). They also recommended further exploration on the need for an aural advisory for new IM speeds.

In support of a retrofit field implementation of IM, MITRE conducted several activities to support the definition of the concept and display requirements. Key activities are reported next.

An initial activity conducted with FAA certification and test pilots was reported in Bone and Penhallegon (2006). An aft retrofit EFB was used to host the CDTI traffic display (Figure 2-33) and for setup. The display included the current IAS and the IM speed, a fast / slow graphical indicator (simply current IAS relative to IM speed), as well as the lead aircraft identification, weight category, ground speed, and distance from the trail aircraft. An AGD was attached to the MCP just below the airspeed window and was intended to provide the key pieces of information for IM conduct. It provided the IM speed, as well as closure rate and range to the lead aircraft (Figure 2-34). New IM speeds were presented in reverse video on the AGD until the pilot set the MCP speed to the IM speed.

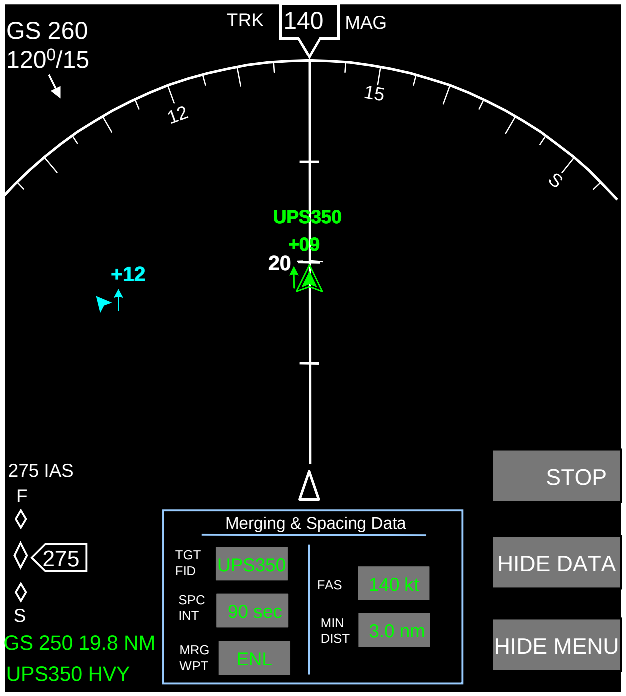

Figure 2-33. CDTI Traffic Display with IM Features from Bone and Penhallegon (2006)

Figure 2-34. AGD with IM Features from Bone and Penhallegon (2006)

The pilots questioned the use of closure rate and thought an aural may be necessary to annunciate a new IM speed. Further research was suggested. The pilots also believed an alert was necessary if the flight crew was significantly off from the IM speed. Pilot opinions were split on the usefulness of the fast / slow indicator.

This work continued with line pilots and the first activity is reported in Bone et al. (2008a). Nominal and off-nominal scenarios were evaluated. The traffic display implementation was the same as in Bone and Penhallegon (2006). One scenario removed the traffic display and the flight crew only had the AGD. The intent was to examine the ability of the flight crew to conduct IM with only the information available on the AGD. The AGD was also the same, except the closure rate field was changed to differential ground speed based on pilot feedback. One scenario included new fields on the AGD. The range to the lead aircraft was replaced by in-trail distance and a new field was added: in-trail time. New IM speeds were presented on the AGD with the same method as Bone and Penhallegon (2006).

All display features were found to be useful and little discrimination was found between the different elements. Pilots reported the in-trail time was useful, but the in-trail distance was less so. Pilots reported wanting additional information for the condition where the spacing was becoming an issue. Pilots had issues determining when to intervene when a spacing issue was noted. All pilots agreed that they had a clear understanding of the target spacing and how well it was being achieved. While the pilots followed a majority of the IM speeds and achieved the ASG within tolerances, the authors report some mistrust of the IM equipment and speed. This was believed to be due in part from the complexity of the algorithm, the algorithm acting on information unknown to the pilot (e.g., trajectory information), a potential for better display elements (e.g., in-trail time versus differential ground speed), and a potentially poor mental model. Finally, pilots were in disagreement on the need for and implementation of an aural alert to indicate a new CMD. Pilots reported an aural may only be necessary if the IM speed has been ignored for some period of time.

A follow-on study was conducted and reported in Bone et al. (2008b). Nominal and off-nominal scenarios were evaluated. The traffic display implementation was the same as in the previous two activities, except a graphical position indicator (aka “picnic table”) was displayed (providing the same information as that in previous NASA activities). The AGD displayed the IM speed and range to the lead aircraft. When new IM speeds were presented on the AGD, they flashed for a set amount of time, depending on the difference between the current IAS and the IM speed. The flashing was cleared when a speed was entered into the MCP (the speed did not need to match the IM speed) within 20 knots of the IM speed.

Pilots reported the displays had the necessary information and that they understood how IM was progressing. The authors speculated that there was less distrust of the algorithm and the associated IM speeds than seen in Bone et al. (2008a). That was stated to be due to increased training and the removal of the differential ground speed on the AGD.

Pilots spent more time viewing the CDTI traffic display when an overtake situation was developing. Most pilots did not report a need for an aural alert to annunciate new IM speeds and opinions were varied on whether an aural alert is necessary if the IM speed has been ignored for some period of time.

An Aviation Communication & Surveillance Systems (ACSS) avionics implementation similar to that studied in the MITRE simulations was certified, implemented on UPS aircraft, and used in limited revenue flight starting in 2008. A field test of that operation is reported in Penhallegon et al. (2016a). One noteworthy display outcome was that the visual-only alerting for new IM speeds was reported by the pilots to be acceptable.

After the ACSS and UPS implementation was fielded, IM research continued. Penhallegon et al. (2011) reported on a simulation investigating IM during the departure phase of flight. The CDTIs discussed in the 2006-2008 studies were largely based on the ACSS SafeRoute system that was hosted on a UPS flight deck implementation. The departure simulation, however, utilized a new CDTI that allowed for the integration, control, and operation of multiple ADS-B functions (Figure 2-35). The auxiliary / EFB displays for this activity were also in a different location and nearly perpendicular to the pilots’ forward position due to the desire to replicate certain actual aircraft space constraints. The new locations were also closer to the pilots’ forward field of view. The traffic displays included new elements such as the lead aircraft route and information shown in a data block next to the lead aircraft (i.e., identification, ground speed, differential ground speed [difference between lead aircraft and ownship groundspeed (sometimes referred to as closure rate in past activities)], range, aircraft category, and altitude). It also included an airspeed tape that showed three speeds: current IAS, MCP speed, and IM speed.

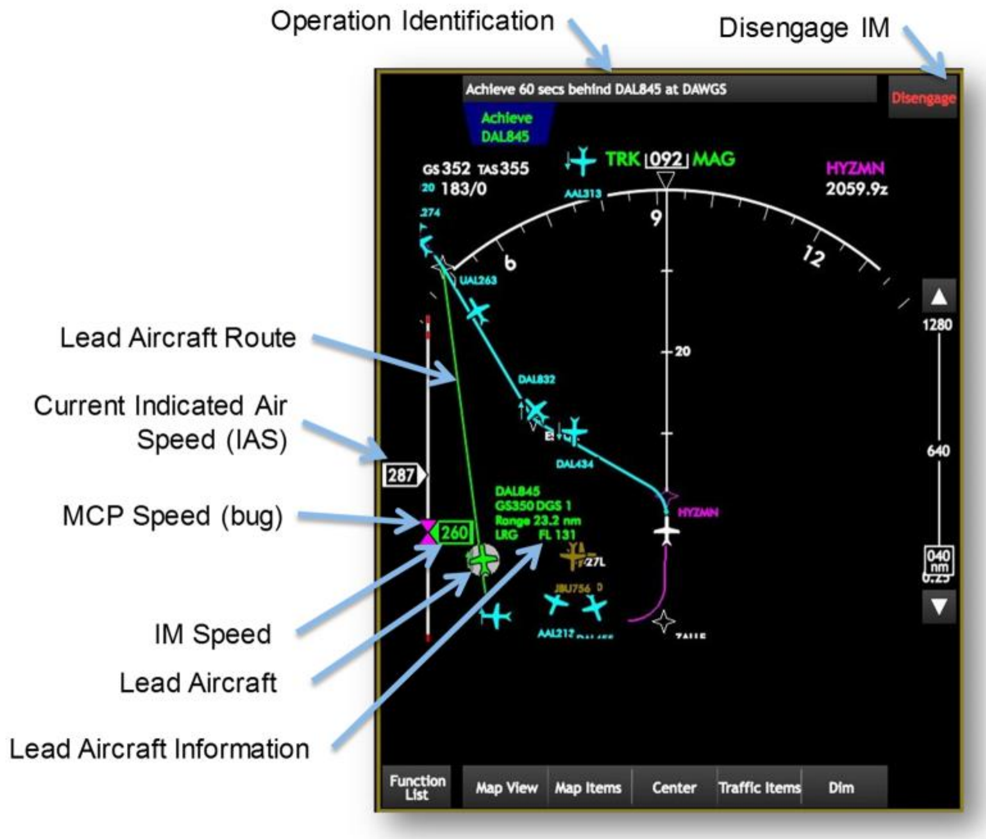

Figure 2-35. CDTI Traffic Display with IM Features from Penhallegon et al. (2011)

The AGD included the lead aircraft identification, in-trail time, and the IM speed (Figure 2-36). New IM speeds were indicated by depicting a box around the IM speed for 10 seconds (to be consistent with the typical time period for PFD autoflight mode annunciation changes).

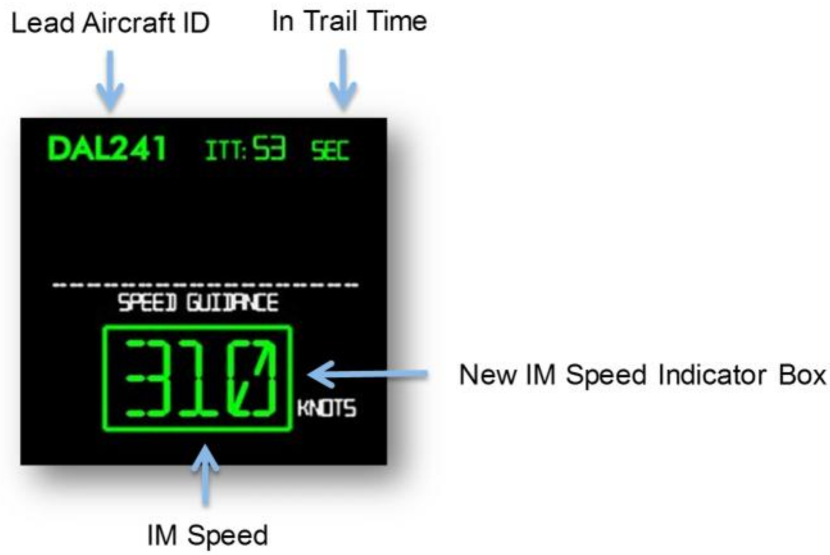

Figure 2-36. AGD with IM Features from Penhallegon et al. (2011)

Pilots showed high compliance with IM speeds and reported that the displays had the necessary information. All display features were found to be useful and little discrimination was found between the different elements. Target aircraft weight category had the most “not very useful” ratings. Differential ground speed was rated overall as more useful than in-trail time; however, they were both rated highly which suggests that pilots used them together to obtain spacing trend / performance information. The information that differential ground speed provides is whether the IM Aircraft is opening or closing on the target, and how quickly. The instantaneous differential ground speed provided differences in ground speeds based on current ground speeds, whereas the algorithm was basing the IM speeds on a past speed and position of the target aircraft. Therefore, pilots would see the differential ground speed increase 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 lead some pilots in other simulations into making a speed change and question why the system was not correcting (e.g., Bone et al., 2008a). However, this effect was not necessarily observed in the current study. The majority of pilots felt that they had a clear understanding of their spacing and how well it was being achieved. This, coupled with high IM speed conformance and minimal initiated speeds not issued by IM, indicated they appeared to trust the performance of the system and were not confused by the differential ground speed. As with other simulations, there were pilots that reported wanting more salient new IM speed annunciations, including mentions of an aural annunciation.

2.5.2.2 Flight Deck Display Spacing Information Research Needs

As can be seen from past work, much is understood about useful IM flight deck display features. However, some questions remain open. Key topics that still need to be resolved are related to the necessary and appropriate spacing and trend information as well as the appropriate alerting associated with IM speed changes and deviations.

Appropriate alerting to IM speed changes has been challenging to specify. Some pilots have expressed a desire for aural alerting, though overall pilot feedback has been varied on whether aural alerting is necessary at all, and, if so, for what issue (e.g., new IM speed, deviation from IM speed). There are also some concerns about the intrusiveness and the appropriateness of aural alerting. This is an area where further study is necessary.

For the spacing and trend information, past simulations have examined different display features to support the flight crews in their desire to monitor the progress of and trust in the IM operation. The spacing information has taken on numerous forms including: current interval relative to the ABP, projected interval at the ABP, differential ground speed, closure rate, straight-line range, etc.

Past work has shown that certain information can lead to confusion, additional workload and head-down time, or lack of use. Most past work has found some analog, graphical display of this information to be most useful. Some work has been successful in specifying and requiring a feature for conveying required spacing relative to current spacing and spacing trend information (i.e., Hoffman et al., 2006). However, other past work has continued to recommend (e.g., Bone et al., 2008a; Baxley et al., 2014) a similar feature, yet the exact implementation has been difficult to specify / develop. DO-361 (RTCA, 2015a) includes requirements and recommendations for a progress indicator that should now be considered in the design of such a feature. This is an area that would benefit from additional study.

The past work shows that an ideal, or even reasonable minimum, implementation has been challenging to finalize. Some tools may also only be necessary for certain IM algorithms (e.g., a fast / slow indicator in the NASA work).

This HITL simulation will continue to study these issues by examining the minimum implementation defined in DO-361 (RTCA, 2015a) and an implementation that adds additional elements to increase pilot confidence in the operation.

3 Method

A majority of the simulation methodology described in this section was reviewed with key FAA stakeholders during the concept evaluations (reviewed in Section 2.4.2.3). Reviews of the methodology allowed the stakeholders to provide feedback that could be incorporated in the final simulation design. After incorporating inputs, dry run testing was executed with internal and external participants. Suggestions for changes from the development activities were incorporated prior to data collection activities.

3.1 Simulation Environment

The simulation was conducted in the MITRE IDEA Laboratory. The simulation utilized controller, flight crew, and pseudo-pilot workstations from past ADS-B simulations that were modified as necessary for this effort. The following sections describe the utilized capabilities.

3.1.1 Flight Deck Workstation

The flight deck simulator consisted of a typical Boeing 777 flight deck layout as shown in Figure 3-1. The equipment included standard elements such as a MCP, two radio management panels, EICAS, a Flight Management System (FMS) with CDU interfaces, dual PFDs, and dual navigation displays. The simulator also included a 180-degree out-the-window visual capability. New traffic display components were added to accommodate IM (i.e., elements on the CDTI traffic display and AGD). Two CDTI traffic displays were hosted on auxiliary displays: one at the captain's eleven o'clock position and the other located at the First Officer's (FO's) one o'clock position. The AGD was located above the stand-by attitude indicator. The locations of the CDTI traffic display and AGD are shown in Figure 3-2. The utilized CDTI traffic display and AGD elements were based on requirements for ADS-B and IM (DO- 317B / RTCA, 2014, DO-361 / RTCA, 2015a). Most all the requirements were met, however, some were not implemented based on the expectation that they would not be utilized in the simulation (e.g., IM turn requirements). The IM algorithm utilized was specified in DO-361 (RTCA, 2015a) and is described further in Section 3.1.2.

The flight deck IM equipment did not have an interface to the FMS or autothrottle system based on the desire to examine a near-term, retrofit implementation. The following sections review the IM implementation in detail.

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Figure 3-1. Flight Deck Simulator

Figure 3-2. CDTI Traffic Display and AGD Locations

3.1.1.1 CDTI

Per DO-317B (RTCA, 2014, p. 96), “the CDTI is defined as the displays and controls necessary to support [ADS-B In applications]...the CDTI may be integrated into a number of display and control sub-elements.” Based on that definition, the CDTI implementation in this simulation consisted of two display elements: the CDTI traffic display and the AGD.

As noted previously, the IM features were based on requirements in DO-361 (RTCA, 2015a). DO-361 (RTCA, 2015a) specifies five CDTI states:

- **Awaiting entry:** IM operation is not yet active but system / input interface is ready for flight crew entry.
- **Evaluate:** IM information is being processed and is available for flight crew coordination / confirmation.
- **Execute:** IM operation is active.
- **Suspend:** IM operation is temporarily inactive.
- **Terminate:** IM operation is complete / inactive.

DO-361 (RTCA, 2015a) also defines over 20 information elements (e.g., IM speed, ASG, suspend indication, alerts) that have different display requirements per each of the five CDTI states. Information elements are either required to be displayed, available to be displayed with simple action, or required to not be displayed. Some of the information elements are required to be displayed in the primary field of view. Other information elements are also recommended to be displayed (e.g., the graphical route of the lead aircraft). The required features were implemented per the standard. Particular features of interest for this simulation and further description include the progress indictor, feasibility check status indication, and the IM speed conformance monitoring status visual advisory.

The behavior of the IM speed conformance is defined in DO-361 (RTCA, 2015a). After an IM speed is presented to the flight crew, an 11 second delay is activated that allows time for the flight crew and aircraft to react to the new speed. After the 11 seconds has transpired, the aircraft’s current speed is compared to an expected speed change profile (0.5 knots [kts] per second), built as a linear change of speed between the current aircraft speed and the IM speed. If the aircraft deviates from that speed change profile by more than 5 knots (faster for a deceleration or slower for an acceleration), the IM speed conformance visual and aural advisory is displayed to the flight crew. When the aircraft speed is brought within 5 knots of the IM speed, the speed conformance monitoring stops and no additional advisories are provided. Monitoring is stopped at this point because the flight crew is within acceptable tolerances of the IM speed. If any corrections are necessary after that point, a new IM speed will be presented and monitoring will be resumed.

The HITL simulation implementation of the conformance monitoring and alerting unintentionally deviated from that defined in DO-361 (RTCA, 2015a). The HITL implementation triggered the advisory at any speed off the expected speed change profile (i.e., the 5 kt tolerance was not implemented). It also advised after the aircraft’s speed got within 5 knots of the IM speed, but then again went greater than 5 knots of the profile speed (i.e., the monitoring and alerting was not inhibited after the aircraft was within 5 knots of the IM speed).

Per DO-361 (RTCA, 2015a), the feasibility check status indication was provided when the equipment determined the ASG could not be achieved even if the IM trail aircraft flew its fastest or slowest speeds relative to the speed profile. It was only provided during the achieve stage when greater than 30 NM from the ABP. A visual advisory was provided to the flight crew. If the aircraft was unable to slow enough to achieve the ASG [as determined by the equation (Predicted Spacing Interval [PSI] + 0.15 x time-to-go [TTG]) < ASG], the flight crew was provided with the message: "Not feasible, ASG too large." If the aircraft was unable to speed up enough to achieve the ASG [as determined by the equation (PSI – 0.11 x TTG) > ASG] the flight crew was provided with the message: "Not feasible, ASG too small." The multiplier for the TTG value is larger because the aircraft has a greater capability to slow down than it does to speed up.

For time-based ASGs, a progress indicator is required to be provided to the flight crew for situation awareness information during the maintain stage and when within 30 NM of the ABP for the achieve stage. At a minimum, the progress indication is defined as simply the display of the numerical values of the ASG and either the PSI (during the achieve stage) or the Measured Spacing Interval (MSI) (during the maintain stage)[3]. The progress indicator is one of the information elements that must be displayed in the primary field of view.

The minimum implementation of the feasibility check and progress indicator in the context of this simulation environment (described in 0) is shown in Figure 3-3. In that figure, the black text relates to information provided when the aircraft is greater than 30 NM from the ABP and the green text relates to information provided when 30 NM or less from the ABP.

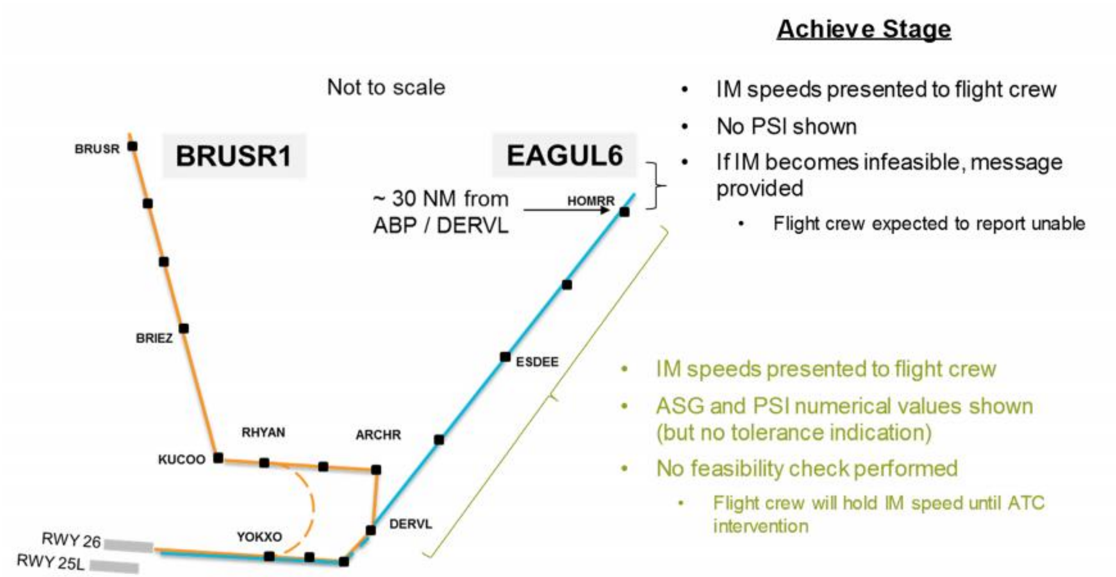

Figure 3-3. Minimum Requirements for Feasibility Check and Progress Indicator

[3] The MSI and PSI were, unintentionally, shown outside of 30 NM from the ABP in the simulation. However, the amount of time that the participant flight crew was actively conducting IM outside of 30NM from the ABP was limited, especially when the DERVL waypoint was the ABP.

A new feature that was examined in this simulation was called the graphical progress indicator. The graphical progress indicator was a feature that was beyond the minimum requirements specified in DO-361 (RTCA, 2015a) but thought by the authors to be a potentially useful feature and worthy of further examination based on the research reviewed and summarized in Section 2.5.2. It was also a topic expanded upon in an appendix titled CDTI Design Considerations in DO-361 (RTCA, 2015a). The implementation utilized in the simulation incorporated both the feasibility check and the progress indicator into a single display element. The feasibility check was continued inside of 30 NM from the ABP and from the achieve to the maintain stage. The progress indictor information was also provided in a graphical format. Figure 3-4 shows the graphical progress indicator.

Figure 3-4. Graphical Progress Indicator

The band on the graphical progress indicator showed acceptable spacing tolerance and anywhere within the boundary was acceptable IM spacing. The triangle the showed MSI or PSI value. During the achieve stage, the graphical progress indicator displayed the PSI with the bounds defined by the feasibility check (reviewed in this section) narrowing to a constant value of +/- 15 seconds of the ASG. In the maintain stage, it displayed the MSI with the bounds defined by +/- 15 seconds (3 SD / 99.7% tolerance) of the ASG. This is shown in Figure 3-5. The transition from the PSI to the MSI was not annunciated to the flight crew because it was not believed to be useful information and it was not a minimum requirement.

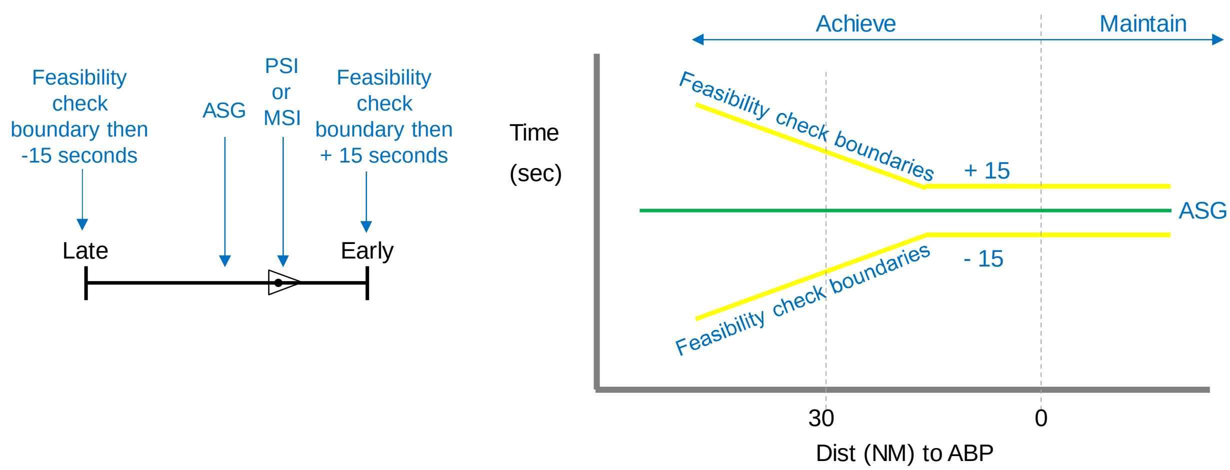

Figure 3-5. Graphical Progress Indicator Design / Behavior

The ASG was known but not displayed on the graphical progress indicator. It was still available numerically on the AGD. This was a specific design decision based on the desire to avoid the flight crew specifically targeting and chasing the ASG while within acceptable spacing as indicated by the band. The graphical progress indicator was intended to support flight crew trust and understanding of the progress of the IM operation. It was also designed to avoid leading the flight crew to outguess the IM algorithm and to implement speeds other than the IM speeds provided.

Another above-the-minimum feature implemented on the CDTI was the speed tape, which was also expected to be useful. The speed tape showed three speeds: the aircraft IAS, the speed set in the MCP, and IM speed. If all symbols aligned, the IM speed was set in MCP and aircraft was flying the IM speed. The speed tape was displayed on the CDTI traffic display and is shown in Figure 3-6.

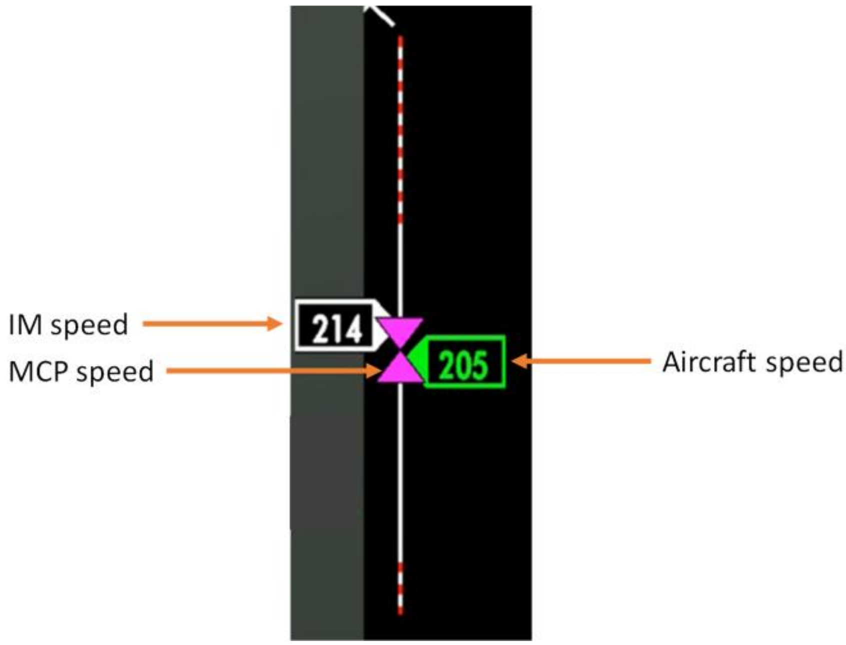

Figure 3-6. Speed Tape

The information provided on the CDTI traffic display and the AGD is shown in Figure 3-7 and Figure 3-8. The CDTI provided basic traffic information, and was used to set up and perform IM operations. The AGD served as the source of key IM information, including alert notification (i.e., advisory [ADV] flag), as specified in DO-361 (RTCA, 2015a). Two flight deck tool sets were examined in the simulation. The first was termed "min" and was built to the standards specified in DO-361 (RTCA, 2015a). The second was termed "min+" and included two features not required in DO-361 (RTCA, 2015a): the graphical progress indicator and speed tape.

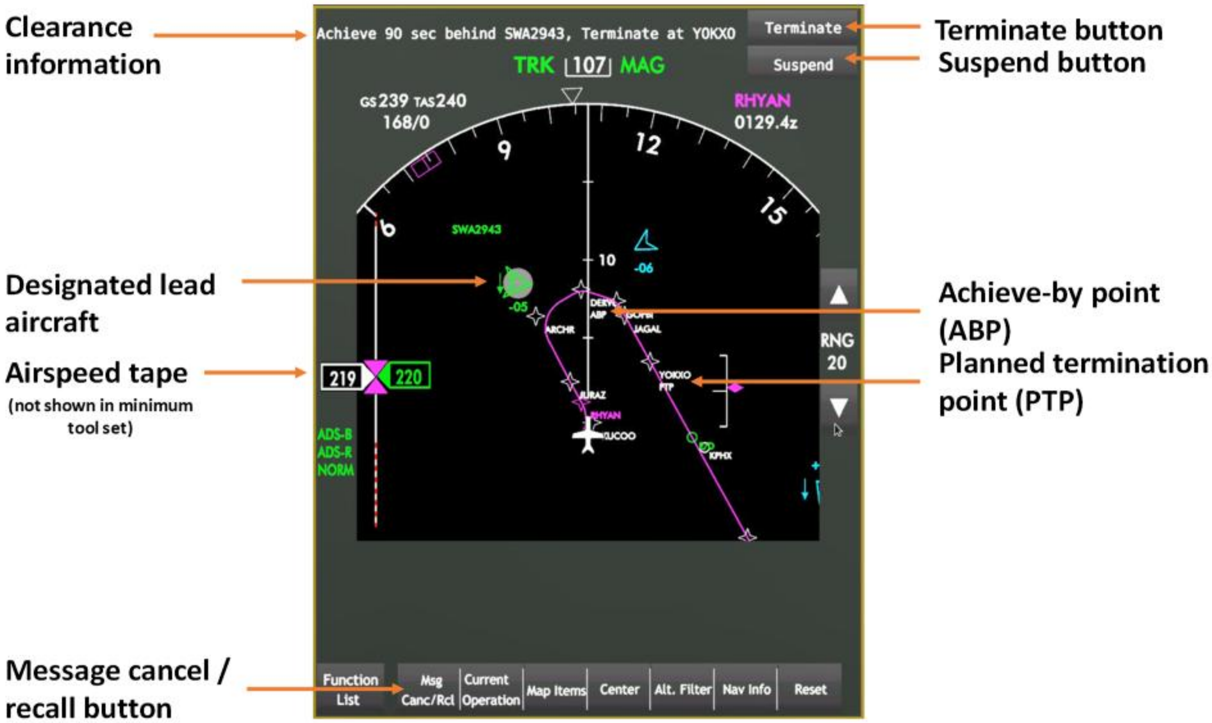

Figure 3-7. CDTI Traffic Display with IM Information Labeled

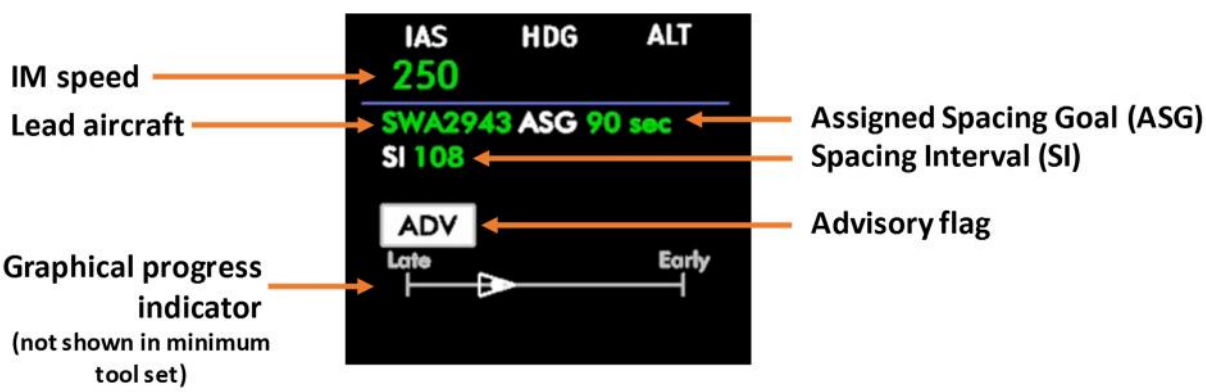

Figure 3-8. AGD with IM Information Labeled

3.1.1.2 CDTI Traffic Display and AGD During CDTI States / Alerts

The following figures show sample CDTI traffic display and AGD displays during IM operations. The implementations are shown with min+ implementation that was used in some scenarios.

Figure 3-9 shows the CDTI traffic display and the transitions when entering information in the interface. The screenshot on the left shows an aircraft selected and the Operation button at the top center of the display. After pressing the Operation button, the display provided options for choosing the ADS-B In application (as shown in the middle screenshot). Once IM was chosen, the IM clearance options were shown. For the participant pilots in this simulation, only the IM achieve options were utilized. After selecting "Achieve", the specific menu to IM achieve operations was displayed and the Pilot Monitoring (PM) then entered the necessary information by selecting a field and using soft keyboards to input the clearance. That menu is shown in the right screenshot and has the lead aircraft field (i.e., "Behind") auto-populated based on that aircraft being previously selected[4]. The lead aircraft field could be manually populated if the lead aircraft had not been selected or a different aircraft had been selected. After entering the necessary information into the menu, a "Confirm" button was provided that allowed for cross-cockpit coordination with the PF. Once the confirm button was pressed, the displays transitioned to the evaluate state.

Figure 3-9. CDTI Traffic Display and AGD During Awaiting Entry State

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4 This feature is not a minimum requirement for a CDTI traffic display.

In the evaluate state, the menu with all the information entered along with the first IM speed was shown to both the PM and the PF for review and coordination (Figure 3-10). The IM speed was also shown on the AGD in white, to differentiate it from the green IM speeds in the execute stage. Once an SI and IM speed had been calculated and provided, an execute (Exec) button was provided on the PM's CDTI traffic display (in the same location as the Confirm button). Once both flight crew members agreed that the information was correct and the operation was feasible, the PM pushed the execute (Exec) button.

Figure 3-10. CDTI Traffic Display and AGD During Evaluate State

The displays during the execute state are shown in Figure 3-11. When a new IM speed was presented on the AGD, a white box surrounded the speed and remained for 10 seconds. The SI field on the AGD presented the PSI if in the achieve stage and the MSI if in the maintain stage.

Figure 3-11. CDTI Traffic Display and AGD During Execute State

Figure 3-12 shows the displays if the IM speed conformance monitoring status visual and aural advisory was triggered. The AGD provided the flag for the advisory notification and the CDTI traffic display presented the content of the advisory. This advisory message and all others were only removed from the CDTI traffic display after the flight crew pressed the “Msg Canc/Rcl” button.

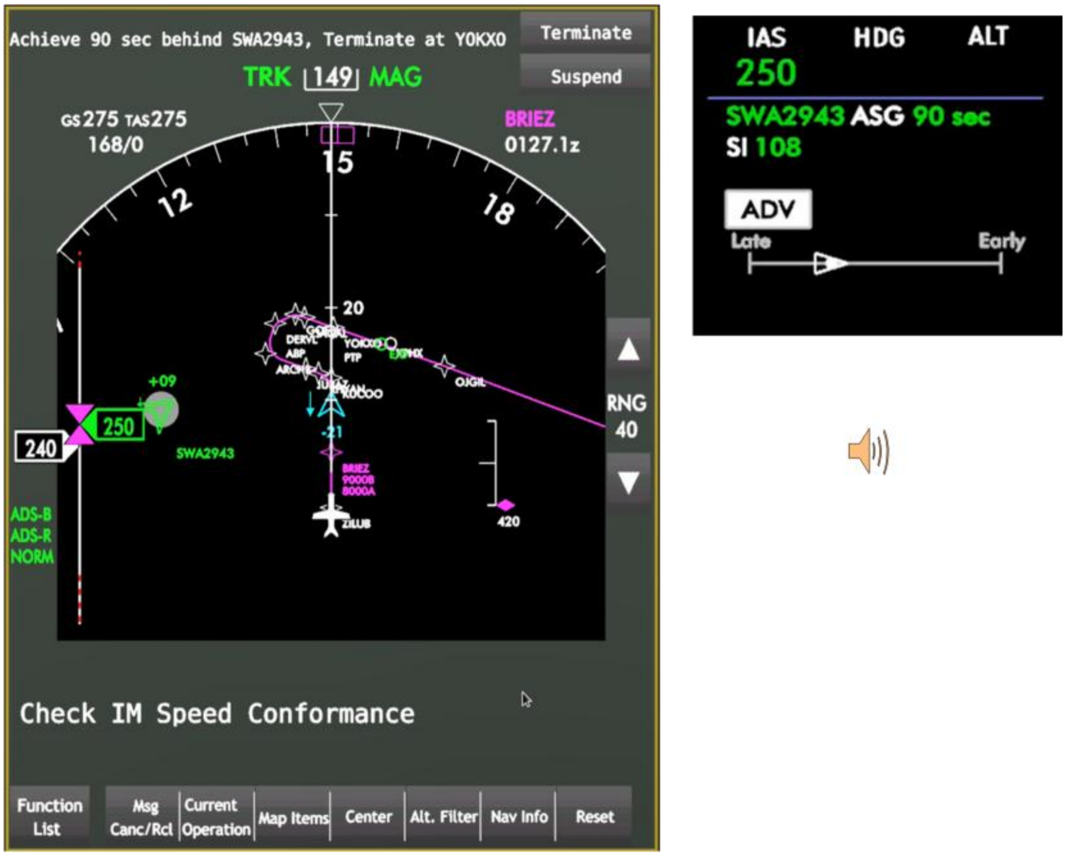

Figure 3-12. CDTI Traffic Display and AGD During Execute State—IM Speed Conformance Monitoring Status Visual Advisory

Figure 3-13 shows the displays if the feasibility check status indication was triggered. The AGD provided the flag for the advisory notification and the CDTI traffic display presented the content of the advisory.

Figure 3-13. CDTI Traffic Display and AGD During Execute State—Feasibility Check Status Indication

Figure 3-14 shows the displays if a suspension occurred by the flight crew pushing the Suspend button. As can be seen, the majority of the information is removed from the AGD. A Resume button was provided on the CDTI traffic display which would call up the clearance menu (as shown in Figure 3-9 in the right screenshot) so that clearance information could be edited if necessary. All fields could be edited except the lead aircraft identification.

Figure 3-14. CDTI Traffic Display and AGD During Suspend State

When reaching the PTP or when IM was terminated by the flight crew pushing the Terminate button, the displays looked like those in Figure 3-15. The AGD provided the flag for the advisory notification and the CDTI traffic display presented the content of the advisory. IM information was removed from the displays.

Figure 3-15. CDTI Traffic Display and AGD During Terminate State

3.1.2 IM Sample Algorithm

The IM algorithm used in the simulation was that defined in DO-361 (RTCA, 2015a). The participant aircraft only used the achieve-by then maintain IM clearance type while the pseudo-pilot aircraft used both the capture then maintain IM clearance type and achieve-by then maintain IM clearance type (with a maintain stage when there was no RNP RF turn, and without a maintain stage for RNP RF turn operations).

The achieve operation was used when aircraft were on different routes at the start of the operation, as depicted in Figure 3-16. In the Achieve stage, the time-to-go algorithm was used. Four-dimensional reference trajectories were used to predict the lead and trail aircrafts' times-to-go to the ABP, the PSI at the ABP (defined as the difference between the trail aircraft's time-to-go at the ABP and the lead aircraft's time-to-go at the ABP), and the IM speeds. IM speeds were calculated to drive the trail aircraft to an along-path position where its time-to-go to the ABP was equal to the lead's time-to-go plus the ASG (as shown by the light-blue dashed chevron in Figure 3-16). IM speeds were flown to make continual progress towards the ASG, with higher error tolerances allowed when further from the ABP where the time-to-go estimates were subject to larger errors. As the trail aircraft got closer to the ABP, errors in the predicted times-to-go were decreased, and the IM speeds aided the flight crew in precisely achieving the ASG.

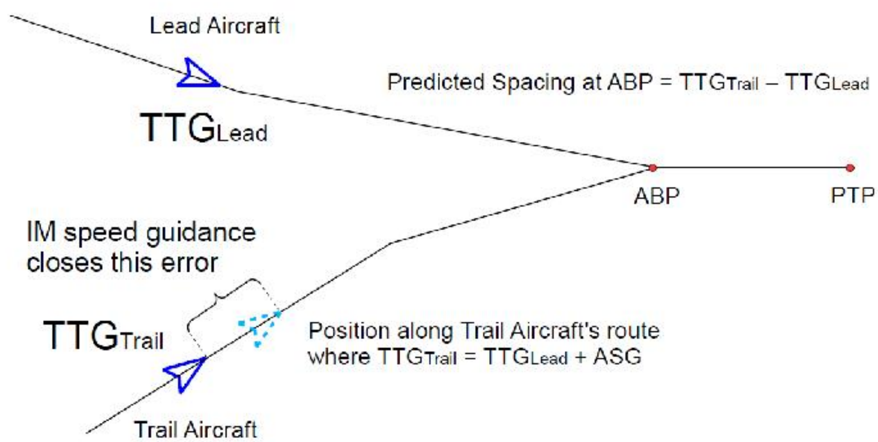

Figure 3-16. IM Operation in the Achieve-by Stage

TTG – Time-To-Go

Once the ABP was reached, the aircraft went into the maintain stage and the time-history control law was used. A MSI was calculated during the maintain stage. The MSI was the difference between the current time and the time when the lead aircraft crossed the trail aircraft's along-path position. If the MSI is equal to the ASG (i.e., no spacing error), IM speeds were calculated to drive the trail aircraft to match the ground speed of the lead aircraft at a time equal to the ASG in the past. If there was a spacing error, the IM speed calculation included the trail aircraft's past speed plus a term that is proportional to the spacing error. The maintain stage ended when reaching the PTP.

The capture operation[5] was used when aircraft were on, and would remain on, a common route. Operationally, the behavior can be related to the achieve stage. However, the trail

[5] DO-361 (RTCA, 2015a) requires extrapolation of aircraft positions at initiation if sufficient historical track data is not available. This allows for the presentation of IM speeds until sufficient data is available and the spacing interval and IM speed can be calculated without extrapolating. This requirement was not implemented for this simulation due to a misunderstanding of the requirement. However, the authors do not believe that this gap in the requirements affected the outcomes of the HITL.

aircraft captured the ASG (without a defined ABP) more quickly and then maintained the ASG until the PTP. The IM speeds were calculated as described for the maintain stage.

For both operations, time-based ASGs were used. The IM speeds were presented in 10 kt increments when greater than 10 NM from the ABP and in 5 kt increments when less than 10 NM from the ABP and when in the maintain stage. The IM algorithm limited the IM speeds to +/- 15% of the arrival procedure profile speed. The IM speeds were also limited by the maximum operating limit, the minimum final approach speed, and a regulatory restriction (250 kts below 10,000 feet).

3.1.3 ATC Workstation

The ATC interface was hosted on a STARS display with added TSAS and IM functionality. The following sections provide details on the implementations.

3.1.3.1 STARS

The terminal workstation had a representative 2K display that hosted a STARS interface that was very similar to the currently fielded STARS system. The workstation had a STARS keyboard and trackball (Figure 3-17). Some keyboard entries were programmed to serve as special IM functions (described in Section 3.1.3.3). The STARS workstation software consisted of a Terminal Controller Workstation display (Figure 3-18), and contained the majority of the basic STARS functionality. A key, relevant spacing feature presented was ATPA, which is a spacing tool used on the final approach course. It provided distance and alerting information relative to the lead aircraft and the associated separation standard (Figure 3-19). The overall functionality available for the simulation was found sufficient for the simulation by controller domain experts during development and concept evaluation activities.

Figure 3-17. STARS Keyboard

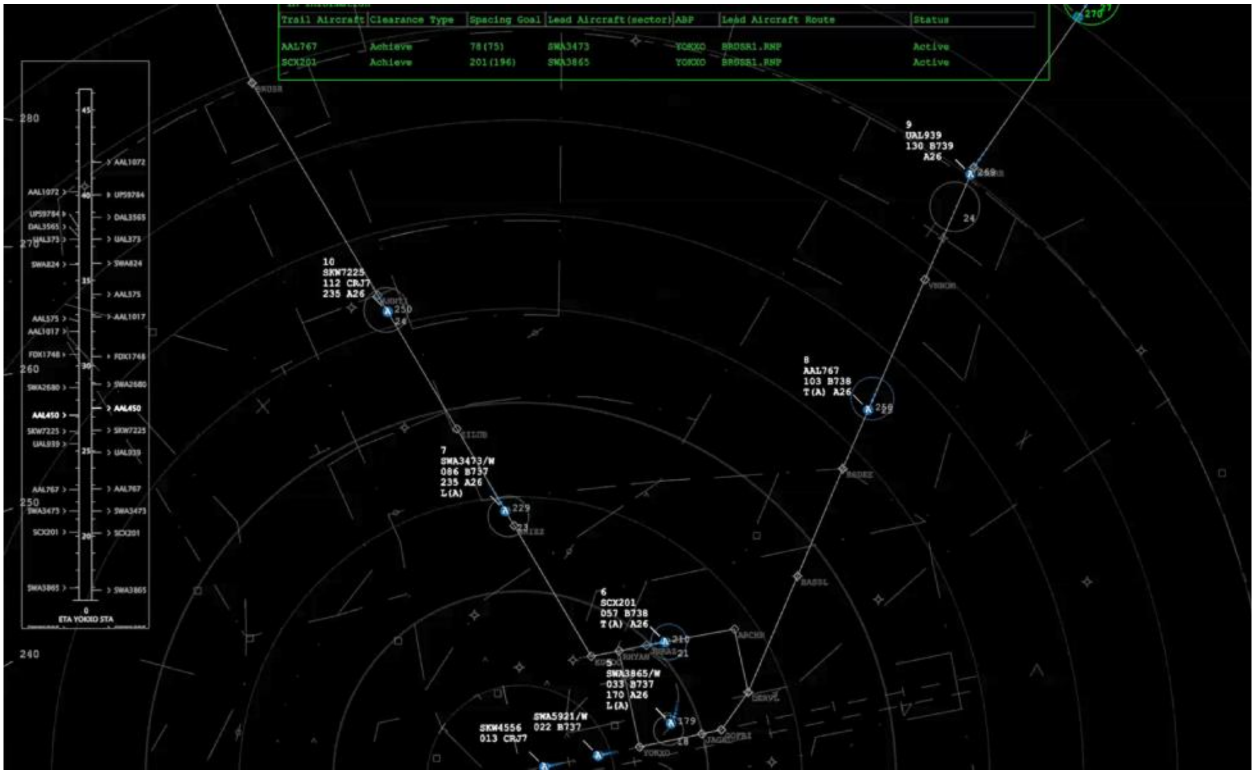

Figure 3-18. STARS-Like Display

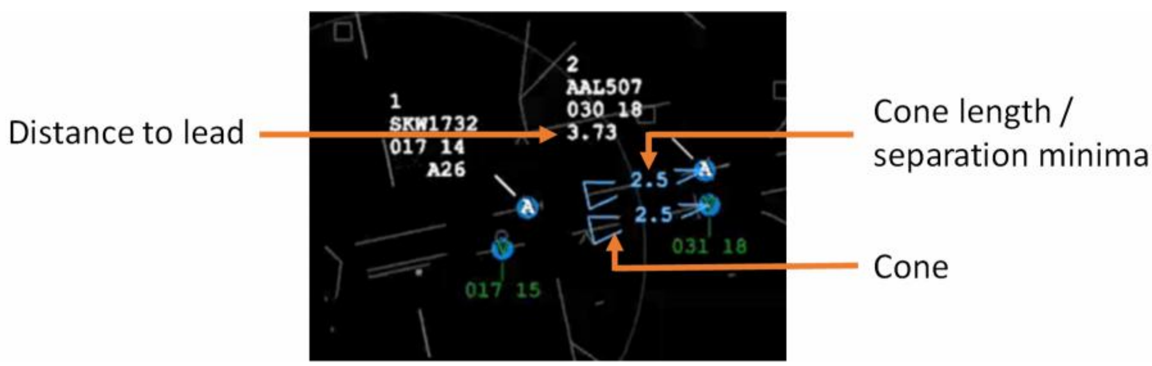

Figure 3-19. ATPA

3.1.3.2 TSAS Interface

For this simulation, TSAS and terminal metering were the foundation upon which IM was implemented. The TSAS software code that was integrated into MITRE's IDEA Lab was that used in the Operational Integration Assessment (OIA) event conducted in May of 2015 at the FAA William J. Hughes Technical Center (Witzberger, Martin, Sharma, and Robinson, 2015). The interface design was heavily based on those used in the OIA because a final design had not been specified and the OIA implementation was that used in the last major ATD-1 TSAS HITL simulation activity. Minor modifications (e.g., sequence number and runway assignment field locations) were made based on feedback from the concept evaluation activities leading up to the HITL simulation. The TSAS features implemented included the following (shown in Figure 3-20) as well as a timeline (shown in Figure 3-21). For more information on these TSAS features see Section 2.1.

- Runway assignment
- Sequence number (for the assigned runway)
- Slot marker
- Slot marker speed
- Speed advisories or early / late indicators
- Aircraft IAS
- Timeline

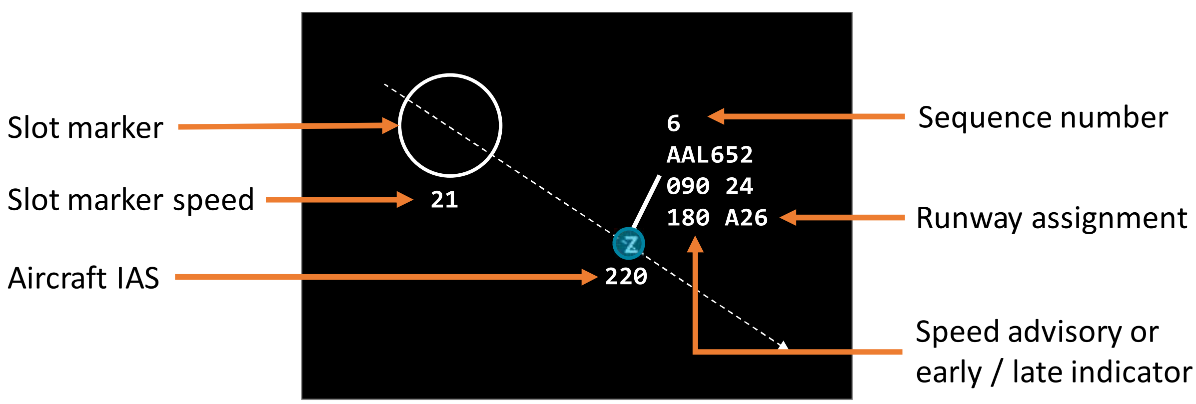

Figure 3-20. Prototype TSAS Features on STARS

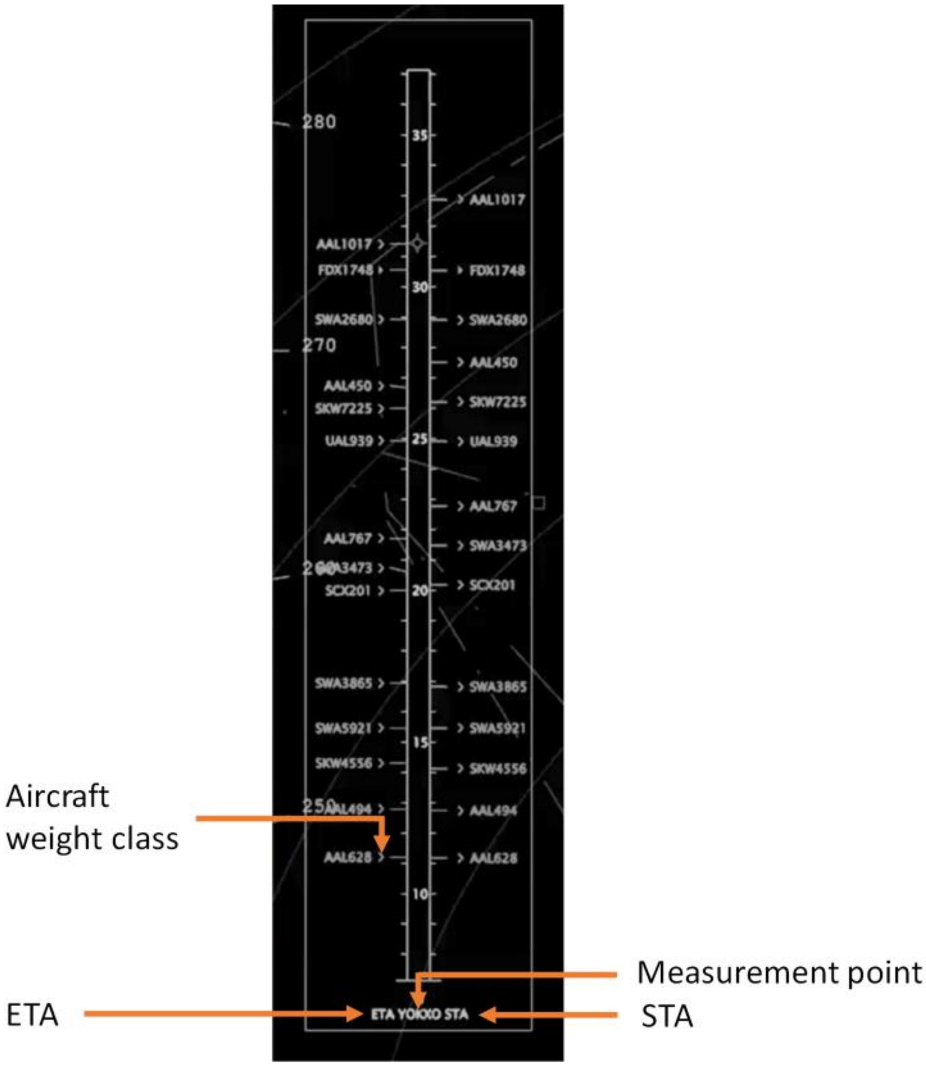

Figure 3-21. Prototype TSAS Timeline on STARS

The appropriate time to remove the TSAS slot markers was discussed during the development of the simulation environment in the concept evaluation activities. At the time, it was expected that the TSAS slot markers would not be shown for aircraft when ATPA is active unless there are aircraft that are part of a RNP RF turn operation (Figure 3-22). It was stated that slot markers would, at least, remain for the aircraft performing the RNP RF turn and the two aircraft that it would go between (because the merge could be challenging for controllers without the slot markers). However, feedback from controller and ground experts indicated keeping the slot markers for all aircraft would be acceptable since the final design had not been specified and previous work had slot markers present on final approach for all aircraft.

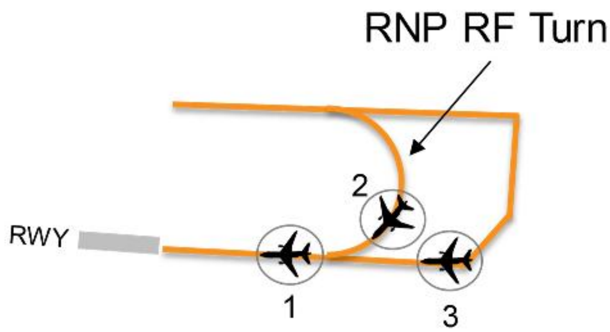

Figure 3-22. RNP RF Turn Traffic Geometry

During the development of the simulation environment, the impact of the TSAS features on IM was considered. When using the TSAS features during terminal metering, the controller actively issues speed instructions to aircraft to get them on schedule. During IM, flight crews fly speeds generated within the flight deck to achieve the ASG issued by the controller. While the IM aircraft is working toward the ASG, it may not be clear to the controller how well the operation is progressing or whether an aircraft will ultimately achieve the ASG or the underlying schedule. This could cause the controller to be concerned about or pay extra attention to the IM aircraft. The controller also needs to maintain awareness of which aircraft are conducting IM (and do not need speed instructions) and which aircraft are not conducting IM (that may need speed instructions).

The use of the TSAS slot marker is likely to be affected by IM. Since IM is a relative spacing operation, an IM trail aircraft is only adjusting its path to move into its slot marker if the lead aircraft is also doing so. While this relative spacing operation is also conducted by the controller at times (e.g., on final approach when not all aircraft are in their slot markers), it may be confusing to the controller to have some aircraft doing it on their own via the IM speeds.

IM may also lead to some confusion relative to the slot markers because it provides speeds to achieve the ASG at the ABP, while TSAS provides speeds to more constraint points and may get the aircraft into the slot markers more quickly. In other words, it is expected that certain geometries will lead to conditions where the IM trail aircraft are outside of their slot markers for longer periods than aircraft being managed by controllers with TSAS features.

IM working toward achieving the ASG at a single point, and TSAS managing to several constraint points, could also 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 current IAS of an aircraft conducting IM. If the controller compares the speeds, it could appear that IM will not meet the ASG. The early / late indication could be confusing for similar reasons. However, the equivalent of the TSAS early / late indication should probably still 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 indicated airspeed, aircraft indicated airspeed, and the timeline, are likely to be used by controllers in a similar way with or without IM. However, the aircraft indicated airspeed could be useful in helping the controller determine what speed the trail aircraft flight crew is flying for IM.

3.1.3.3 IM Interface

The ATC IM interface was added to the lab implementation of STARS. The display was developed in consideration of past work (e.g., Benson et al. 2011; Callantine et al., 2013) 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 (Thipphavong et al., 2013) and removed in other simulations (Callatine et al., 2012) as well as concept evaluations prior to this simulation.

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. This section will provide introductory / background information and then review the specific features.

IM states were shown in previous simulations, though not all the states were the same (e.g., Aligne et al., 2003; Benson et al., 2011; Baxley et al., 2016). For this simulation, the following states were defined from a ground system perspective and were relevant to the IM interface:

- **Pre-initiation:** Automation is evaluating pairs of aircraft for IM. Eligible pairs are presented to the controller as an IM operation proposal.
- **Initiation:** Automation has proposed the IM clearance to the controller but the IM operation has not been started.
- **Conduct:** IM proposal has been accepted by the controller and is active if the controller issued the clearance and the flight crew engaged IM.
- **Suspension:** IM operation is temporarily inactive.
- **Termination:** IM operation is inactive.

Each of the states can have sub-states related to the validity and feasibility of the operation (as shown in Figure 3-23). Transitions between states were either through controller or automation action. See Appendix A for further information on the validity and feasibility checks. Controller inputs to change states are shown in Table 3-1.

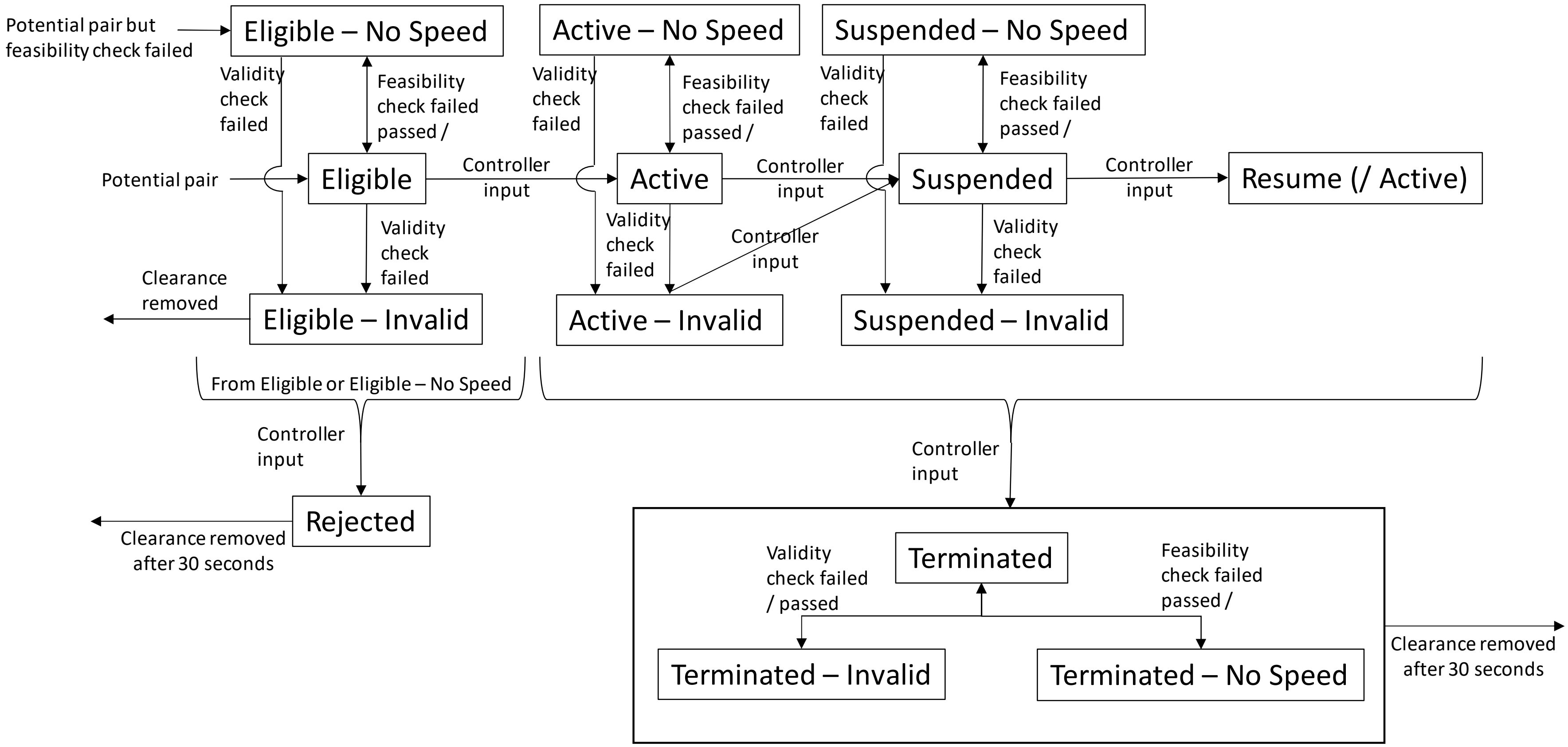

Figure 3-23. IM Clearance States and Transitions

Table 3-1. STARS IM Prototype Controller Input Commands

Desired outcome	Input commands
Activate / resume IM	[MULTI FUNC] TA [SLEW TO TRAIL AIRCRAFT] [LEFT CLICK]
Terminate / reject IM	[MULTI FUNC] TT [SLEW TO TRAIL AIRCRAFT] [LEFT CLICK]
Suspend IM	[MULTI FUNC] TS [SLEW TO TRAIL AIRCRAFT] [LEFT CLICK]
Re-propose rejected IM	[MULTI FUNC] TE [SLEW TO TRAIL AIRCRAFT] [LEFT CLICK]
Acknowledge alert	[SLEW TO TRAIL AIRCRAFT] [LEFT CLICK]

Prior to providing the clearance information to the controller, validity checks were conducted (see Appendix A). Validity checks were made to determine whether the criteria for initiating IM were met. If any of the validity check failed, the clearance was not proposed to the controller. Feasibility checks were also conducted prior to proposing and during any eligible IM clearance proposal. Feasibility checks determined whether the IM operation could achieve the ASG with speed alone (the equivalent of the TSAS early / late indicator). If any of the feasibility checks failed, that information was presented to the controller in the status field as “Eligible – No Speed.” In order to overcome the feasibility issue, the controller needed to provide a vector or speed greater or less than that IM would provide (i.e., greater or less than 15% of the profile speed). Feasibility checks were also conducted during the suspended and terminated states (see Appendix A).

3.1.3.3.1 IM Clearance Window

Based on past work, it was determined that an IM clearance window should be used to provide information that the controller would communicate as part of the IM clearance. The STARS display did not have a metering list to integrate the IM information into, so one had to be developed.

It was determined that the clearance window should also show the status of the clearance information (e.g., a proposed IM clearance versus an active IM operation). The information provided in the IM clearance window is expected to support that shown in the data block. Such information may be necessary if not all states are shown in the data block (e.g., suspension or invalid) or may be necessary to specify that status of each pair in the list so data blocks do not need to be cross referenced.

Four of the five defined states were shown to the controller. Pre-initiation and initiation were combined and labeled as “Eligible.” Conduct was labeled as “Active.” Suspension and termination were labeled as “Suspended” and “Terminated” respectively.

If the 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 information in the IM clearance window was only shown to the controller with the trail aircraft, whether or not that controller also had the lead 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 an operation had been rejected, it was not proposed again to the same controller / sector. However, it was proposed to the final controller. The same held true for terminated operations. If the clearance was accepted, instead of rejected, the status field changed to “Active.”

The order of the IM clearances in the IM clearance window were based on the runway sequence. This means a new proposal did not always appear at the top of the list but could appear somewhere further down the list based on the lead aircraft sequence number for the runway. This order was consistent with the order of the TSAS timeline.

The text in the window was color-coded to indicate different statuses (shown in Figure 3-24 and summarize with other information in Table 3-2 at the end of this section). White text indicated an action was possible (i.e., activation possible). The white text status states were one of the following: “Eligible,” “Eligible – No Speed,” or “Suspended.” Green text indicated an IM operation had been accepted by the controller. The status state was “Active.” Yellow text indicated an action was required (i.e., termination or a maneuver). The yellow text status states were one of the following: “Active – Invalid,” “Active – No Speed,” “Suspended – Invalid,” “Suspended – No Speed,” or “Terminated,” “Terminated – Invalid,” or “Terminated – No Speed.” Dark gray text indicated the information was going to be removed (based the proposal being inactive). The dark gray status state was “Rejected.” Note that the “Terminated” status was intended to be dark gray instead of yellow but the mismatch was not detected in time to correct the error before data collection.

IM information

Trail Aircraft	Clearance Type	Spacing Goal	Lead Aircraft (sector)	ABP	Lead Aircraft Route	Status
SWA1825	Achieve	85 (72)	AWE209	DERVL	EAGUL6	Eligible
SWA947	Capture	83 (99)	AAL431			Rejected
AAL529	Achieve	100 (115)	AAL227	DERVL	EAGUL6	Active – No speed
SWA1011	Capture	93 (99)	SWA2053 (F)			Active

Figure 3-24. IM Clearance Window

Each of the fields in the IM clearance window are labeled and were in the same order as was expected in the issuance of the IM clearance over the voice frequency. Fields of note will be reviewed next.

The clearance types used in the simulation were achieve-by then maintain and capture then maintain. They were abbreviated as “Achieve” and “Capture” for brevity in the display and when issuing the clearance over the voice frequency. The ASG in the spacing goal field, was calculated by TBFM and was the trail aircraft STA at the ABP minus the lead aircraft 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 was a spacing prediction value in parentheses (shown in some scenarios). Benson et al. (2011) and Aligne et al. (2003) reported that controllers found the predicted interval at the ABP to be useful. It may become more critical as the ABP is close to or within a controller’s airspace, as was the case for this simulation. Peterson et al. (2012) also reported controllers finding it useful to having delay information. However, only a slight majority of controllers reported that the MTE was useful for maintaining awareness of IM operations. Since this information is not available in the TRACON with TSAS, it was added with the granularity reduced to second (from a minute shown in en route). For achieve operations, the difference between the TSAS-calculated trail aircraft ETA at the ABP and the lead aircraft ETA at the ABP value was shown. For capture operations, the difference between the TSAS-calculated trail aircraft ETA at the FAF and the lead aircraft ETA at the FAF value was shown. These values were provided to allow the controllers to compare the spacing estimated by TBFM / TSAS (ETA differential / prediction) to the ASG and to determine how the operation was progressing.

After the lead aircraft identification in the lead aircraft field, the sector of the lead aircraft was included if both aircraft were not in the same sector (in case coordination between the controllers was necessary). The ABP was either DERVL (the merge point) or YOKXO (the FAF and RNP RF turn final approach intercept) (later shown in Figure 3-32). The lead aircraft route was the IFPI of the lead aircraft. If it was a capture operation, the lead aircraft route was not shown since it is a requirement that both aircraft be on the same route to conduct the capture operation (which was checked by TBFM in this simulation as noted in Appendix A). It was also not shown so the controller knew that it was not necessary to convey in the IM clearance. If the routes were different because the achieve operation was being conducted, the three options for the lead aircraft route were: EAGUL6, BRUSR1, and BRUSR1.RNP (i.e., the BRUSR1 arrival with the RNP RF turn).

The clearance information was removed for the feeder controller during a handoff of active IM operations two minutes after the handoff of the trail aircraft. This delay was utilized to avoid IM information being cleared from the IM clearance window when a handoff of the trail aircraft was accepted prior that aircraft crossing the sector boundary. It was desirable to have the IM information cleared from the IM clearance window when the trail aircraft crossed the sector boundary, but it was reported that this information was not readily available within the STARS system. Two minutes was chosen as a reasonable number to test. Further testing would be needed to determine whether two minutes is reasonable. The clearance information was removed for the final controller when the trail aircraft landed.

3.1.3.3.2 Other IM Information on the STARS Display

IM information was also provided in other locations on the STARS display. The aircraft role in and status of IM indications are shown in Figure 3-25. The information for the trail aircraft was shown in the third line of the data block. The field was not time-shared with other information.

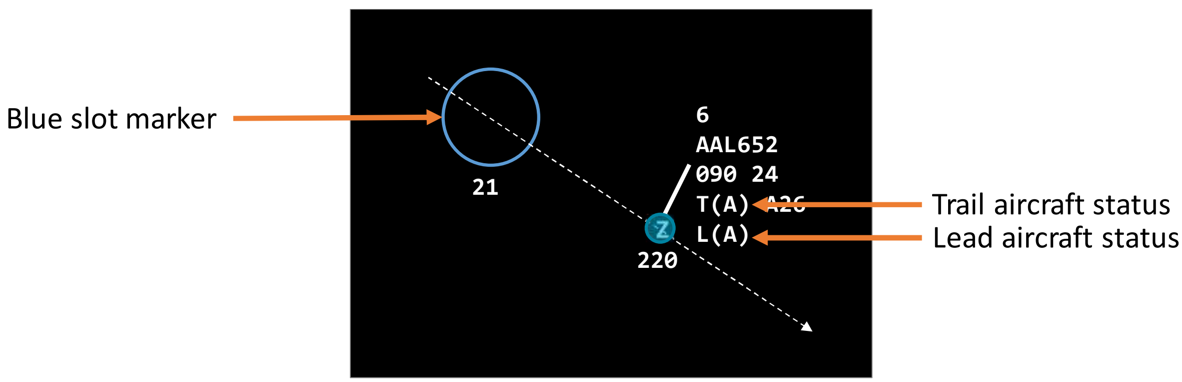

Figure 3-25. Prototype IM Features on STARS

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. However, an early / late indication relative to IM operations could still be a key piece of information. As mentioned previously, such information was shown in the IM clearance window.

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. Termination was not shown. The transitions between the major states are shown in Figure 3-26. The transitions to infeasible / no speed states is shown in Figure 3-27. The infeasible state was only shown in yellow / as alerted for active of suspended operations because controller action was required prior to the operation returning to an active state.

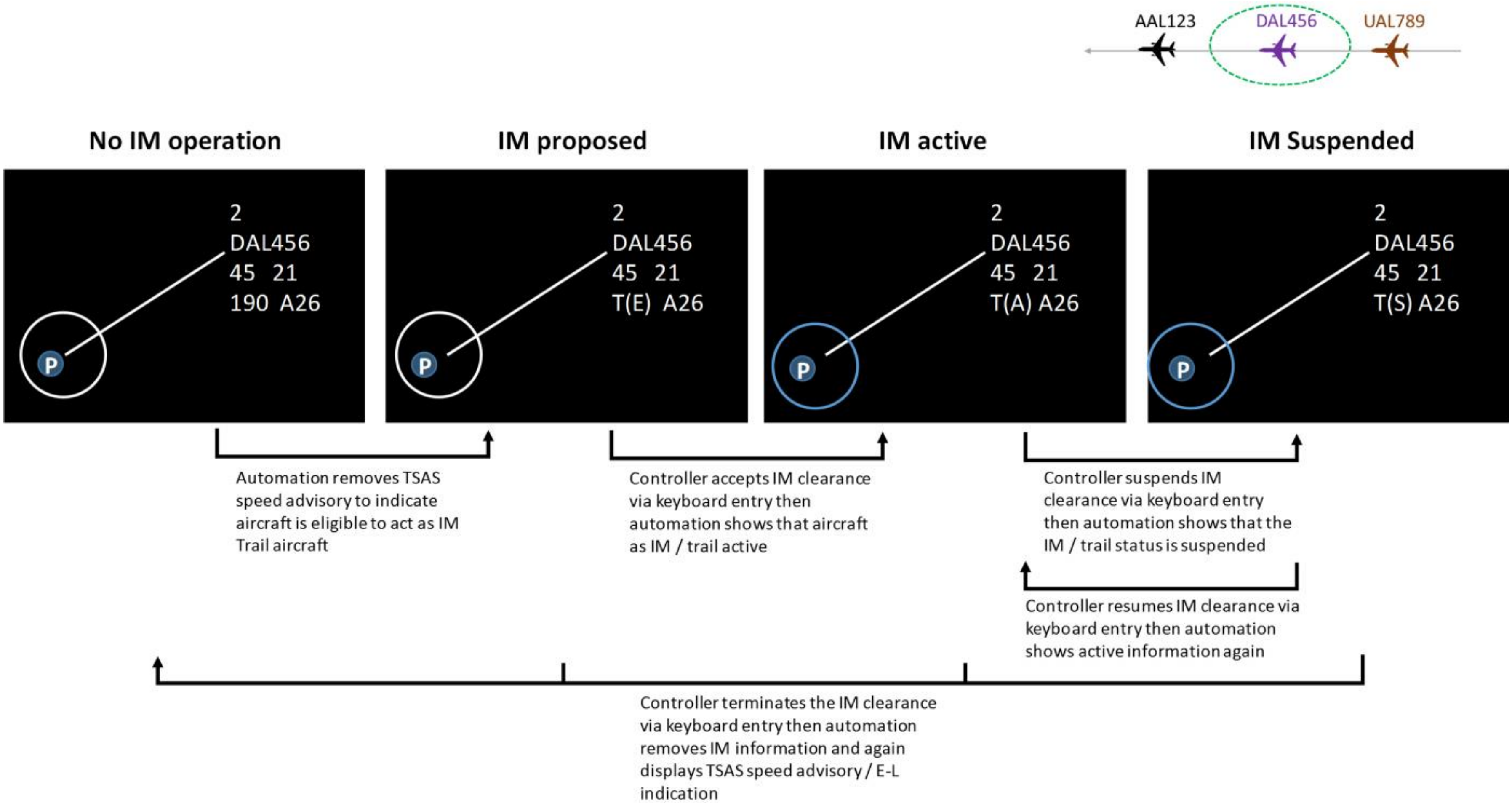

Figure 3-26. IM Information in Trail Aircraft Data Block

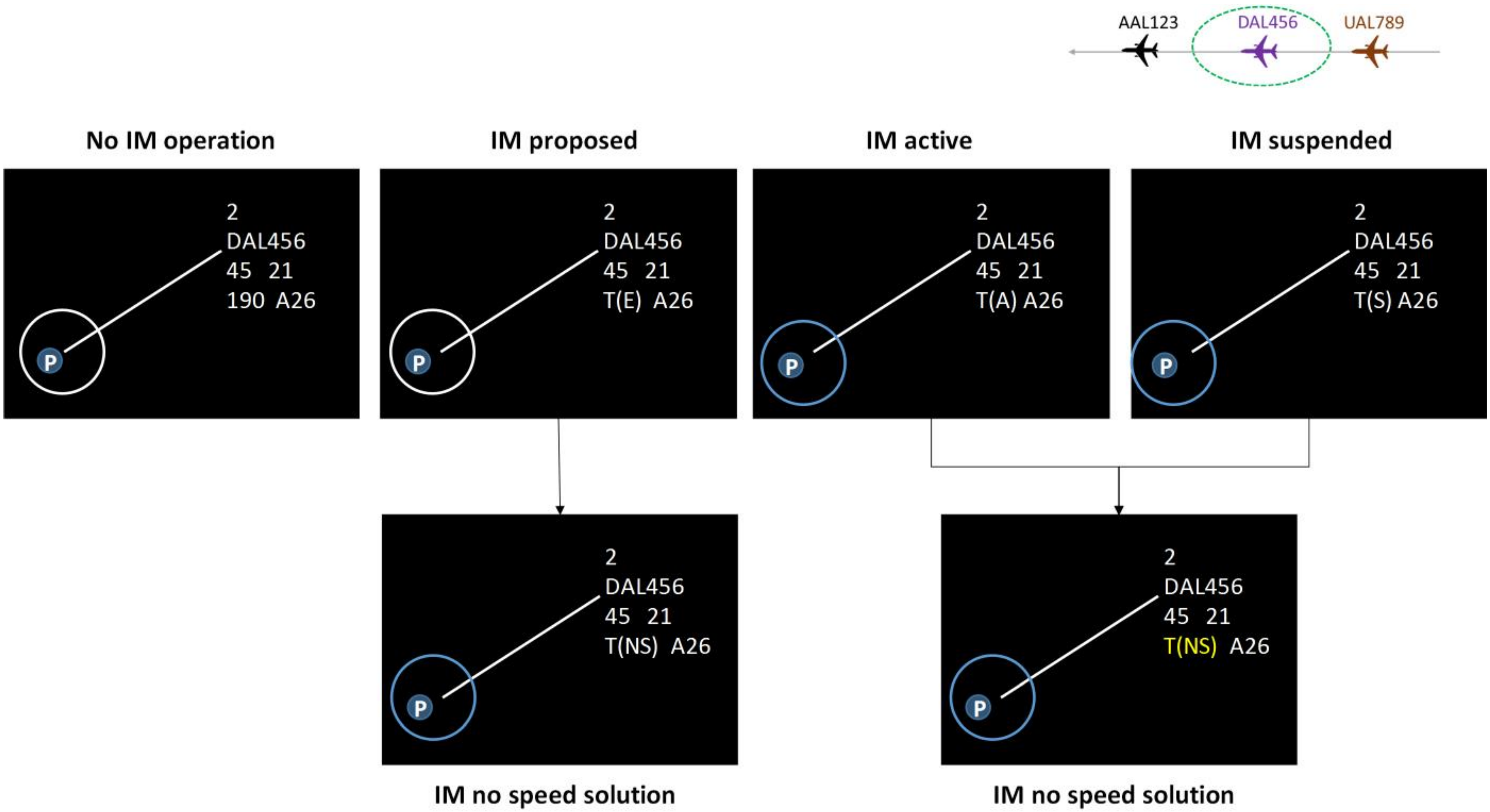

Figure 3-27. IM Information in Trail Aircraft Data Block When Transitioning to a No Speed (NS) Solution

Based on positive feedback in previous simulations (e.g., Thipphavong et al., 2013), lead aircraft information was also shown in the aircraft data block. The information for the lead aircraft was shown in the fourth line of the 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 infeasible 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. During the invalid and infeasible state, the controller with the trail aircraft was either working to correct the issue or would soon terminate IM. It was not expected that the lead aircraft controller needed to be notified of invalid and infeasible states when the trail aircraft controller was working on the issue. It was expected to be sufficient for the lead aircraft controller to simply know the lead aircraft was part of an active operation. Therefore, the lead aircraft controller was only notified when the lead aircraft was part of an IM operation. The lead controller was not notified of a proposed, infeasible, or invalid operation. The lead aircraft controller was notified of a terminated operation by the removal of IM information. The transitions between the major states are shown in Figure 3-28. If an aircraft acted as both a lead and trail aircraft, the information was the same as shown in the figures but the trail and lead information would be present in one aircraft's data block.

The capability of an aircraft to conduct RNP RF turns was also shown in the aircraft data block and was shown as "/W" after the aircraft flight identification. Although it would have been preferable to show the "/W" after the aircraft type, it was not possible due to the available development time.

Table 3-2 summarizes the information shown in the IM Clearance Window and the data blocks.

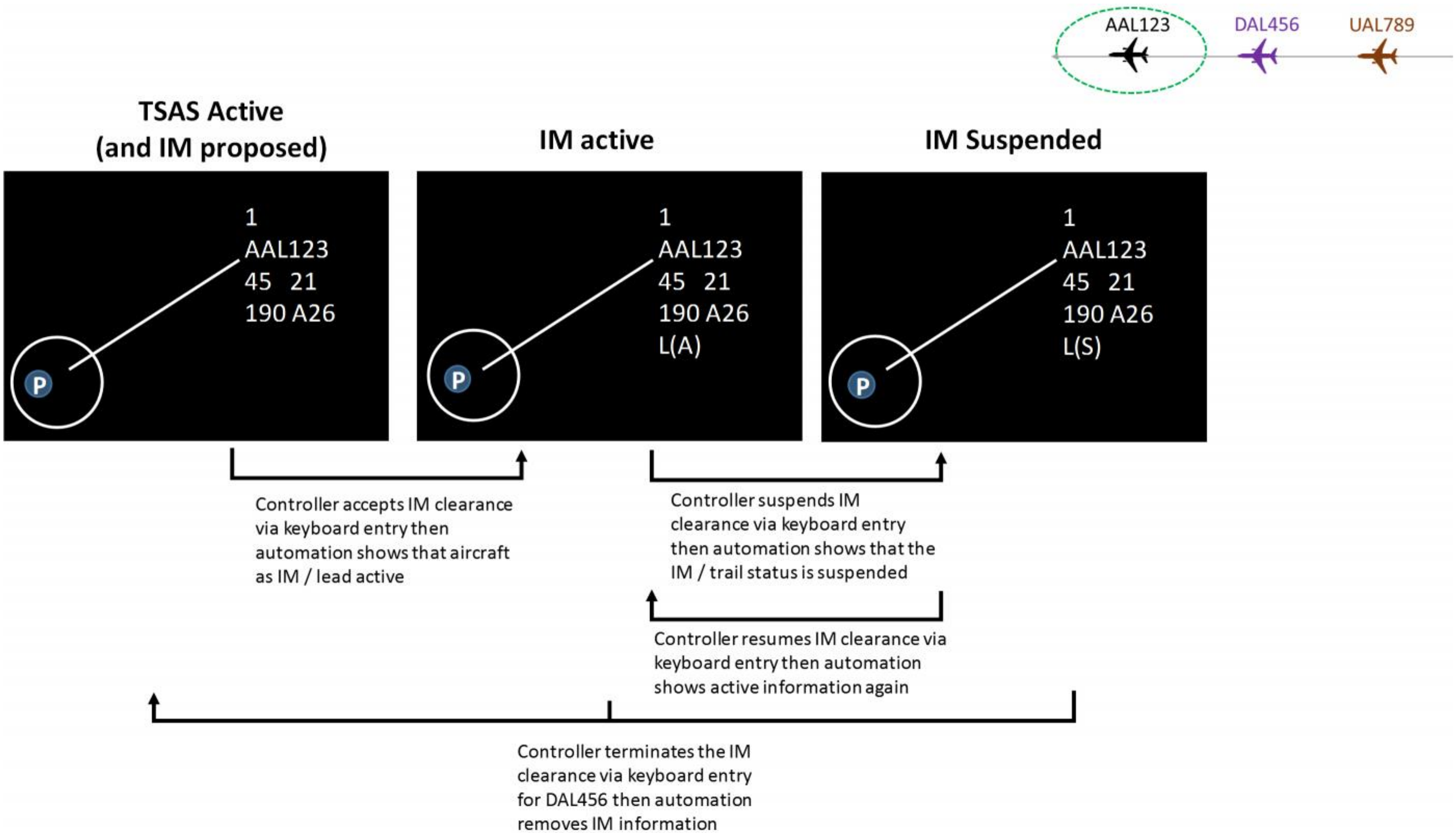

Figure 3-28. IM Information in Lead Aircraft Data Block

Table 3-2. Summary of Displayed IM Information in the IM Clearance Window and Aircraft Data Blocks

Stage	State	IM clearance window presentation text and (color)	Trail aircraft data block presentation	Lead aircraft data block presentation
Pre-Initiation	Valid and feasible	Eligible (white)	T(E)	None
	Infeasible	Eligible – No Speed (white)	T(NS)	None
Initiation	Valid and feasible	Eligible (white)	T(E)	None
	Invalid	None[1]	None[1]	None[1]
	Infeasible	Eligible – No Speed (white)	T(NS)	None
Conduct	Valid and feasible	Active (green)	T(A)	L(A)
	Invalid	Active – Invalid[2] (yellow)	T(I)[2]	L(A)
	Infeasible	Active – No Speed[2] (yellow)	T(NS)[2]	L(A)
Suspension	Valid and feasible	Suspended (white)	T(S)	L(S)
	Invalid	Suspended – Invalid[2] (yellow)	T(I)[2]	L(S)
	Infeasible	Suspended – No Speed[2] (yellow)	T(NS)[2]	L(S)
Termination	Valid and feasible	Terminated (yellow)	None	None
	Invalid	Terminated – Invalid (yellow)	None	None
	Infeasible	Terminated – No Speed (yellow)	None	None

Notes

1. The clearance proposal is removed so no information is shown.

2. An alert is associated with this information. The alerts are triggered during Active and Suspended stages. Alerts are not triggered if the IM operation is at the Pre-Initiation, Initiation, or the Termination stages since the controller has not started or has ended the IM operation.

3.1.3.3.3 Slot Marker Color Change

At the concept evaluation activities, it was determined that continued examination of the IM lead aircraft behavior relative to the slot markers was important for acceptable integration of IM and TSAS operations. At least two resolutions were discussed: the first was to make TSAS spacing and IM spacing operations more similar. A second option was to make modifications to the TSAS slot markers for IM trail aircraft.

Making IM behave similar to TSAS was considered less feasible than making modifications to the slot marker. Three possibilities for slot marker modifications were considered. One option was to remove the slot marker for the IM trail aircraft. This would completely remove key schedule information and relative spacing information. Controllers use the TSAS slot markers to determine how to manage relative aircraft positions. If controllers are dealing with a set of aircraft where: (1) the lead is behind its slot marker, (2) it will be difficult to get that aircraft back into it slot marker, and (3) there is sufficient space between subsequent aircraft, the controller will make sure the trail aircraft is also behind its slot marker to ensure spacing / separation. Slot markers are a key visual cue to determining that relationship. Therefore, complete removal of the slot markers was determined to be undesirable.

A second possibility was to modify the slot marker for IM trail aircraft to make it a relative spacing slot marker. For reasons similar to those mentioned above, this may be undesirable as it removes information that conveys the underlying absolute spacing schedule. A third possibility was to keep but modify the existing slot marker by adding IM spacing information to it. This option continues to convey the information related to the underlying schedule, and adds information about how well the IM trail aircraft is achieving its ASG in relation to the lead aircraft. The exact method for implementing this was not determined.

Options for modifying the slot markers to make them convey relative spacing were tested but not presented to participants in the first two concept evaluations. Additionally, initial fast-time studies were conducted to determine how often the IM trail aircraft would be expected to deviate from the slot markers. The fast-time simulations were expected to be used to understand the expected behavior and to determine whether slot marker manipulation was desirable. Only preliminary data was available at the time of the third concept evaluation so that data was presented to the controllers so they could be informed of the expected behavior they would see in the laboratory. Therefore, none of the slot marker modifications mentioned above were implemented. However, the third evaluation did include simply changing the color of the slot marker to blue (instead of white) for the IM trail aircraft. The goal was to see whether simply differentiating IM trail aircraft from non-IM aircraft allowed the controller to accept the different behavior of the IM trail aircraft based on knowing who was conducting IM at a glance. In other words, the controllers could note that any aircraft with a blue slot marker may be off its slot marker, but would be working toward that slot marker while conducting IM (and therefore, did not need to be issued a speed).

Controllers in the third evaluation found it was helpful to differentiate the IM trail aircraft, though this did not overcome all concerns about IM aircraft not being in the slot markers. Controllers did appear to have a better understanding of IM spacing behavior and reported seeing aircraft closing to their ASG. However, they still expressed concern about on-going deviations from the slot markers in the feeder's airspace. They reported that their goal was to get all aircraft into their slot markers so that the handoff to the final controller would be acceptable and that they felt uncomfortable when aircraft were not in the slot markers.

Based on this feedback, it was decided that the slot marker color modification (shown in Figure 3-25) was a good initial change to test. Therefore, the chosen modification to test was the trail aircraft slot marker color change from white to blue during some scenarios when controller made the keyboard entry to indicate IM was active. The slot markers for trail aircraft remained blue when an IM trail aircraft was in the suspended state but returned to white when controller made the keyboard entry to indicate IM was terminated. The slot markers for trail aircraft and all other aircraft remained white.

3.1.3.3.4 Controller Tool Sets for Evaluation

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

- **Basic:** TSAS features, the IM clearance window, as well as the IM trail and lead aircraft status fields in the data blocks
- **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 (shown in parentheses after the lead aircraft identification in the IM clearance window)

3.1.4 Pseudo-Pilot Workstation

Pseudo-pilots acted as "pilots" for all (some IM capable and some not IM capable) aircraft other than the participant flight crew's aircraft. This allowed the controller to interact normally with the traffic. It also allowed aircraft to maneuver based on controller instructions, which is reflected on both the controller and flight crew displays. The pseudo-pilots used an interface termed Simpilot which allowed users to simultaneously control multiple simulated aircraft (Figure 3-29). It provided basic information about the aircraft (e.g., aircraft call sign, type) and allowed the pseudo-pilot to control various aspects of the aircraft (e.g., heading, airspeed, altitude, route, communications frequency) and respond to controller instructions by entering commands.

The pseudo-pilots also initiated, suspended, resumed, and terminated IM per instructions from the controller. When the controller entered the command to accept the IM clearance, a pop-up window with the clearance information was displayed to the pseudo-pilot. Once the controller issued the IM clearance via a voice communication, the pseudo-pilot acknowledged the clearance and then pressed "ok" in the window to engage the IM sample algorithm. This implementation was to assist the pseudo-pilot (who was managing several aircraft) in entering all the information associated with the IM clearance. However, it made the acceptance and entry of the clearance easier than it was for the participant aircraft flight crews and is more like a CPDLC implementation that allowed for loading of the IM clearance into the fight deck IM equipment without the need to memorize or write down the information and then type it in.

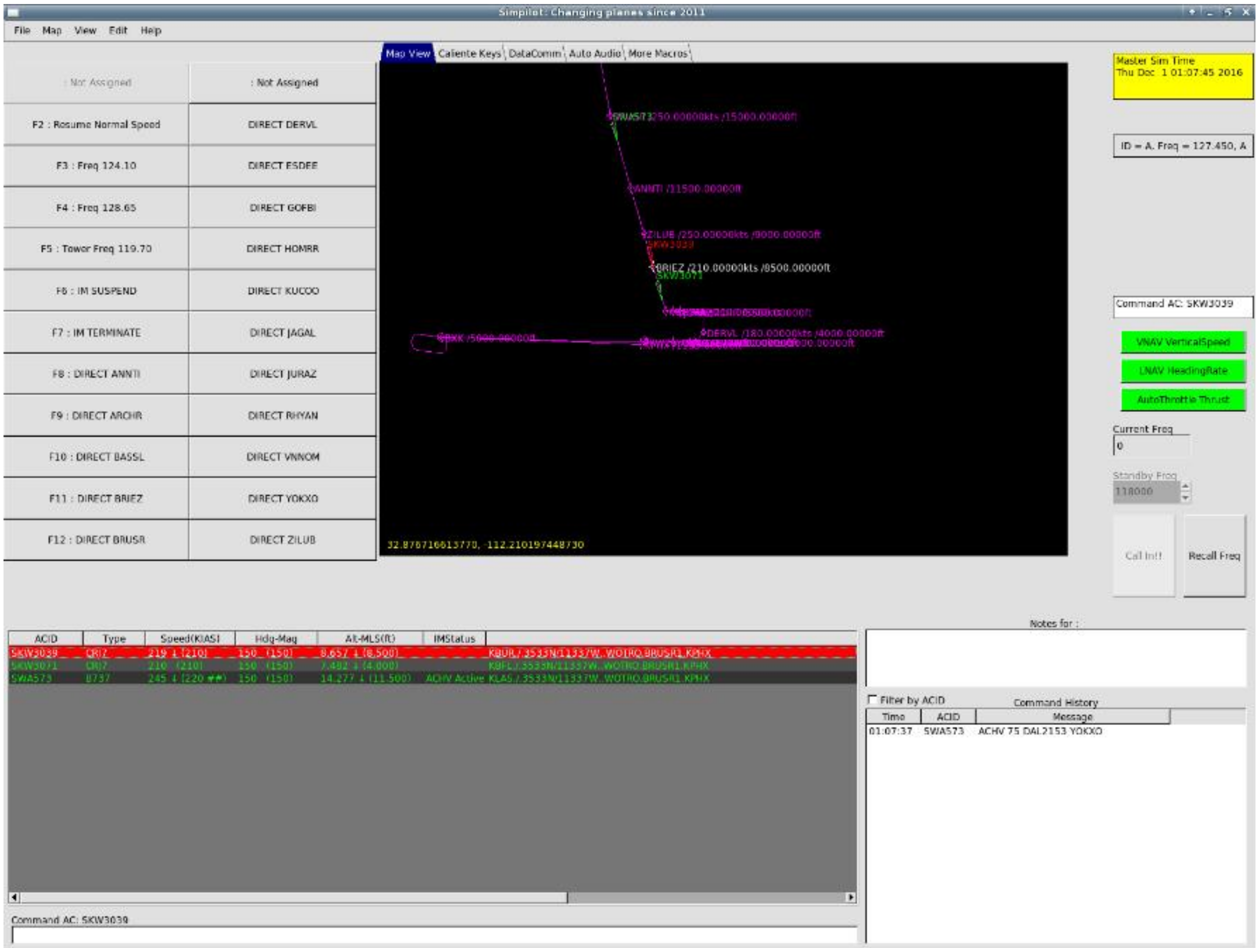

Figure 3-29. Pseudo-Pilot Interface (Simpilot)

3.1.5 Airspace

The airspace modeled for this simulation was based on Phoenix International Airport (KPHX). North RNAV operations were run and aircraft landed to the west on runway 26, which was operated as a landing only runway. Aircraft also landed on runway 25L but as independent operations (even though real-world operations at KPHX are not run independently). The airport environment is shown in Figure 3-30. The weather was visual meteorological conditions.

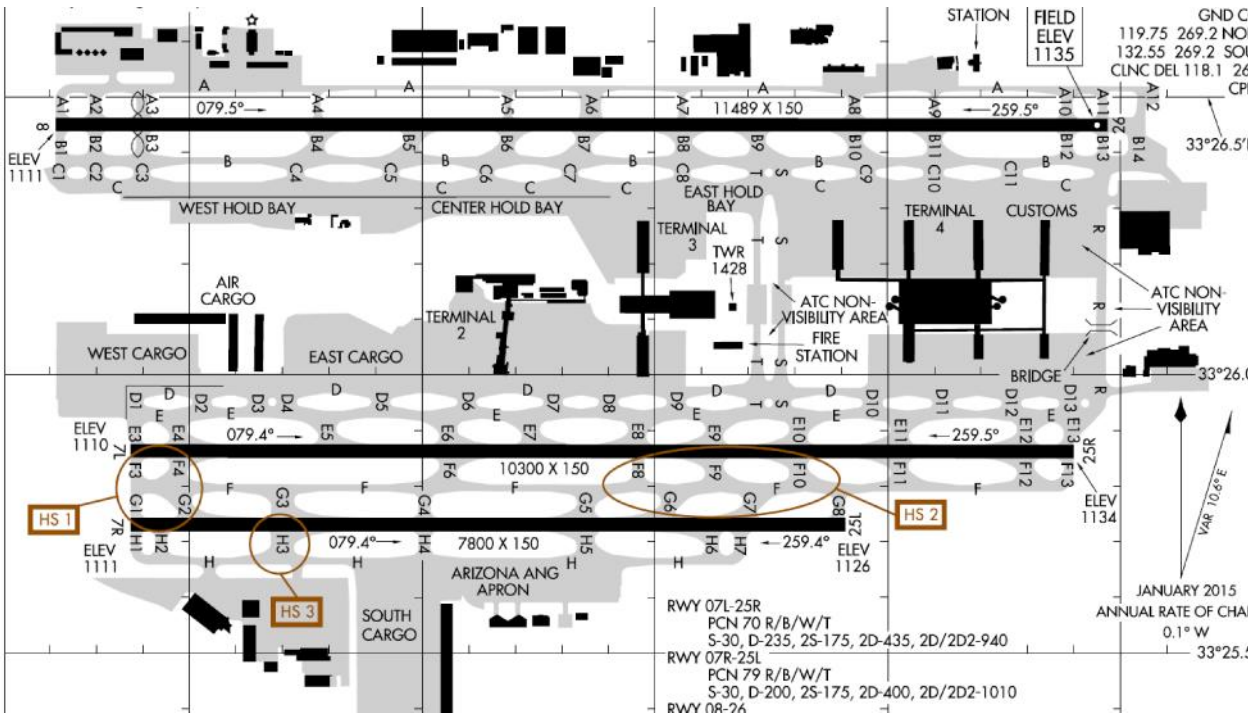

Figure 3-30. PHX Airport.

The two RNAV arrival procedures (BRUSR1 and EAGUL6) that were used were heavily based on current arrival procedures. Minor modifications were made to have the arrival connect to the instrument approach procedure. Modifications were also made to accommodate the RNP RF turns. RNP RF turns onto final approach can be challenging for controllers but are expected to be supported by TSAS and will continue to be part of arrival and approach procedures in the terminal metering environment (Wynnyk and Kopald, 2013). Therefore, they were examined to determine the impact of IM.

The airspace had one feeder (Apache airspace) and one final (Freeway airspace) position. Figure 3-31 provides an overview of the airspace. The waypoints and the associated altitude and speed constraints for the arrival procedures as shown in Figure 3-32. The TSAS constraint points used in the simulation were RHYAN (RNP RF turn start), DERVL (merge point outside final), and YOKXO (FAF).

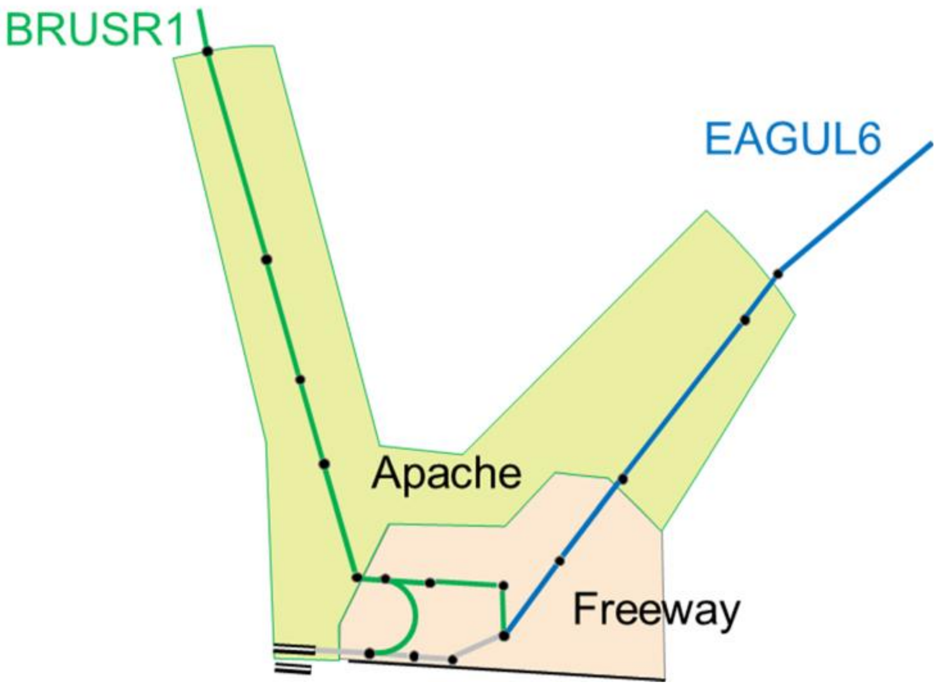

Figure 3-31. PHX-Like Airspace Overview: Arrival Procedures and Controller Airspace

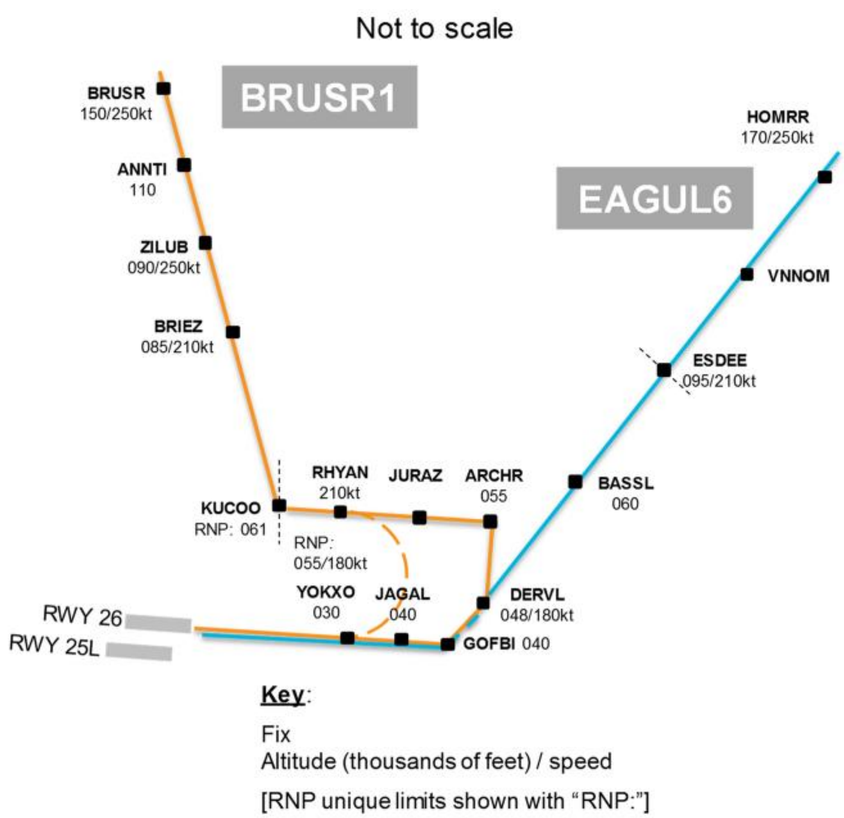

Figure 3-32. Arrival Procedures

Based on the arrival and approach geometries, a mix of different types of aircraft pairings could occur. For example, aircraft flying RNAV arrivals could follow aircraft flying the same or a different RNAV arrival. An aircraft flying the BRUSR1 arrival with the RNP RF turn could follow another aircraft flying the RNP RF turn, or it could follow an aircraft flying either RNAV arrival without the RNP RF turn. Aircraft flying either arrival could follow an aircraft flying the BRUSR1 arrival with the RNP RF turn. The geometries are shown in Figure 3-34 on the next page (with potential IM pairings noted). One of the more interesting geometries is shown in Figure 3-33, where an aircraft flying the BRUSR1 RNAV arrival is following an aircraft flying the BRUSR1 with the RNP RF turn. The sequence to the runway designed by TBFM can initially appear confusing if the RNP RF turn is not considered.

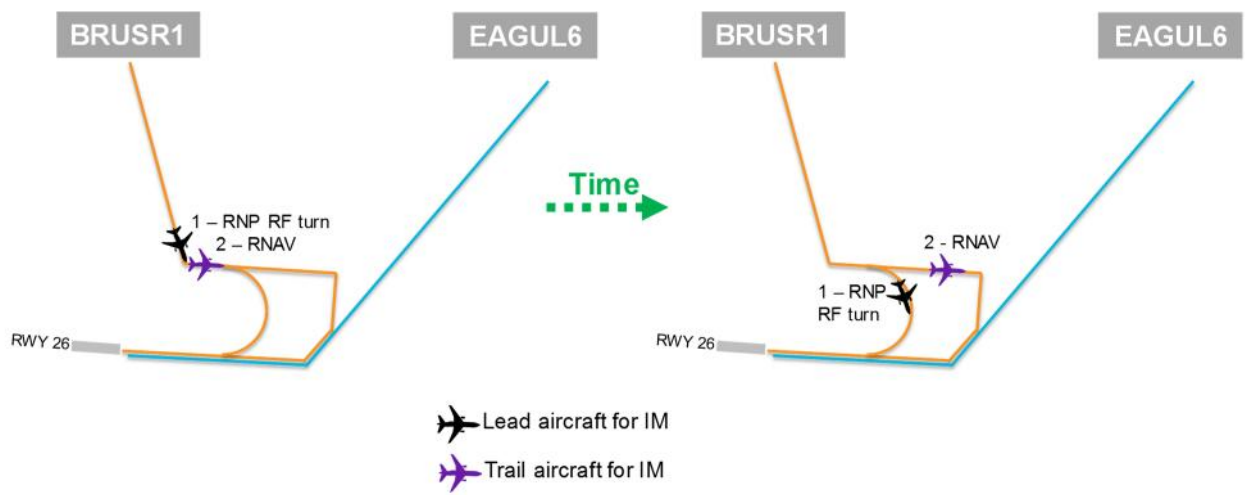

Figure 3-33. Geometry Where RNAV Aircraft is Following RNP RF Turn Aircraft on the Same Arrival

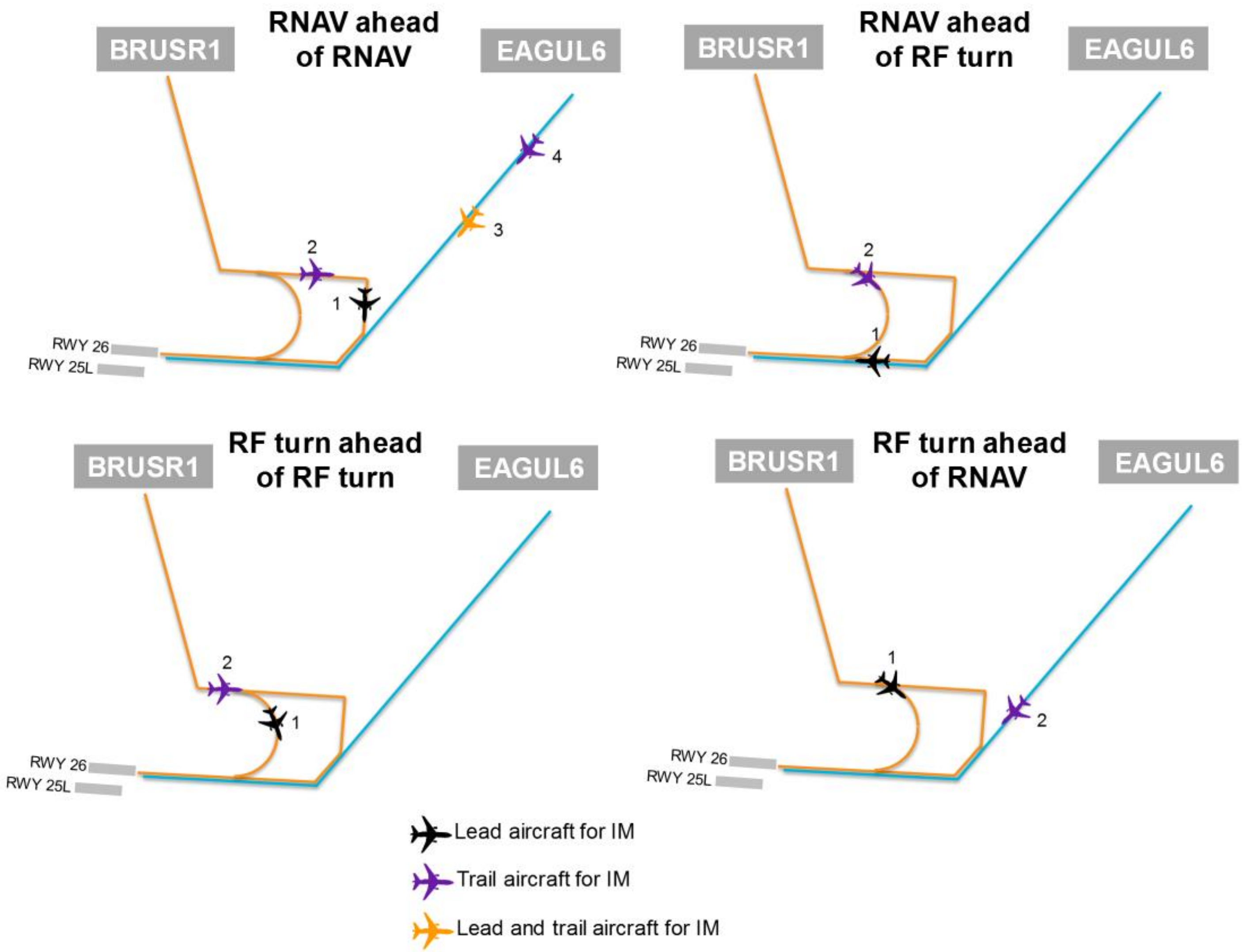

Figure 3-34. Traffic Pairing Geometries

The IM operations were Multi-Stream Arrivals with Metering, as defined in Hicok and Barmore (2016) (Figure 3-35).

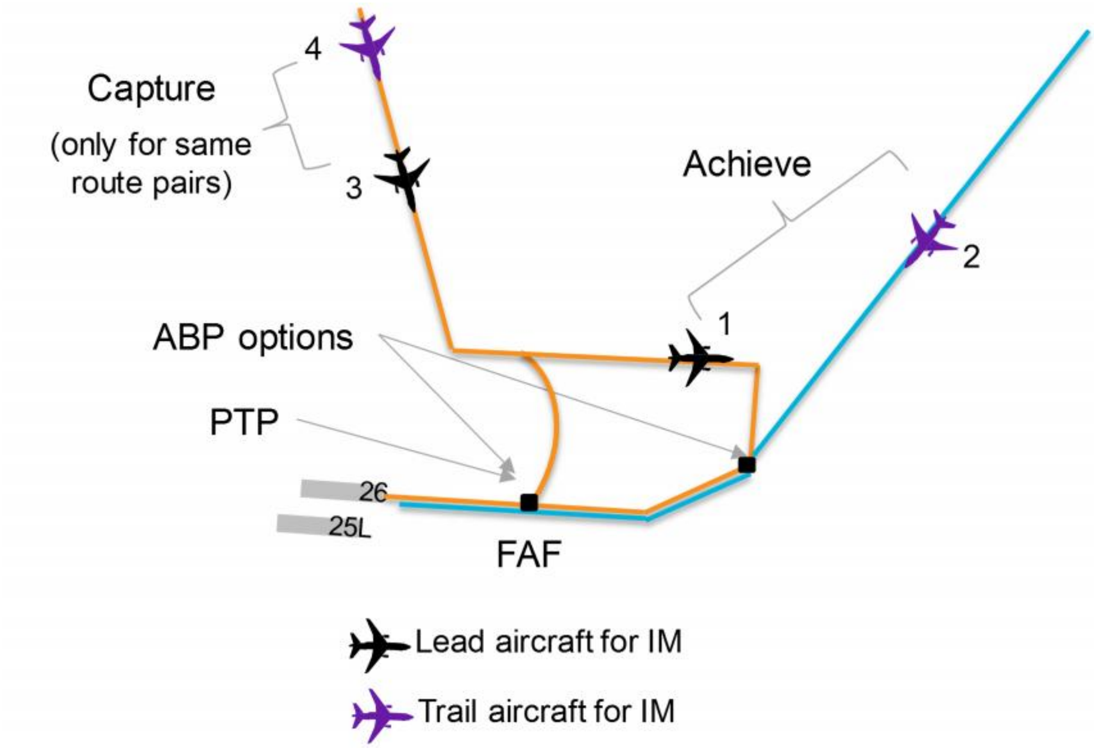

Figure 3-35. Sample IM Operations with the PTP and ABP Options

3.1.6 Traffic

Simulation traffic included the participants' aircraft along with other aircraft arriving from the north for the RNAV approach to Runway 26 (as shown previously in Figure 3-31). Aircraft also landed on runway 25L, but as independent operations. Attempts were made to develop traffic flows that were high density and kept the controller workload at a high but reasonable level. 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. The density of the flow was modified several times prior to selecting the final density for data collection based on controller and ground expert inputs during the concept evaluations. Equivalent traffic levels were used through the entire simulation to avoid workload differences between scenarios. Each traffic file was derived from real world traffic files with arrivals to KPHX.

At scenario start, traffic started arriving from the two flows and gradually built to the full density of traffic that lasted until the data collection was complete for the scenario and the scenario was terminated by one of the researchers (typically at the point where the participant aircraft landed and / or when the final off-nominal event occurred).

All aircraft in the simulation were capable of flying the RNAV arrivals. There was a mixture of aircraft that were capable of flying the RNP RF turn (approximately 20%) and aircraft that were not capable of flying the RNP RF turn (approximately 80%). This RNP RF turn capability split was coordinated with key stakeholders and believed to represent a reasonable number of aircraft capable in the future of flying the more challenging routing.

All aircraft in the simulation were ADS-B out and capable of as acting as an IM lead aircraft. There was a mixture of aircraft that were capable as acting as an IM trail aircraft (approximately 60%) and aircraft that were not capable as acting as IM aircraft (approximately 40%). This IM capability split was also coordinated with key stakeholders and believed to represent a reasonable mix of aircraft. It was also an increase over past work done under ATD-1 (as reviewed in Section 2.4.2.2). However, it is reasonably short of 100% equipage, which is unlikely to be realistic in the near term and may be easier to manage based on not having to deal with the difficulties of mixed equipage. The participant aircraft was always IM capable (except in one baseline condition).

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 prior to them entering the TRACON. Aircraft arrived no earlier than 30 seconds and no later than 15 seconds, with a distribution between those maximum values. The expected delivery for terminal metering operations is approximately +/- 30 seconds (Robinson et al., 2015). However, based on aircraft being able to more easily decelerate than accelerate in the TRACON, and the chosen arrival procedures, the 15-second threshold was chosen for this activity. This is consistent with a simulation reported in Callatine et al. (2014) in which en route controllers were asked to deliver aircraft +/- 30 seconds with a preference for the early side.

Pseudo-piloted aircraft were mainly large but also included heavy category aircraft. Aircraft types included: Airbus A306, Airbus A319, Airbus A320, Airbus A321, Boeing 717-200, Boeing 737-300, Boeing B737-700, Boeing 737-800, Boeing 737-900, Boeing 767-300, Bombardier CRJ200, Bombardier CRJ700, Bombardier CRJ900, McDonnell Douglas DC-10, McDonnell Douglas MD-11, and McDonnell Douglas MD-90. Pseudo-piloted aircraft flew final approach speeds of either 140 or 150 kts[6]. The aircraft started to slow to the final approach speed at the FAF. Pseudo-piloted aircraft that performed the achieve or capture IM clearance types used the IM sample algorithm. The speeds were not entered by the pseudo-pilots, but were flown automatically once the pseudo-pilot engaged IM.

The participant flight crew aircraft was always capable of RNAV (but not the RNP RF turn) and IM. The participant aircraft utilized the IM sample algorithm and always flew an achieve IM clearance type.

[6] TBFM assumed a final approach speed of 140 kts for all aircraft.

3.2 Participants

Participant controllers were coordinated through the FAA and NATCA. The standard procedures involved submitting a request with specific requirements, followed by approvals, and finally identification of participants. Controllers were compensated for their participation through standard FAA processes. Controller requirements included:

- Currently working at an ATC-10 or above STARS-equipped TRACON facility
- At least 2 years of experience as a Certified Professional Controller (CPC)
- Certified, operationally current, and holding a valid medical certificate (temporarily medically disqualified may qualify if current)
- No prior TSAS simulation experience

Twelve controllers were desired for the simulation, but recruiting difficulties lead to nine total controllers participating. The controllers acted as TRACON final and feeder controllers and were from a variety of TRACONs, including: Atlanta (A80), Charlotte (CLT) [x2], Miami (MIA), Orlando (F11), Philadelphia (PHL) [x2], Potomac (PCT), and Tampa (TPA). The tower controller positions were not staffed. Controllers had an average experience of 15.4 years (with a minimum of 7 years and a maximum of 30.5 years) actively controlling air traffic. The average age of the controllers was 39 years with a minimum of 30 years and a maximum of 53 years.

Flight crews were recruited by MITRE. A request for participation was developed and distributed to members of the MITRE database. The request stated that each pilot was required to be an Air Transport Pilot (ATP), have at least 100 hours of Federal Aviation Regulation Part 121 "glass cockpit" experience, be qualified in turbojet aircraft with auto throttles, and have operated an aircraft using their ATP rating within the last 12 months. Pilots were told they would be compensated for their participation.

It was desirable to have both pilots be from the same airline and to have a pairing of a Captain and a First Officer (FO) for each simulation day. However, prior to recruiting, it was determined the results were not likely to be affected by not meeting either of these conditions. Therefore, these were determined to be goals but not requirements.

A total of 18 pilots (acting as nine flight crews) were recruited and participated in the study. Seven of the pilots were qualified as Captains and 11 were FOs. Their estimated average total flight hours was 10,110 hours (with a minimum of 2500 hours and a maximum of 25,000 hours). The pilots were currently flying a variety of aircraft types, i.e., Airbus A319, A320, and A321, as well as Boeing 717, 737, 747, 757, 767, and 777. During the simulation, one pilot acted as the PF, and one pilot acted as the PM. The roles were not switched during the simulation.

MITRE staff members acted in two to four pseudo-pilot positions (depending on the number of controller participants). The authors served as observers for both the flight crew controllers.

3.3 IM Operations

The IM operations conducted in the simulation were as described in Section 2.2.1. This section notes some specific topics where changes, or specific implementation decisions, were made for this simulation.

3.3.1 Procedures

Controllers were instructed to manage aircraft and sector operations as normal for TRACON facilities. They were also asked to keep aircraft on their RNAV or RNP RF route while using the TSAS features and IM to achieve the schedule. They were told to intervene when necessary for spacing or separation issues. Controllers were reminded that if they intervened when aircraft were flying the profile speeds on the arrival that they needed to direct the aircraft to resume the profile / normal speed. They were told to clear aircraft for the instrument approach when acting as a final controller. Finally, the controllers were asked to hand off all aircraft to the tower controller around the FAF. This is common at some facilities but less common at other facilities. Handing off around the FAF gave a consistent hand off point and allowed the controller to monitor IM operations for as long as reasonably possible.

For metering operations, controllers were told that the TSAS speed advisories were additional information for issuing an appropriate speed and that they did not need to be implemented exactly as presented.

Controllers were asked to conduct IM and follow IM procedures and phraseology for any aircraft that was IM capable. Controllers were told that only the feeder controller should issue the IM clearance. They were asked to issue as many IM operations as possible, but that they could reject a proposed IM clearance if there was an operational reason to do so. They were told that when a “no speed” issue was presented to them, IM was possible between the pair of aircraft if a more aggressive speed assignment (than the 15% of the profile speed restriction) or vector was utilized prior to initiating IM. They were also reminded that coordination was necessary between the lead aircraft controller and the trail aircraft controller if the lead aircraft controller needed to vector that aircraft.

Pilots were told they would be assigned the role of PF or PM and would remain in that role throughout the simulation. They were told to follow normal cockpit procedures and if there were differences in airline policies they should agree on an approach during training. They were also asked to fly the flight deck simulator as if it were a large category aircraft (versus a heavy). This was done based on expectations of having a larger pool of large category aircraft pilots and because the aircraft model was more similar to a large aircraft model.

Pilots were briefed that the PM should enter the IM clearance information and then coordinate with the PF on the entered information and the first IM speed prior to executing IM. They were reminded that their tasks were to fly the IM speeds and to monitor the IM operation. They were told that the IM speeds overrode the profile speeds and that they should not announce each IM speed to the controller. They were told that if the IM speed conformance advisory was triggered, that they should ensure the appropriate speed was set in the MCP and the aircraft was working toward the IM speed. Pilots were told that if the feasibility check was triggered (and they could not continue IM), to fly the current speed, contact ATC, and report "unable interval spacing." When the feasibility check was not in effect, but the pilots had either the progress indicator or the graphical progress indicator, they were told they should determine whether IM was progressing toward the ASG. If not, they were told to maintain the current speed, contact ATC, and report "unable interval spacing." Pilots were told that the graphical progress indicator showed the acceptable tolerances of spacing and that they should not deviate from IM speeds to keep the triangle symbol centered. The PF was told to fly the IM speeds unless conditions prevented it or there were other operational reasons not to do so. The PM was told to call out any nonconformance with IM speeds or infeasible indications. Pilots were told they did not need to monitor for separation issues, as that remained the responsibility of ATC.

3.3.2 Communications

This section will describe the specific communications used in this simulation. The phraseology was developed based on the most recent IM communications material at the time of simulation design (DO-328A / RTCA, 2015b, DO-350A / RTCA, 2016a, DO-351A / RTCA, 2016b). During the development of DO-350A (RTCA, 2016a) and DO-351A (RTCA, 2016b), controllers reported issues with the use of the terms "interval management" or "IM." The discussion led to the use of "interval spacing" in that material. Therefore, that term was used in this simulation. Steps were taken to keep the IM clearance concise (e.g., avoiding using the PTP in the clearance by making it part of the procedure and known to pilots [shown in the arrival and approach procedures] and controllers)

The controllers had four specific IM communications:

- Initiation (samples)
  - "AAL245 achieve 100 seconds by DERVL behind United 123 on EAGUL6"
  - "SWA2598 capture 78 seconds behind FDX783"
- Suspend
  - "Suspend interval spacing" with speed instruction
- Resume
  - "Resume interval spacing"
- Terminate
  - "Terminate interval spacing" with speed instruction

The controllers were asked to issue the IM clearance only as feeder controllers. However, either the feeder or final controller could suspend, resume, or terminate IM. The final controller was responsible for issuing the approach clearance for the RNAV approach with or without the RNP RF turn. The phraseology consisted of:

- "Cleared RNAV runway two six approach" or
- "Cleared RNP runway two six approach"

Flight crews were told to perform normal readbacks. The only new phraseology for the flight crews was when reporting being unable to continue IM. They were told to say:

- "Unable interval spacing"

3.4 Simulation Procedures

A total of eighteen pilots participated in the simulation. Two pilots participated for one day per pair over the course of nine days. Controllers participated for a total of five days. During simulation planning, the expectation was that four controllers would participate over three five-day periods. However, due to recruiting issues, the number of controllers varied by the five-day period. The first five-day period had two controllers, the second had three, and the third had four. The controller and pilot groupings as well as the main daily activities are shown in Table 3-3. The following sub-sections will provide details on simulation procedures for the controllers then the pilots.

Table 3-3. Controller and Pilot Grouping and Daily Activities

Day	Controller Group	Controller Activity	Pilot Group	Pilot Activity
1	1 (n = 2)	Training - TSAS		
2		Training - IM during metering		
3		Data collection	1 (n = 2)	Training and data collection
4			2 (n = 2)	Training and data collection
5			3 (n = 2)	Training and data collection
6	2 (n = 3)	Training - TSAS		
7		Training - IM during metering		
8		Data collection	4 (n = 2)	Training and data collection
9			5 (n = 2)	Training and data collection
10			6 (n = 2)	Training and data collection
11	3 (n = 4)	Training - TSAS		
12		Training - IM during metering		
13		Data collection	7 (n = 2)	Training and data collection
14			8 (n = 2)	Training and data collection
15			9 (n = 2)	Training and data collection

3.4.1 Controller Training

Based on feedback from the concept evaluation activities leading up to the HITL, the training started with a day of terminal metering and TSAS-only training. While the simulation activity was not examining terminal metering and TSAS operations alone, these operations were new to the controllers so it was introduced before adding IM into those operations. The following day was used to introduce IM into that terminal metering environment.

The first day started with having each participant complete a demographics questionnaire. This was followed by the first part of the pre-simulation briefing which contained information on the research background, the operational reason for introducing terminal metering, the terminal metering concept and TSAS, the simulation environment (e.g., airport, arrivals, airspace, RNP RF turns), roles and responsibilities, as well as operational considerations.

After the first day pre-simulation briefing, controllers were taken to the IDEA lab to familiarized themselves with the STARS workstation and to ask any questions. Controllers were briefed on the basic display features, information new for terminal metering and TSAS, as well as the simulated KPHX airspace. Controllers were then given a "cheat sheet" with key information on it such as keyboard entries. The remainder of the day involved running through training scenarios. The training progressed from low to medium and finally high-density traffic during terminal metering operations. Controllers trained with each density and in both the feeder and final roles. The first day ended with a high-density traffic during terminal metering operations scenario that acted as a baseline.

The second day started with the second part of the pre-simulation briefing that described IM operations during terminal metering. Controllers were told the simulation activity was not trying to force a choice between TSAS and IM, but that they may get asked questions comparing the operations and associated tools to ensure proper integration of the operations. They were also informed that the researchers were not soliciting feedback on STARS and TSAS independent of IM, as the goal was to have integrated IM and terminal metering operations and not independent operations. The briefing provided background information on IM and the integration of IM into the terminal metering environment. It also provided the operational reason for introducing IM, IM operations, and operational considerations when conducting IM during terminal metering. The briefing provided details on pilot and controller roles and responsibilities, IM display features, and the communications procedures as detailed in Section 3.3.2.

After the second day briefing, controllers were taken to the IDEA lab to be familiarized with IM. They were briefed on the new information for IM. The "cheat sheet" was reviewed for the IM elements such as the sample IM communications and IM keyboard entries. The remainder of the day involved running training scenarios. The training progressed from low to medium and finally high density traffic with IM aircraft now present in the terminal metering operations. Controllers training with each density and in both the feeder and final roles.

Based on past research (e.g., Bone, Penhallegon, Benson, and Orrell, 2013; Cardosi, personal communication, October 4, 2014), it was felt that controllers would benefit from understanding the information available to flight crews. Therefore, in addition to the overviews of the flight deck displays and the associated information from the briefing, demonstrations in the flight deck simulator were provided.

3.4.2 Pilot Training and Data collection

The next three days for the controllers consisted of data collection. A new set of pilots joined the simulation each day. While the pilots were being trained each day in the morning, the controllers participated in data collection scenarios where IM was initiated in the en route environment and continued IM into the TRACON. Only pseudo-piloted aircraft were part of these scenarios.

For pilots, the day started by completing a consent form and demographics questionnaire. This was followed by the pre-simulation briefing. The briefing provided background information on IM, IM operations and communications, pilot and controller roles and responsibilities, display features and the simulation environment, as well as operational considerations when conducting IM. The pilots were also given basic information about the relationship between time and distance spacing during IM.

After the pre-simulation briefing, the pilots were taken to the flight deck simulator for familiarization and training on the various interfaces and procedures they would encounter during the data collection scenarios. The flight crew first conducted an arrival and approach, without IM or a CDTI, to become familiar with the flight deck simulator. They then conducted a practice BRUSR1 arrival and approach with IM where they were taught how to interact with and utilize the min tool set. They then conducted the EAGUL6 arrival and approach with IM but with the min+ tool set.

When pilot training was completed, both the controllers and pilots started the joint data collection activities. Each scenario lasted approximately 40 minutes and post-scenario questionnaires were given after each run / scenario. Prior to executing each scenario, pilots and controllers were informed of the specific conditions for the current scenario. Pilots were informed of their call sign for the run via a note placed in the flight deck (Sun Country [SCX] was always used as the company name but the flight number changed for each approach).

After data collection runs, participants were provided with a final questionnaire encompassing the entire simulation. Once they completed the final questionnaire, the controllers and pilots were offered an opportunity to have a short, informal debrief.

3.5 Experimental Design

The independent variables for the simulation are shown in Table 3-4. The variables were intended to test where pilots and controllers had sufficient information, in their role, to determine how well IM was progressing and whether spacing issues were developing. The testing of the controller variables was expected to provide some data on the necessary information for the controller that would be specified in a ground requirements document. Only a very preliminary version of such a document existed at the time the simulation was being defined. However, for the flight deck displays, requirements have been already written for the CDTI (traffic display and AGD implementation in this simulation) so the testing of the independent variables could provide validation of the minimum set of requirements and could provide data on necessary additions.

Table 3-4. Independent Variables

Controller	Flight Crew
Role (Within)	
Feeder	
Final	
Tool Set (Within)	**Tool Set (Within)**
Basic	MOPS CDTI minimum (min)
Basic+ cue	MOPS CDTI minimum plus (min+) [Graphical progress indicator and speed tape]
Basic+ cue and prediction	

MOPS – Minimum Operational Performance Standards

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 (approximate rate of 40 aircraft per hour), mix of aircraft type and category (larges and heavies), aircraft capabilities (IM and RF RNP), and delivery relative to the schedule from the simulated en route controller. Each traffic file lasted approximately 40 minutes and the controller managed traffic for the full scenario. The flight crew could fly one arrival and approach to landing and then be repositioned outside of the TRACON airspace to fly the arrival and approach a second time within the same traffic file. The participant aircraft flight crew was given sufficient time to get acclimated to the new position and aircraft state before checking in and receiving the first controller instruction. Each participant experienced the same set of data collection scenarios (in a repeated measures design).

One of the traffic files (traffic file 4) was used as the en route initiation scenario without participant flight crew participation. This same traffic file was then used for the baseline condition for the flight crew. In that case, the traffic file looked like the other traffic files to the controller, but the participant flight crew was not equipped to do IM.

Over the course of each data collection day, flight crews flew twice through each traffic file. The participants flew a baseline without IM in traffic file 4 and flew IM in traffic files 1, 2, 3, 5, and 6. While all pilots experienced the independent variables in the same run within the traffic file, the run order of the traffic files was counterbalanced across participant groups. Flight crews flew two arrivals and approaches within each traffic file. The run in which they utilized either the min CDTI implementation or the min+ implementation is shown in Table 3-5.

Table 3-5. Flight Crew Independent Variable Exposure by Traffic File and Run

Operation	IM Tools / Independent Variable	(T)raffic File-(R)un
Baseline	NA	T4-R1; T4-R2
IM	Min	T1-R1; T2-R2; T3-R2; T5-R1; T6-R2
IM	Min+	T1-R2; T2-R1; T3-R1; T5-R2; T6-R1

Over the course of the three-day data collection days, the controllers experienced traffic file 4 with en route initiation, 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 each 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. Table 3-6 shows the traffic file run order and traffic overtake events for the three groups of controllers.

Table 3-6. Controller Independent Variable Exposure by Day, Traffic File, and Run

Group	Operation	IM Tools	A Controller Role / B Controller Role	(D)ay-(T)raffic File-(R)un Order		
1	Baseline	NA	Feeder/Final	D1-T4-R1		
	Baseline	NA	Final/Feeder	D1-T4-R2		
	IM En Route Initiation	TSAS tools	Feeder/Feeder	D4-T4-RC1		
	IM En Route Initiation	TSAS tools and slot marker color change	Feeder/Feeder	D3-T4-RC1		
	IM En Route Initiation	TSAS tools, slot marker color change, and ETA differential	Feeder/Feeder	D5-T4-RC1		
	IM	TSAS tools	Feeder/Final	D3-T4-R1	D4-T5-R1	D5-T6-R1
	IM	TSAS tools and slot marker color change	Feeder/Final	D3-T1-R2	D4-T6-R2	D5-T4-R2
	IM	TSAS tools, slot marker color change, and ETA differential	Feeder/Final	D3-T2-R3	D4-T4-R3	D5-T1-R3
	IM	TSAS tools	Final/Feeder	D3-T3-R4	D4-T1-R4	D5-T2-R4
	IM	TSAS tools and slot marker color change	Final/Feeder	D3-T5-R5	D4-T2-R5	D5-T3-R5
	IM	TSAS tools, slot marker color change, and ETA differential	Final/Feeder	D3-T6-R6	D4-T3-R6	D5-T5-R6
2	Baseline	NA	Feeder/Final	D1-T4-R1		
	Baseline	NA	Final/Feeder	D1-T4-R2		
	IM En Route Initiation	TSAS tools	Feeder/Feeder	D3-T4-RC1		
	IM En Route Initiation	TSAS tools and slot marker color change	Feeder/Feeder	D5-T4-RC1		
	IM En Route Initiation	TSAS tools, slot marker color change, and ETA differential	Feeder/Feeder	D4-T4-RC1		
	IM	TSAS tools	Feeder/Final	D3-T4-R2	D4-T1-R2	D5-T6-R2
	IM	TSAS tools and slot marker color change	Feeder/Final	D3-T1-R3	D4-T2-R3	D5-T4-R3
	IM	TSAS tools, slot marker color change, and ETA differential	Feeder/Final	D3-T6-R1	D4-T4-R1	D5-T5-R1
	IM	TSAS tools	Final/Feeder	D3-T3-R5	D4-T5-R5	D5-T2-R5
	IM	TSAS tools and slot marker color change	Final/Feeder	D3-T5-R6	D4-T6-R6	D5-T3-R6
	IM	TSAS tools, slot marker color change, and ETA differential	Final/Feeder	D3-T2-R4	D4-T3-R4	D5-T1-R4
3	Baseline	NA	Feeder/Final	D1-T4-R1		
	Baseline	NA	Final/Feeder	D1-T4-R2		
	IM En Route Initiation	TSAS tools	Feeder/Feeder	D5-T4-RC1		
	IM En Route Initiation	TSAS tools and slot marker color change	Feeder/Feeder	D4-T4-RC1		
	IM En Route Initiation	TSAS tools, slot marker color change, and ETA differential	Feeder/Feeder	D3-T4-RC1		
	IM	TSAS tools	Feeder/Final	D3-T4-R3	D4-T1-R3	D5-T2-R3
	IM	TSAS tools and slot marker color change	Feeder/Final	D3-T5-R1	D4-T6-R1	D5-T4-R1
	IM	TSAS tools, slot marker color change, and ETA differential	Feeder/Final	D3-T6-R2	D4-T4-R2	D5-T1-R2
	IM	TSAS tools	Final/Feeder	D3-T3-R6	D4-T5-R6	D5-T6-R6
	IM	TSAS tools and slot marker color change	Final/Feeder	D3-T1-R4	D4-T2-R4	D5-T3-R4
	IM	TSAS tools, slot marker color change, and ETA differential	Final/Feeder	D3-T2-R5	D4-T3-R5	D5-T5-R5

Note: Traffic overtake conditions are highlighted in orange.

A summary of each data collection day (1 day for pilots; 3 days for controllers) is provided in Table 3-7.

Table 3-7. Data Collection Day Details

Traffic File(s)	Flight Crew (2 per day)	Controllers (3 per day)
4 (with en route initiation)	**Introductory Briefing and Background Questionnaire. Training in lab**	**Controller role**: A - Feeder; B- Feeder **Scenario**: TSAS and IM en route initiation **Independent variable (order varied between days)**: (1) Basic, (2) Basic+ cue, or (3) Basic+ cue and prediction
1, 2, 3, 4, 5, and 6	**Pilot role (remained fixed)**: PF; PM **Operation (order varied within day)**: (1) Baseline - No IM (x2 runs) (2) IM (x10 runs) **Tools (order varied within day)**: Min CDTI then Min CDTI+ or Min CDTI+ then Min CDTI	**Controller role (swapped after 3rd scenario)**: Feeder; Final **Operation (traffic file order varied within day)**: TSAS and IM (x6) **Tools (order varied within day)**: (1) Basic, (2) Basic+ cue, or (3) Basic+ cue and prediction

3.6 Data Collection

Four methods of data collection were used for this simulation: paper questionnaires, system recorded data, observations, and final debriefs (when chosen by the participants). Three types of questionnaires were used, including:

1. **Demographics:** Upon arrival, participants were asked to fill out a demographics questionnaire which captured participants' experience. Controllers and pilots had separate questionnaires.

2. **Post- scenario:** After each run / scenario, participants were asked to fill out a questionnaire based on the run / scenario just experienced. All post-scenario questionnaires included the Bedford Workload Rating Scale (Roscoe, 1984) along with additional rating scale and yes / no questions with a comment field for each. The controller questionnaires included the Controller Acceptance Rating Scale (Lee, Kerns, Bone, and Nickelson, 2001). Pilot participants completed a post-scenario questionnaire after each run during a scenario (two runs per scenario) and controllers completed this questionnaire after each scenario. Separate post-scenario questionnaires were used for the baseline and IM scenarios. Controllers and pilots also had separate questionnaires (Appendix B).

3. **Post-simulation:** After the final scenario, participants were asked to complete the longer, final questionnaire covering all the scenarios experienced. The questionnaire included a series of rating-scale and yes / no questions with a comment field for each. Controllers and pilots had separate questionnaires (Appendix C).

In these questionnaires, participants were asked to provide subjective feedback on areas such as the overall IM concept, workload, situation awareness, head down / scan time, displays, communications, and simulation realism.

Objective metric data was automatically recorded by the simulation platform or by the observers and included:

- ATC
  - Interactions with displays
    - Inputs for IM initiation, rejection, suspension, resumption, and termination
  - IM initiation delay
  - Location of IM initiations, rejections, suspensions, resumptions, and terminations
- All aircraft
  - Schedule conformance
  - Slot marker deviation
  - Events below the applicable separation standard
  - Frequency of infeasible / no speed events
  - Time on the RNAV procedure
  - Spacing error at key locations
  - How well the ASG was maintained
  - Arrival rates / throughput
- Participant aircraft
  - IM speeds
  - MCP selected speed
  - Distance to ABP
  - Frequency of IM terminations
  - Interactions with displays (e.g., TTF selection and data entry)

4 Results

This section begins with a description of the analysis method for both subjective and objective data. It then describes baseline scenarios and the operations (terminal metering and RNP RF turns) that form the operational foundation for IM. It then covers the objective data, including: the conduct of IM operations (mainly controller actions related to IM), IM speeds (for participant pilot aircraft) and flight crew actions related to those speeds, and aircraft spacing and separation results (for pseudo-pilot and participant pilot aircraft). Subjective data for both pilots and controllers is covered next (e.g., acceptability of IM, displays, responsibilities). Time on RNAV arrivals and communication results are then provided, followed by en route IM initiation results, as related to controllers. Finally, the section ends with results for the participants' assessments of the simulation.

4.1 Analysis Method

4.1.1 Subjective Data

The subjective results are based on responses to the statements from both the post-scenario and post-simulation questionnaires. The post-simulation questionnaires comprise most of the data so in these cases, the source will not be noted unless it helps for clarity. Any data from the post-scenario questionnaires will be noted. Controller and pilot comments were included if they were enlightening or if a sufficient number of participants made similar comments.

Controller results are based on nine participants while pilot results are based on 18 participants. Controller responses are divided by the independent variable of controller role. Pilot responses are usually combined (as role was not a planned independent variable), unless there was a clear reason to report the roles separately.

Some questions in the questionnaires were yes / no with an opportunity for open-ended comments. Most response-scale items were statements with 100 hash marks (without numeric labels) and an opportunity to provide open-ended comments. The scale was anchored on the left with the label "Strongly Disagree" and on the right with the label "Strongly Agree" (Figure 4-1).

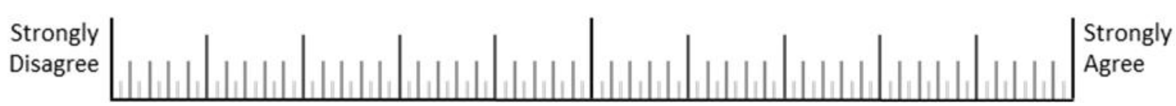

Figure 4-1. 100-Point Agreement Scale

Most items were presented as a statement, and participants were asked to rate their level of agreement. Participants were told to draw a straight line anywhere on the scale, including between the lines and right on the end points. During data reduction, responses were rounded to the nearest single digit between 0 and 100. In the presentation of the results, any 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" (Figure 4-2).

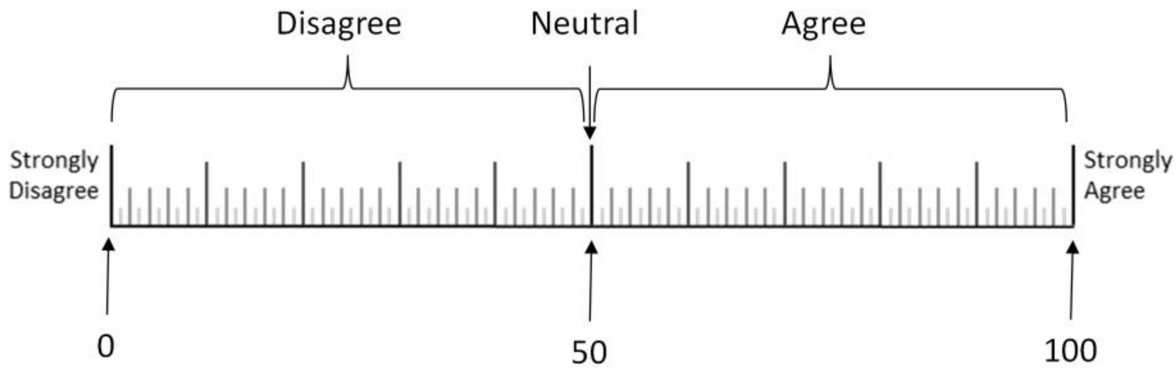

Figure 4-2. 100-Point Agreement Scale Agreement Rating Breakdown

When presenting results on the 100-point agreement scale in the post-simulation questionnaires, the following terminology / methodology is used to describe the levels of agreement.

- All [controllers / pilots] [agreed / disagreed]
  - All of the participants are on the agree or disagree side of the scale
- The majority (n; %) of [controllers / pilots] [agreed / disagreed]
  - Low variability, e.g., SD of less than approximately 25 (unless one value is driving a SD slightly higher)
- [Controller / Pilot] responses were variable but the majority (n; %) [agreed / disagreed]
  - Responses have a SD of greater than approximately 25 and distribution is relatively biased in one direction
- [Controller / Pilot] responses were variable
  - Responses have a SD of greater than approximately 25 and the distribution is relatively flat across the scale

To summarize a series of related statements, figures like that shown in Figure 4-3 are shown later in the relevant section to show the scale and the disagreement and agreement sides. "Smiling" or "frowning" faces are shown on the scale where the replies to the statements have a subjectively positive or negative meaning. For the post-simulation questionnaires, the statement is directly quoted from the questionnaire and shown to the left of the graph. If the same statement was used for both controllers and pilots, it is only shown once. When the controller and pilot statements were slightly different, brackets are used and the controller text is presented before the "/" and the pilot text is presented after. For example, "The spacing [achieved by the aircraft / I achieved] was acceptable." Figures for the post-scenario individual questions show the tool set to the left of the graph.

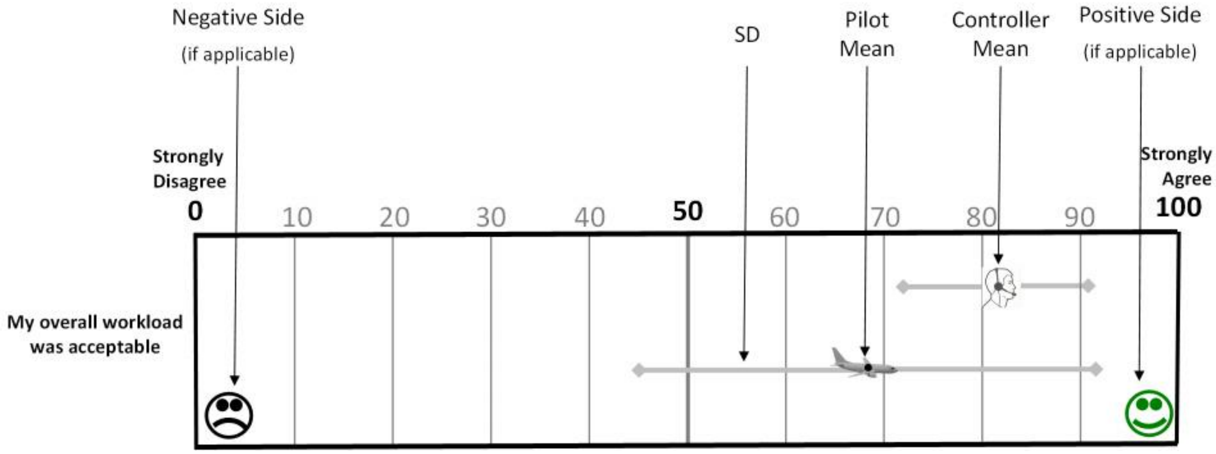

Figure 4-3. Sample Summary Figure

The means (M) and SDs are included on the figures. The means are shown by points and the SDs are shown by the bars. Symbols are also used to indicate the responding party and the particular condition the reply relates to. Note that the symbol labels may be combined in the figures where necessary. See Figure 4-4 for details on the symbols and their use.

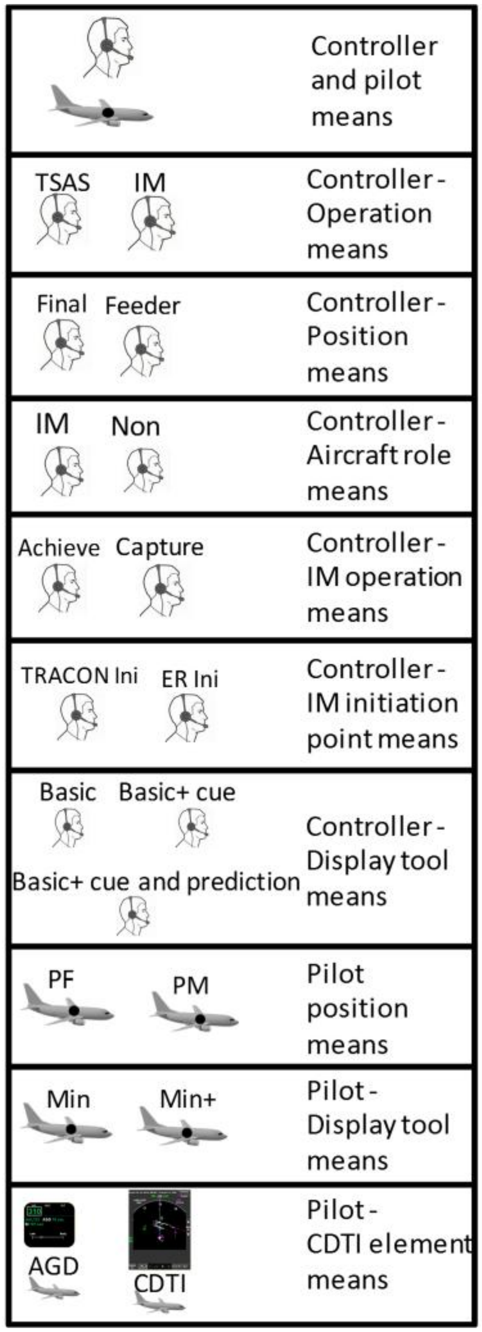

Figure 4-4. Symbols Used in the Summary Figures and Their Meaning

The Bedford Workload Rating Scale was used to measure subjective workload across scenarios. The Controller Acceptance Rating Scale was used for controllers to measure operational acceptability.

4.1.2 Objective Data

The objective data for aircraft is either shown as pseudo-pilot, participant pilot / flight crew aircraft, or combined data. Generally, the pseudo-pilot and participant pilot data is combined to provide detail of the controller's experience on the overall set of aircraft (e.g., in Section 4.5 - Aircraft Spacing and Separation). However, participant pilot aircraft data is reported separately when a distinction is made between the behavior of the participants (who operated the aircraft according to their own desires during the IM operation) versus the behavior of the pseudo-pilot aircraft (which behaved as designed by the IM sample algorithm (e.g., Section 4.4.5 - IM Speeds and Flight Crew Actions).

The arrival procedures were not the same length and did not take the same amount of time to fly. The BRUSR1 arrival from TRACON entry to touchdown was on average 14.2 minutes (SD = 0.8) and the EAGUL6 arrival was 11.5 minutes (SD = 1.4).

The majority of the data is comprised of IM initiations in the TRACON. Baseline / non-IM operations are reported in Section 4.2 and IM en route initiation is reported in Section 0.

The arrival rate targeted for the simulation was 40 aircraft per hour to the runway. The average arrival rate realized across the IM TRACON initiation scenarios was 46.5 (*SD = 7.*6). The average arrival rate across the IM en route initiation scenarios was 55.1 (*SD = 2.5*).

When the IM clearance types and stages are mentioned, the following conventions are used.

- Both achieve-by then maintain clearance type options
  - Achieve-by
  - Achieve-by then maintain
    - Achieve stage
    - Maintain stage
- Capture then maintain
  - Maintain stage

When flying the achieve-by option, the ABP and PTP were YOKXO (FAF) and there is no maintain stage. When flying the achieve-by then maintain option the ABP was DERVL (merge point) and the PTP was YOKXO (FAF). Aircraft were considered in the maintain stage of the achieve-by then maintain clearance type once the ABP was reached. For the capture then maintain clearance type, aircraft were considered in the maintain stage once the aircraft got inside the 10-second maintain tolerance. Data reported for the maintain stages can include the maintain stages of both clearance types.

Participant flight crews flew both achieve-by then maintain clearance type options. Pseudo-pilot aircraft flew both clearance types.

When the data is presented, box and whisker plots are used. Figure 4-5 shows a sample with a description of the various points.

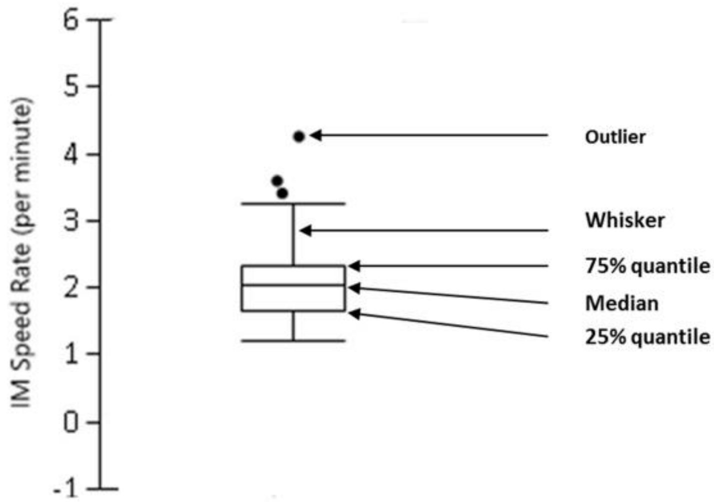

Figure 4-5. Sample Box and Whisker Plot Defined

Heat maps are also utilized to show the frequency of events along the arrival procedure. Figure 4-6 shows an example. Colors with longer wavelengths (e.g., reds) indicate more frequent events than colors with shorter wavelengths (e.g., blues).

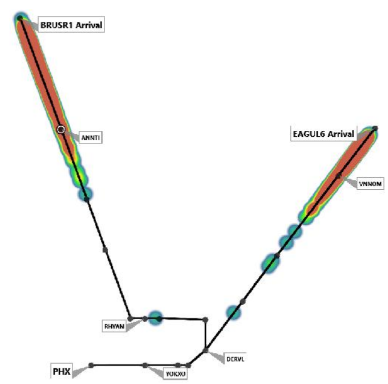

Figure 4-6. Sample Heat Map

4.1.3 Statistical Method and Results

Four hypotheses were tested across pilot and controller participants as listed in Table 4-1. Hypotheses one, three, and four consisted of more than one dependent measure. In these cases, statistical tests were used to test each measure. Alpha was set at 0.05.

Table 4-1. List of Hypotheses and Statistical Tests

#	Particiants	Hypothesis	Dependent Measure	Statistical Test
1	Pilots	Flight crews will achieve and maintain spacing better with the min+ tool set as compared to the min tool set	1a. Spacing error at ABP	Paired Samples t-test
			1b. Spacing error during maintain	Paired Samples t-test
2	Pilots	Flight crews will comply with more IM speeds with the min+ tool set as compared to the min tool set	Frequency of IM speeds complied with	Chi-square
3	Pilots	Flight crews will find the min+ tool set more acceptable than the min tool set	*1) Subjective question*: I could detect whether I would remain within tolerances to achieve and maintain the assigned spacing goal	2 x 2 Mixed ANOVA
			2) Subjective question: I had the necessary display elements for conducting IM	2 x 2 Mixed ANOVA
4	Controllers	Controllers will find the new display elements for IM useful as compared to only the basic	1) *Subjective question:* I was confident that the spacing of the [IM] aircraft would remain outside my separation requirement	Repeated Measures ANOVA
			2) *Subjective question*: I had the necessary display elements for conducting IM operations	Repeated Measures ANOVA

Table 4-1 also cites the statistical test used to measure each hypothesis. The researchers considered a Multivariate Analysis of Variance (MANOVA) for hypothesis three and four given there are several dependent variables to measure and to control for Type I family-wise error. The general assumption for a MANOVA is for there to be some level of correlation between dependent measures within a range from 0.3 to 0.7 (Mayers, 2013). To test for this, a series of Pearson Correlations were conducted across the dependent measures. All correlations exceeded $r = 0.7$ for both hypotheses; therefore, a separate Analysis of Variance (ANOVA) was conducted for each dependent measure. This resulted in a total of seven statistical tests. To adjust the alpha level of $p < 0.05$ for family-wise error, a Bonferroni Correction was employed, resulting in a familywise alpha level of $p < 0.01$. This was the criterion used to determine statistical significance.

4.1.3.1 Hypothesis 1: Flight Crews will Achieve and Maintain Spacing Better with the Min+ Tool Set as Compared to the Min Tool Set

This hypothesis only includes participant aircraft. Therefore, it is a subset of the data presented in Sections 4.5.3 and 4.5.4 that includes both participant and pseudo-pilot aircraft. The spacing error for the achieve and maintain stages is shown in Table 4-2.

Table 4-2. Mean Spacing Error in Seconds (SD) for Participant Flight Crews

Flight crew tool set	Stage of achieve-by then maintain	
	Achieve	Maintain
Min	**2.5** (1.2)	**0.96** (0.05)
Min+	**1.9** (0.7)	**1.0** (0.00)

For the measure of spacing error at the ABP, two measurement points were used. DERVL was used for trail aircraft that performed the achieve-by then maintain clearance type and had DERVL as the ABP (Note: Those aircraft then went into the maintain stage until the PTP). YOKXO was used by trail aircraft that performed the achieve-by clearance type and had YOKXO as the ABP. A dependent t-test was used to measure for statistical differences between the min and min+ tool sets. No statistically significant result was found.

Participant flight crews performed achieve-by then maintain operations with the maintain phase occurring after the aircraft crossed the ABP at DERVL and until crossing the PTP at YOKXO. This is a relatively short portion of the arrival and approach. A dependent t-test was used to measure for statistical differences between min and min+ tool sets. No statistically significant result was found.

4.1.3.2 Hypothesis 2: Flight Crews will Comply with More IM Speeds with the Min+ Tool Set as Compared to the Min Tool Set

This hypothesis was measured using the number of IM speeds the flight crews complied with. Differentiating crew role is irrelevant for this measure since only the PF was responsible for implementing the IM speeds. The type of data analyzed is binary since the PF either implements or does not implement a speed; therefore, a chi-squared analysis was used to measure the frequency difference between complying or not complying to each IM speed between the min and min+ tool sets. This test did not reveal any statistically significant differences between the tool sets.

4.1.3.3 Hypothesis 3: Flight Crews will Find the Min+ Tool Set More Acceptable than the Min Tool Set

The third hypothesis addressed whether flight crews will find the min+ tool set more acceptable than the min tool set. The hypothesis was measured using the following post-scenario subjective questions: 1) "I could detect whether I would remain within tolerances to achieve and maintain the assigned spacing goal," and 2) "I had the necessary display elements for conducting IM." The researchers tested for statistical equivalence using the Two One-Sided Test (TOST) between both pilot roles (i.e., PF and PM) so that the PF and PM results for each tool set could be combined across all measures. This method would increase the sample size within each condition (i.e., from nine to 18).

Four TOST comparisons were conducted, one for each set across the two measures (i.e., post-scenario questions). None of the tests revealed statistically equivalent results. This suggests different uses of the tool sets between the roles, which resulted in different perceptions. In this instance, pilot role was treated as another independent variable. Therefore, two 2 x 2 Mixed ANOVAs were conducted for the tool sets and pilot role across the two measures. The tests did not reveal any statistically significant results.

4.1.3.4 Hypothesis 4: Controllers Will Find the New Display Elements for IM Useful as Compared to Only the Basic

The forth hypothesis addressed if controllers found the new display elements for IM useful compared to the basic tool set. Two post-scenario questions were developed to address this hypothesis: 1) I was confident that the spacing of the [IM] aircraft would remain outside my separation requirement, and 2) I had the necessary display elements for conducting IM operations. A 3 x 2 Repeated Measures ANOVA was conducted for controller role (i.e., feeder and final) and IM tool set (i.e., basic, basic+ cue, and basic+ cue and prediction) across each of the two dependent measures. This was done in lieu of one MANOVA due to the previously-described unfavorable correlations between dependent measures. There were no main effects or interactions for both Repeated Measures ANOVAs.

4.1.4 Summary Data

One hundred thirty participant controller runs and 108 participant flight crew runs were planned. Due to technical issues with the simulation environment, three controller IM TRACON initiation runs were excluded from data analysis, which also resulted in the loss of six participant flight crew runs. An additional 11 participant flight crew runs (that did not affect the overall controller runs) were excluded due to technical issues with the simulation environment. Table 4-3 shows the number of runs for both controllers and participant flight crews by scenario type. Table 4-4 shows the number of aircraft per environment.

Table 4-3. Number of Planned and Analyzed Runs per Scenario Type

Scenario	Planned # of runs		Analyzed # of runs	
	Controller	Flight crew	Controller	Flight crew
Baseline	10	18	10	18
IM En Route Initiation	27	---	27	---
IM TRACON Initiation	90	90	87	73
Total	127	108	124	91

Table 4-4. Aircraft Participants Across Scenarios Types

IM initiation location	Aircraft role	Total aircraft
En route	**IM trail**	306
	Non-IM	418
TRACON	**IM trail**	1151
	Non-IM	1356
None (Baseline)	**Non-IM**	265
Total		3496

Table 4-5 summarizes the IM initiations for both the TRACON and en route scenarios. For IM TRACON initiation scenarios, 1203 total IM operations were proposed to the controllers. Of those, 2.7% (33 of 1203) IM proposals were rejected by the controllers and 1170 IM operations were issued. Of those, 1.6% (19) were not engaged due to the pseudo-pilot not properly engaging the operation or simulation technical issues[7]. Therefore, a total of 1151 (95.6%) IM operations were properly engaged and initiated. For the en route initiation scenarios, 306 IM operations were conducted. Table 4-5 summarizes the number of IM proposals, clearances, and initiations. Table 4-6 summarizes the IM operations by IM initiation point and clearance type. Table 4-7 summarizes the IM operations by controller tool set and clearance type. While there are different totals for the different clearance types and for the three controller tool set options, it is not believed to impact any feedback / results as both were frequently experienced.

[7] These aircraft flew the RNAV profile instead of IM.

Table 4-5. IM Initiation Sequence

	TRACON IM initiation			En route IM initiation	Total
	Both achieve-by	Capture then maintain	Combined		
IM proposals presented to the controller	924	279	1203	--	--
IM proposals issued by controller	894	276	1170	--	--
IM operation initiated and engaged / flown	882	269	1151	306	1457

Table 4-6. Frequency of IM Operations by IM Initiation Location and IM Clearance Type

	IM clearance type			
IM initiation location	Achieve-by (no maintain)	Achieve-by then maintain	Capture then maintain	Combined
TRACON	449	433	269	1151
En route	145	81	80	306
Combined	594	514	349	1457

Table 4-7. Frequency of IM Operations by Controller Tool Set and IM Clearance Type

	IM clearance type			
Controller tool set	Achieve-by (no maintain)	Achieve-by then maintain	Capture then maintain	Combined
Basic	134	147	87	368
Basic+ cue	153	157	95	405
Basic+ cue and prediction	146	145	87	378
Combined	433	449	269	1151

It should be noted that controllers sometimes had difficulty allowing aircraft to arrive in their planned sequence or to achieve a large interval[8] if they thought manual controller action would result in a more efficient operation. They preferred to shortcut the route and / or tighten the spacing between aircraft (which was the reason for most vectoring). However, this did not always lead to a better traffic situation, and sometime led to spacing issues.

[8] Large intervals were due to the initial sequence and spacing of arrival aircraft. The TBFM/TSAS schedule does not contain logic to speed an aircraft up above the profile speed to close a naturally occurring large gap.

4.2 Terminal Metering Only Operations (Baseline)

The baseline condition for the controllers was terminal metering operations without IM. The post-scenario results are presented in this section. The majority of controllers agreed with all statements regardless of role (Figure 4-7).

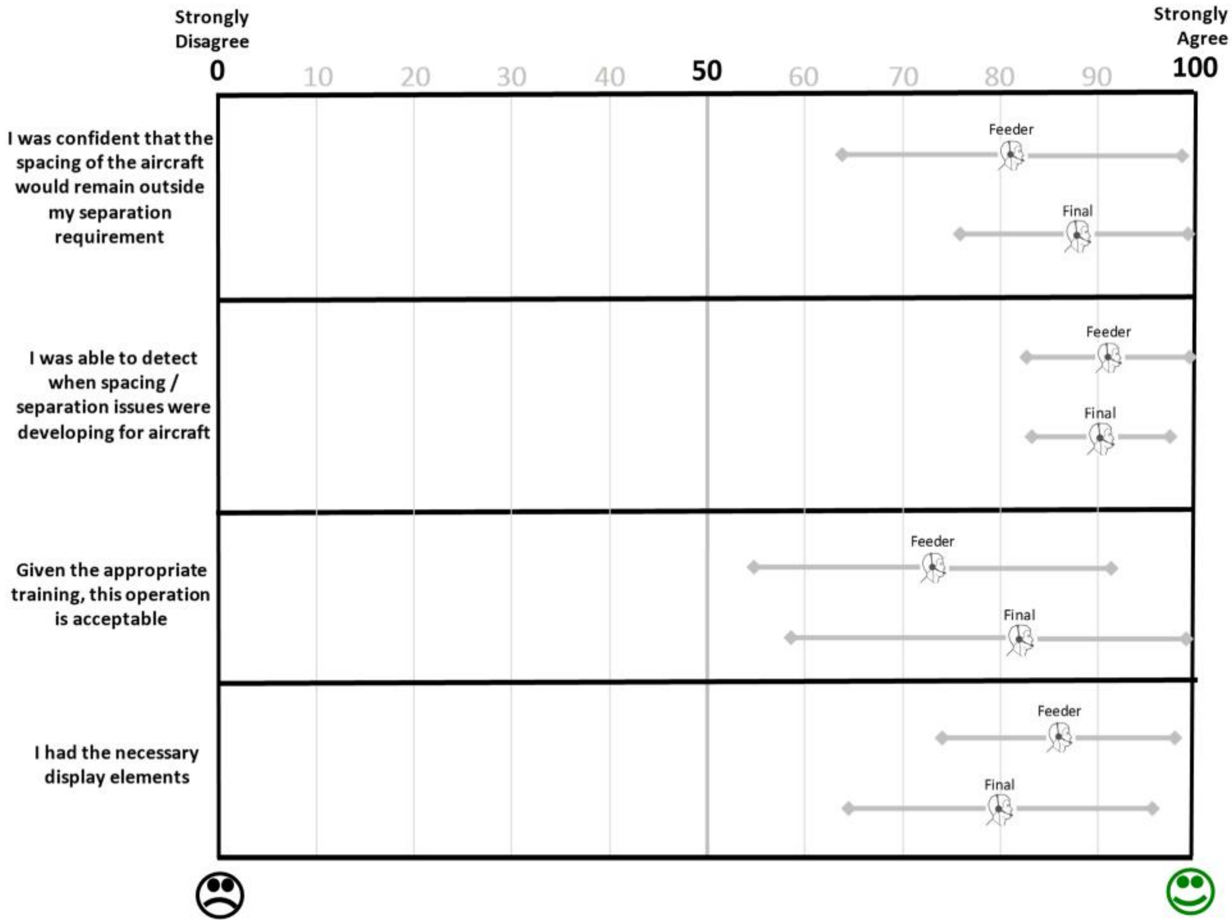

Figure 4-7. Controller Responses to Post-Scenario Statements on the Baseline Condition without IM

In the post-scenario questionnaire, controllers were asked to rate their average overall workload during the baseline on the Bedford Workload Rating Scale. The majority of controllers found workload to be acceptable for both roles (Figure 4-8).

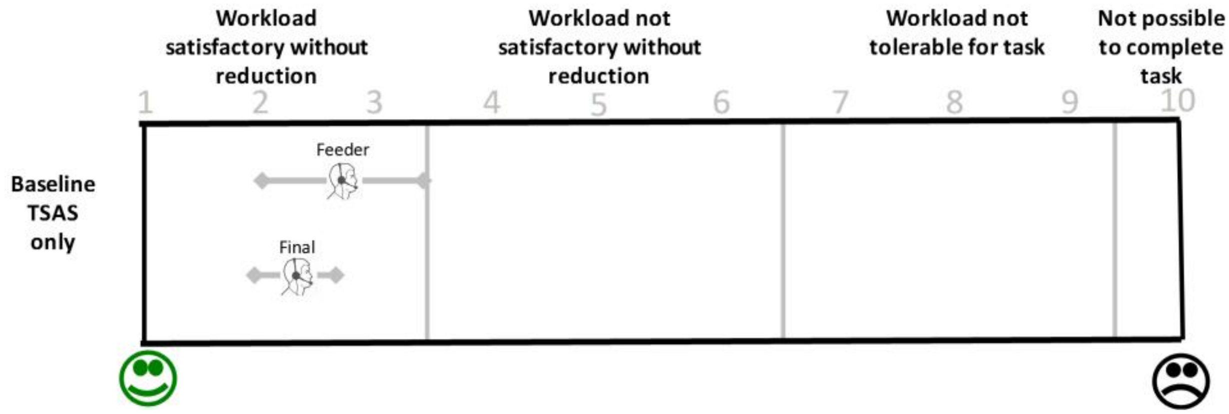

Figure 4-8. Controller Responses to the Bedford Workload Rating for the Baseline

In the post-scenario questionnaire, controllers were asked to rate their acceptability of the baseline with Controller Acceptance Rating Scale. The majority of controllers found IM operationally acceptable across the tool sets (Figure 4-9). Finally, there was one condition where an aircraft pair's spacing was below the applicable separation standard that occurred for unknown reasons and was not analyzed further.

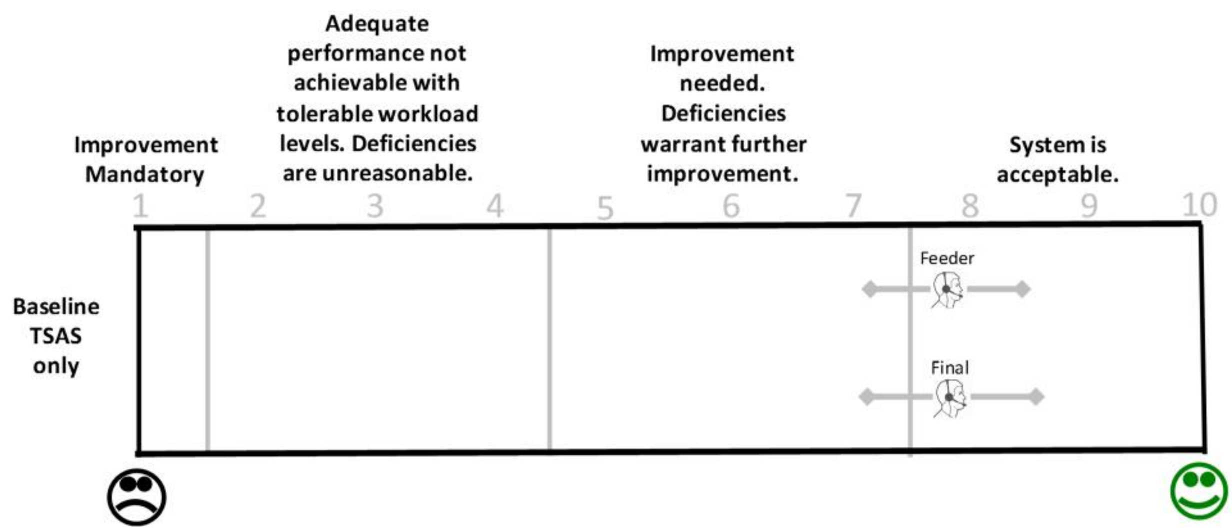

Figure 4-9. Controller Responses for Controller Acceptance Rating Scale for the Baseline

4.3 Integrated Ground Operations

While the focus of the simulation was the integration of IM into the terminal metering environment, it was desirable to understand all three operations that were new to the controllers: terminal metering, RNP RF turn operations, and IM. Therefore, controllers were asked to rank the three operations relative to one another from the most to least challenging. Figure 4-10 shows each operation and how often each appeared in each category. Figure 4-11 shows each operation and the relative ranking. RNP RF turns operations had the fewest "least challenging" rankings and appears to be the most challenging operation. Terminal metering had the fewest "most challenging" rankings. IM ranked between RNP RF turn and metering complexity.

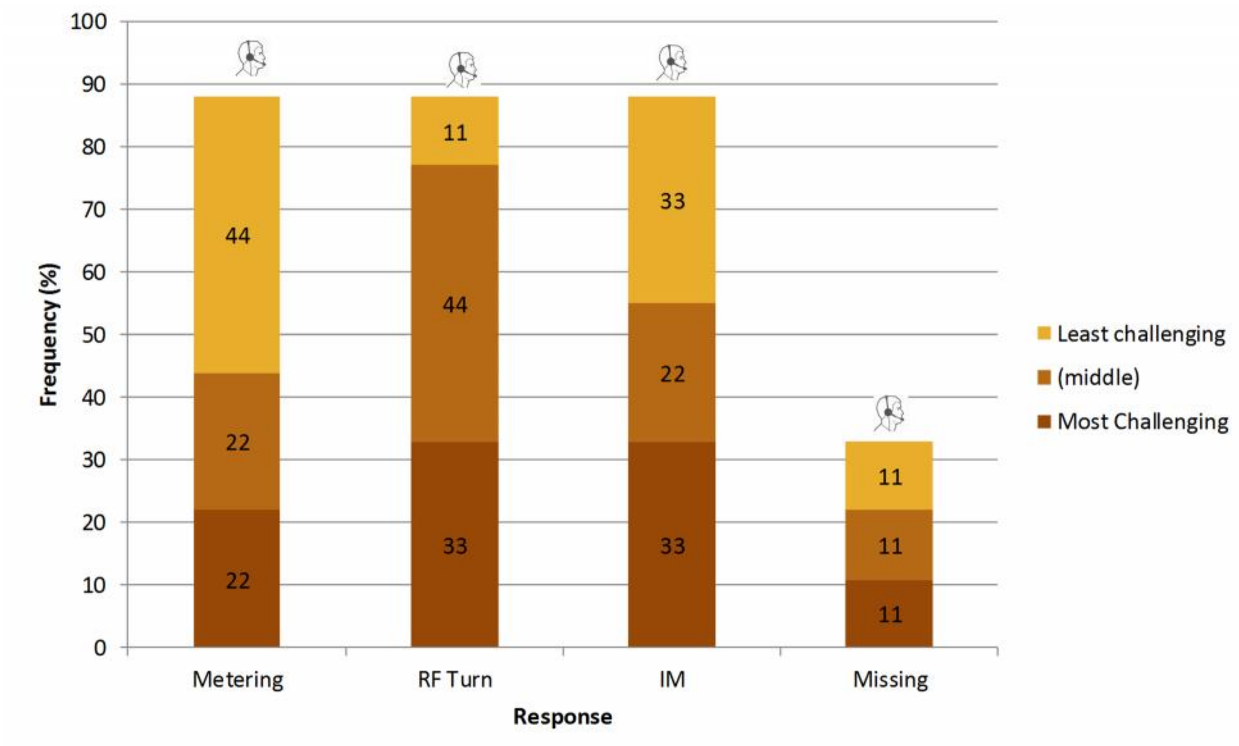

Figure 4-10. Controller Ranking of Operations. Frequency by Category

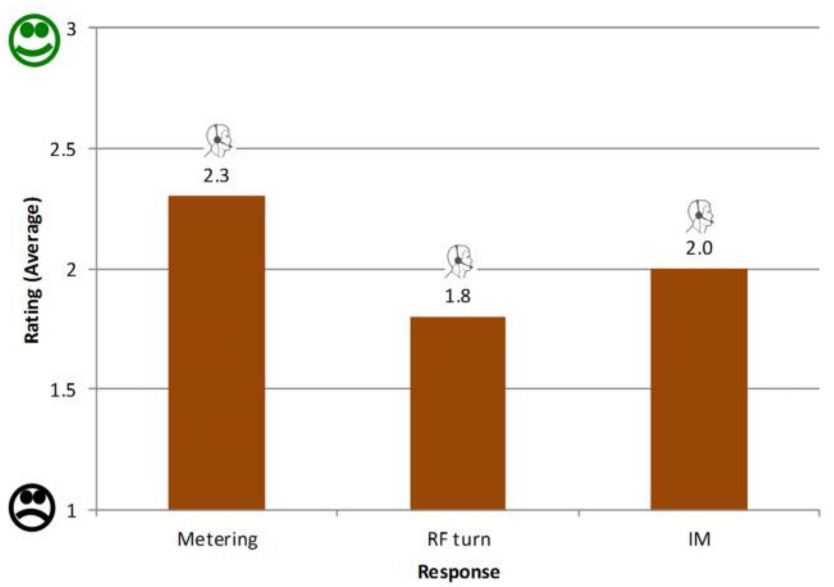

Figure 4-11. Controller Average Ranking of Operations Relative to One Another

Controllers were asked whether IM was compatible with terminal metering operations. The majority (8/9; 89%) agreed (M=69.9; SD=22.1) (Figure 4-12).

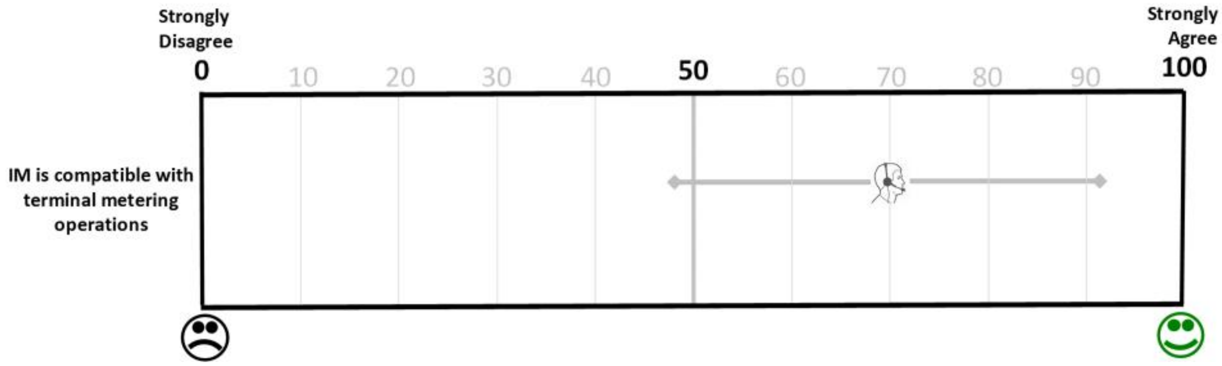

Figure 4-12. Controller Responses to "IM is compatible with terminal metering operations"

4.4 IM Operations Conduct

This section covers controller actions based on an IM clearance proposal as well as controller and participant flight crew actions related to IM once active.

4.4.1 IM Initiation

As described previously, a total of 1203 IM clearances were presented / proposed to controllers. Of the 1203 proposals, 97.2% (1170 of 1203) were initiated by controllers. Of initiated IM aircraft, 76.4% (894 of 1170) were achieve-by then maintain operations and 23.5% (276 of 1170) were capture then maintain operations. Table 4-8 shows the distribution of IM initiations by IM operation and condition.

Table 4-8. Frequency of IM Initiations as a Percentage of the Sample

	IM clearance type		
Controller tool set	**Both achieve-by**	**Capture then maintain**	**Combined**
Basic	76.2	23.8	32.0
Basic+ cue	76.0	24.0	35.2
Basic+ cue and prediction	77.1	22.9	32.8
Combined	76.4	23.6	100

Of the 1203 IM clearance proposals presented to the controller, thirty-three were rejected by the controller entering the keyboard command. Of the 33 rejections, thirty (2.5% of all initiations presented and 3.3% of all achieve-by clearances) were one of the achieve-by clearance type options and three (0.2% of all initiations presented and 1.0% of all capture then maintain clearances) were capture then maintain (Table 4-9). On average, controllers rejected IM clearances 116.7 sec (SD=132.6; Range= 20 – 703 seconds) after they were proposed. One controller accounted for 19 (58%) of the rejections.

Table 4-9. Frequency of IM Proposals Rejected

Controller tool set	IM clearance type		
	Both achieve-by	Capture then maintain	Combined
Basic	10	2	12
Basic+ cue	10	1	11
Basic+ cue and prediction	10	0	10
Combined	30	3	33

The reasons for the rejections were often not clearly articulated but some that were noted included simply not wanting to use IM or the ASG being too large (e.g., 232 seconds).

After excluding rejections, a total of 1170 IM operations were initiated by the controllers by entering the keyboard command. On average, controllers entered the keyboard command 30.6 seconds (SD=28.8) after an IM operation was proposed / displayed. Table 4-10 shows IM initiation delay by scenario and condition. Controllers were on average 11 seconds faster initiating IM for capture then maintain clearances (M=25.3; SD=22.7), as compared to both achieve-by clearance type options (M=35.9; SD=36.2). Initiation delay across the controller tool set were similar but the basic+ cue and prediction tool set was 4.3 seconds faster than the basic tool set.

Table 4-10. IM Initiation Delay in Mean Seconds (SD)

Controller tool set	IM clearance type		
	Both achieve-by	Capture then maintain	Combined
Basic	**38.5** (39.0)	**26.2** (25.4)	**32.4** (32.2)
Basic+ cue	**35.6** (34.3)	**27.0** (20.6)	**31.3** (27.5)
Basic+ cue and prediction	**33.8** (35.2)	**22.4** (18.5)	**28.1** (26.9)
Combined	**36.0** (36.2)	**25.2** (21.5)	**30.6** (28.8)

Of the total IM initiations then were engaged / flown, 74.1% (853 of 1151) occurred in the first segment of the BRUSR1 (between BRUSR and ANNTI) and EAGUL6 (between HOMMR and VNNOM) STARs. Figure 4-13 and Figure 4-14 show the IM initiation locations by IM clearance type[9]. As would be expected, the majority of the operations were engaged in the feeder controller's airspace. For both arrivals combined, more capture then maintain clearance (85.9%) initiations occurred earlier (i.e., in the first segment) than did the achieve-by clearance (70.5%) (Table 4-11).

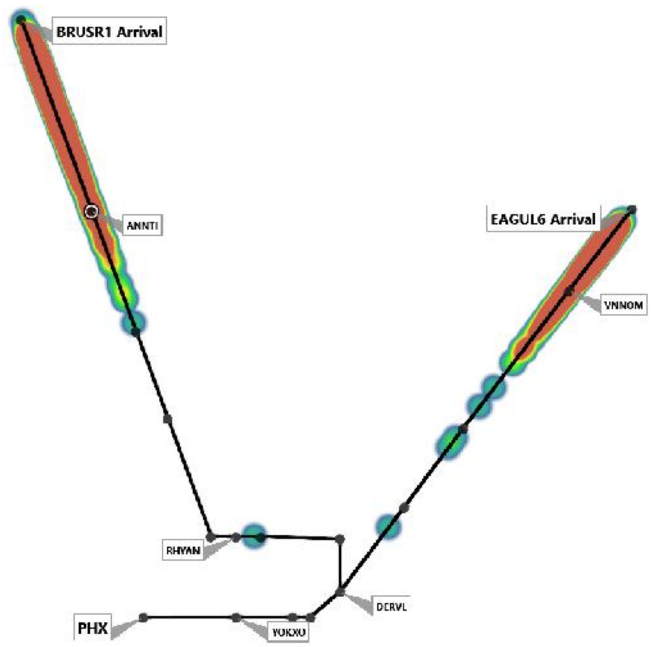

Figure 4-13. IM Initiation Locations for Both Achieve-by IM Clearance Types

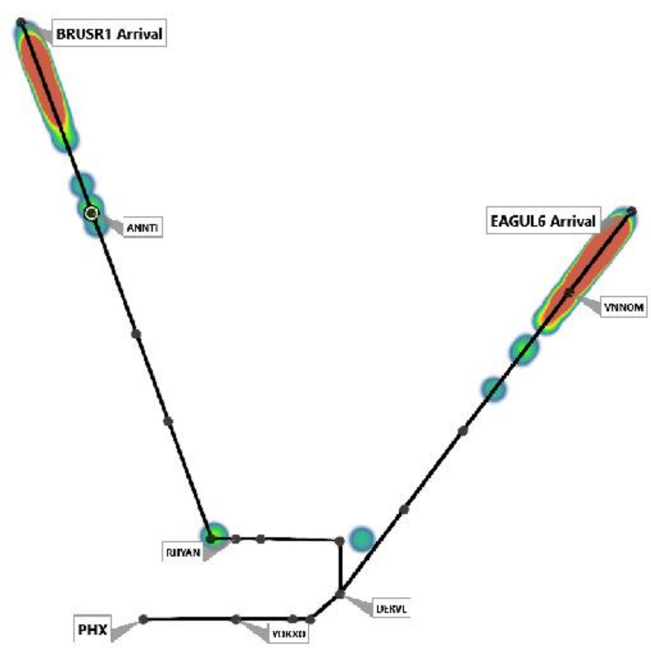

Figure 4-14. IM Initiation Locations for Capture then Maintain IM Clearance Type

9 The colors with longer wavelengths (e.g., reds) indicate more frequent events than the colors with shorter wavelengths (e.g., blues).

Table 4-11. IM Initiation Location as a Percentage of the Sample

Location	BRUSR1		EAGUL6		Combined	
	Both achieve-by	Capture then maintain	Both achieve-by	Capture then maintain	Both achieve-by	Capture then maintain
First segment	69.9	84.5	71.4	86.7	70.5	85.9
After first segment	30.1	15.5	28.6	13.3	29.5	14.1
Combined	82.9	17.1	69.7	30.3	76.6	23.4

4.4.2 IM Suspensions

Eight IM active operations were suspended (less than 1% [8 of 1151]). The locations of the suspensions are shown in Figure 4-15. The reasons for the suspension, and the action after the suspension, are shown in Table 4-12. Of the eight suspended IM operations, three later resumed, three never resumed,[10] and two were later terminated. Five of the eight (63%), were from one controller. The times to resume or terminate the IM operation are shown in Table 4-13.

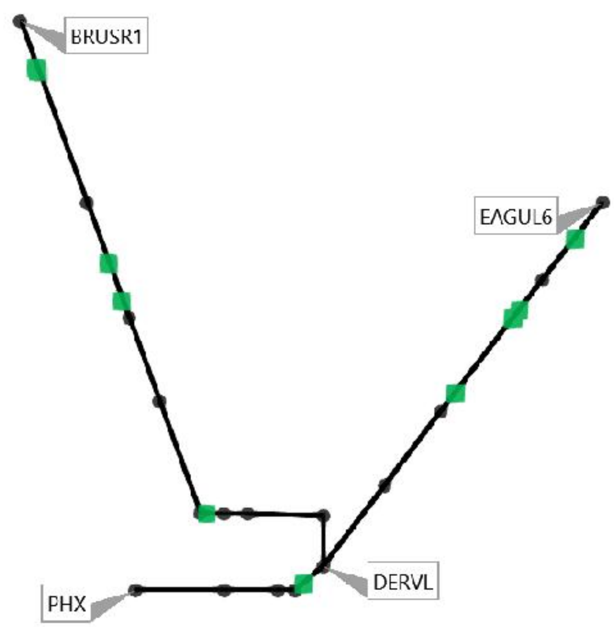

Figure 4-15. Location of Controller Suspensions

[10] These were cases were the controller entered a suspend command but never re-engaged. Therefore, while the controller entered the command for suspension, IM was terminated since it never resumed. The controller, however, did not enter the command for termination.

Table 4-12. Frequency of IM Suspensions by Suspension Reason and Subsequent Action

	Subsequent action			
Reason	Resumed	Not resumed	Terminated	Combined
Perceived potential to increase efficiency / spacing			2	2
Lead vectored	2			2
Spacing concern		2		2
Unknown	1	1		2
Total	3	3	2	8

Table 4-13. Mean Time to Resume or Terminate in Seconds (SD) after IM Suspension

Subsequent action	
Resumed (n = 3)	83.3 (59.1)
Terminated (n = 2)	91.0 (118.8)

4.4.3 Controller IM Terminations

Forty-eight terminations occurred accounting for 4.2% (48 of 1151) of the IM operations. Forty-four terminations were for pseudo-pilot aircraft and four were for flight deck participant aircraft. Table 4-14 shows the terminations by controller tool set. Percentages are based on the number of total operations conducted when that tool set was used. A higher number of terminations occurred for the basic+ cue and prediction tool set as compared to both other tool sets, with more (7) relative to the basic tool set. Figure 4-16 and Figure 4-17 show the IM termination locations by IM clearance type.

Table 4-14. Percentage (and Frequency) of IM Terminations

Controller tool set	Total
Basic	3.5 (13)
Basic+ cue	3.7 (15)
Basic+ cue and prediction	5.3 (20)
Combined	4.2 (48)

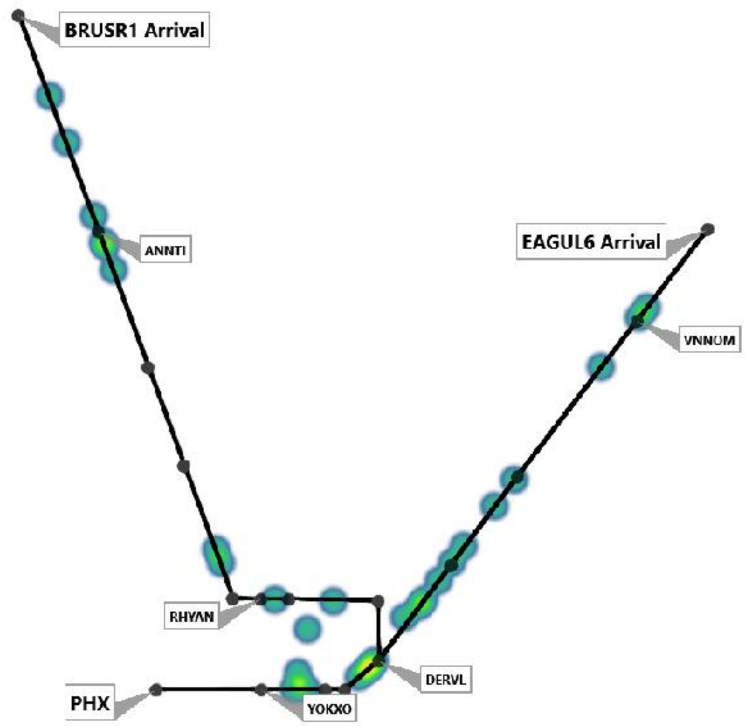

Figure 4-16. IM Termination Locations for Both Achieve-by IM Clearance Types

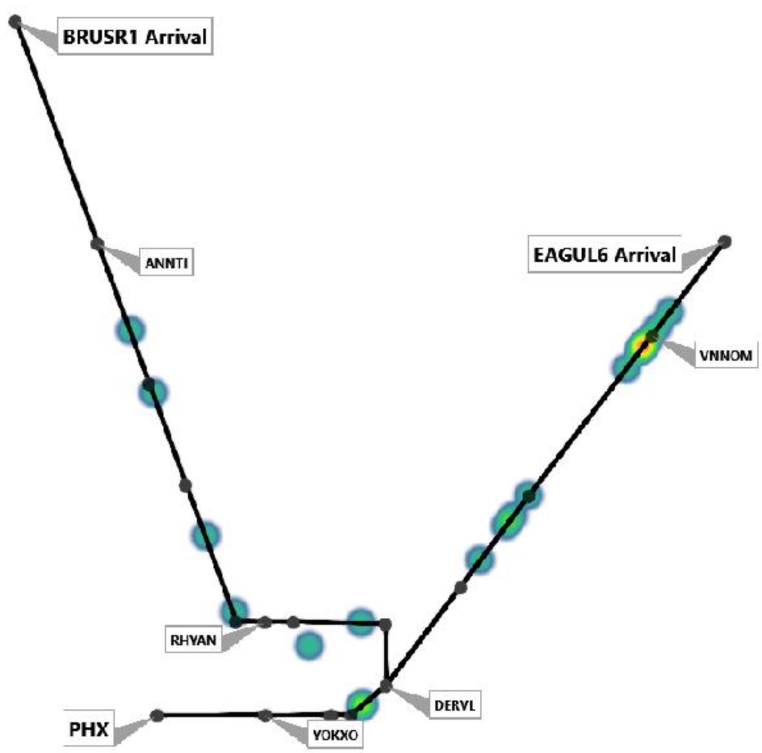

Figure 4-17. IM Termination Locations for Capture then Maintain IM Clearance Type

Of the 48 IM terminations, 60.4% (29 of 48) were achieve-by clearances and 39.6% (19 of 48) were capture operations (Table 4-15). However, 3.3% (29/882) of the terminations were from all the achieve-by clearances and 7.1% (19/269) were from all the capture then maintain clearances.

The majority (81.3%; 39 of 48) of terminations were terminated by ATC, followed by the pilot responding to the controller's termination instructions. Thirteen percent (6 of 48) of cases were where only the pseudo-pilot or flight crew terminated. In all six cases, the controller either gave a speed or told the flight crew to terminate IM, but neglected to make the keyboard entry. Finally, there were 6.3% (3 of 48) cases where only the controller made a keyboard entry to terminate and potentially issued a voice instruction. In all three cases, the pseudo-pilots appeared to have forgotten to terminate IM (but this did not appear to cause any spacing issues).

Table 4-15. Frequency of IM Termination Actions

Termination actions	IM clearance type		
	Both achieve-by	Capture then maintain	Combined
ATC termination entry only	3	0	3
ATC termination entry and pilot termination entry	22	17	39
Pilot termination entry only	4	2	6
Total	29	19	48

The mean time from initiation to termination is shown in Table 4-16. Clearances were terminated later for achieve-by clearance types (M = 298.7; SD = 190.3) as compared to the capture then maintain clearance types (M = 196.0; SD = 166.1) . The tool sets had similar times and variances, although the basic+ cue tool set had a lower variance than the others.

Table 4-16. Mean Time to Terminate after Initiation in Seconds (SD)

Controller tool set	IM clearance type		
	Both achieve-by	Capture then maintain	Combined
Basic	**303.1** (198.8)	**200.6** (203.1)	**251.9** (201.0)
Basic+ cue	**332.2** (183.1)	**147.3** (74.0)	**239.8** (128.6)
Basic+ cue and prediction	**260.8** (189.0)	**240.0** (221.1)	**250.4** (205.1)
Combined	**298.7** (190.3)	**196.0** (166.1)	**247.4** (178.2)

Table 4-17 shows the reasons for the IM terminations. These reasons were stated to the observer or noted in the post-scenario questionnaire by the controller (if they are in a category other than "unknown"). The "perceived potential to increase efficiency / spacing" category includes situations such as those where the controller thought the ASG was too large or that a lead or trail aircraft could be given a vector. It should be noted that some of the actions after the termination made the traffic situation more complex and created a worse spacing situation than if the original schedule and sequence had been utilized. However, in other situations it was possible to space an aircraft closer than the ASG that was provided by TBFM (e.g., 180 seconds)[11]. Approximately half (10 of 21; 48%) of the "perceived potential to increase efficiency / spacing" events could be attributed to one controller who vectored more frequently than other controllers.

Table 4-17. Frequencies for Reasons for Controller IM Termination

Reason	Total
Perceived potential to increase efficiency / spacing	21
Unknown	12
Spacing concern	10
RF turn concerns	2
Prefer not using IM	1
Forgot IM active	1
"Trying something"	1
Total	48

The "spacing concern" category includes situations where the controller noted an IM operation would create a problematic spacing situation (e.g., IM trail aircraft not slowing). The "RNP RF turn operation concern" were situations where the controller terminated IM based on a concern for spacing with an aircraft that was part of an RNP RF turn operation. The "prefer not using IM" was where a controller preferred to manually manage the speed of the aircraft. The "forgot IM active" was a situation where the controller issued a speed to an IM trail aircraft after forgetting the aircraft was flying IM. Observers noted other situations where this occurred, but the pilot reported doing IM and the controller chose not to terminate. Finally, the "'Trying something" category was where the controller stated either he wanted to try a maneuver to see how IM would react, or to see if an instruction would improve a situation.

[11] Large intervals were due to the initial sequence and spacing of arrival aircraft. The TBFM/TSAS schedule does not contain logic to speed an aircraft up above the profile speed to close up a naturally occurring large gap.

4.4.4 Flight Crew Reports of Unable

In addition to the controller terminations, there were five participant flight crew reports of unable[12]. Two were due to receiving an "ASG too large" message when trying to initiate IM (Table 4-18). Three were made by the flight crews based on the information provided by the IM display information.

Table 4-18. Frequencies and Reasons for Participant Flight Crew Reports of Unable IM

Flight crew tool set	Reason		
	"ASG too large" message	Display info indicated a need	Combined
Min	1	1	2
Min+	1	2	3
Combined	2	3	5

4.4.5 IM Speeds and Flight Crew Actions

This section reports data related to IM speed characteristics and participant flight crew / aircraft behavior relative to those IM speeds[13]. Flight crew participants flew the BRUSR1 arrival 33% (24 of 73) of the time and EAGUL6 arrival 67% (49 of 73) of the time. The BRUSR1 arrival from TRACON entry to touchdown was on average 14.2 minutes (SD=0.8) and the EAGUL6 arrival 11.5 minutes (SD=1.4) based on the length of flight path for each arrival. The PTP was always YOKXO. If the lead aircraft was not flying the RNP RF turn (45/73; 62%), the ABP was the merge point / DERVL. However, when the lead aircraft was flying the RNP RF turn (28/73; 38%), the ABP was at the FAF / YOKXO and there was no maintain stage.

[12] Pseudo-pilots did not have enough information to report unable, so none did so.
[13] As a reminder, the pilot participants only flew achieve-by then maintain IM type (no capture then maintain).

4.4.5.1 Frequency of IM Speed Changes

Table 4-19 shows the number of speeds received by participant flight crews. The average number of IM speeds is shown in Table 4-20. The average number of IM speeds is higher for the achieve-by stage based on the IM aircraft flying for a longer period of time in that stage (on the order of 7 minutes) while the average number of speeds for the maintain stage is less based on the shorter period of time in that stage (on the order of one minute).

Table 4-19. Total Frequency of IM Speeds

	Stage of achieve-by then maintain		
Flight crew tool set	**Achieve-by**	**Maintain**	**Combined**
Min	526	53	579
Min+	469	65	534
Combined	995	118	1113

Table 4-20. Average Number of IM Speeds (SD)

	Stage of achieve-by then maintain		
Flight crew tool set	**Achieve-by**	**Maintain**	**Combined**
Min	**14.2** (2.1)	**1.5** (2.5)	**15.7** (3.6)
Min+	13.0 (2.7)	2.1 (2.0)	15.1 (3.4)
Combined	**13.6** (2.4)	**1.8** (2.3)	**15.4** (3.5)

While the overall number of IM speeds is important, it may be more important to understand the rate of IM speeds. The rates are shown in Table 4-21. The rates were similar for the two tool sets. The rate of IM speeds per minute was higher with less variance for the achieve-by stage (M = 2.1; SD = 0.6) as compared to the maintain stage (M = 1.5; SD = 1.3). The rates for the stages and tool set are shown in Figure 4-18.

Table 4-21. Average Rate of IM Speeds (SD) per Minute

Flight crew tool set	Stage of achieve-by then maintain Achieve-by (n = 73)	 Maintain (n = 45)	 Combined (n = 73)
Min (n = 37)	**2.1** (0.4)	**1.7** (1.5)	**2.0** (0.4)
Min+ (n = 36)	**2.1** (0.7)	**1.2** (1.0)	**1.9** (0.5)
Combined (n = 73)	**2.1** (0.6)	**1.5** (1.3)	**2.0** (0.5)

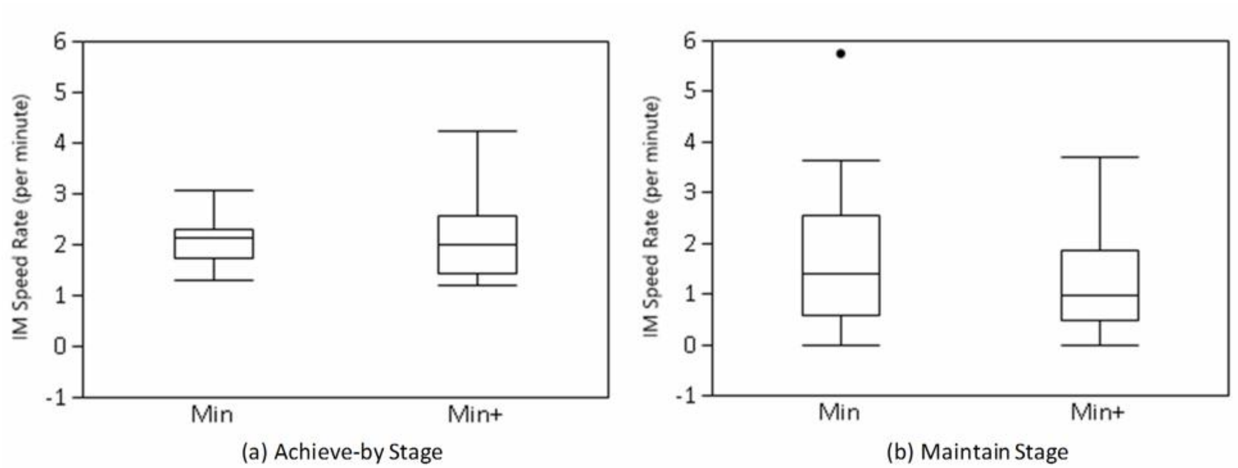

Figure 4-18. Average Rate of IM Speeds per Minute for (a) Achieve-by and (b) Maintain Stages

The distributions of the IM speeds are shown in Figure 4-19, Figure 4-20, and Figure 4-21 with shading to show density (wider shaded areas have more data points). As can be seen in the achieve-by stage figures, the speed are less frequent further out (e.g., 45 – 30 NM), then become more frequent (30 – 15 NM), and are most frequent close to the ABP. Figure 4-21 for the maintain stage, shows the IM speeds to be fairly evenly distributed across the entirety of the stage (note the different scale based on the maintain stage being conducted for a shorter amount of time).

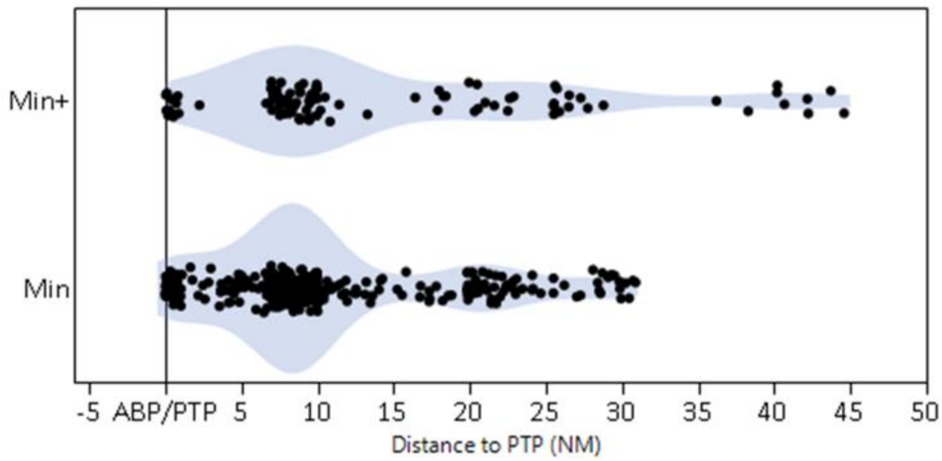

Figure 4-19. Distribution of IM Speeds for Achieve-by Stage with FAF / YOKXO as ABP

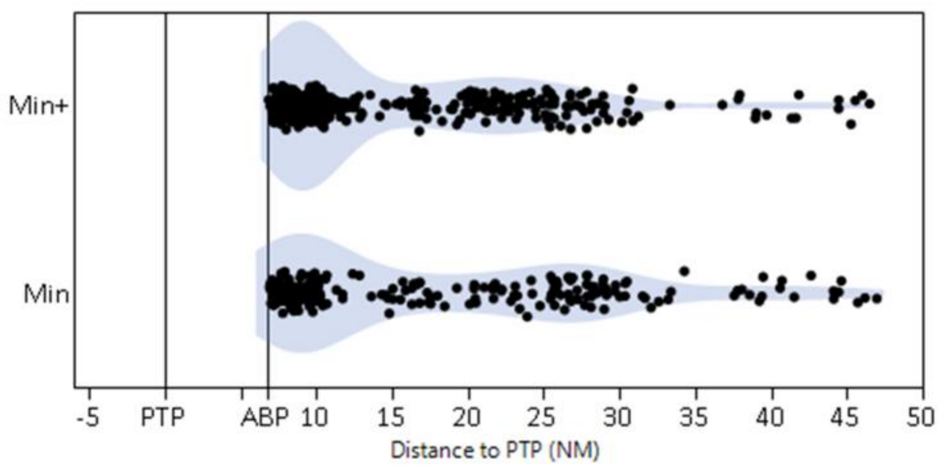

Figure 4-20. Distribution of IM Speeds for Achieve-by Stage with Merge / DERVL as ABP

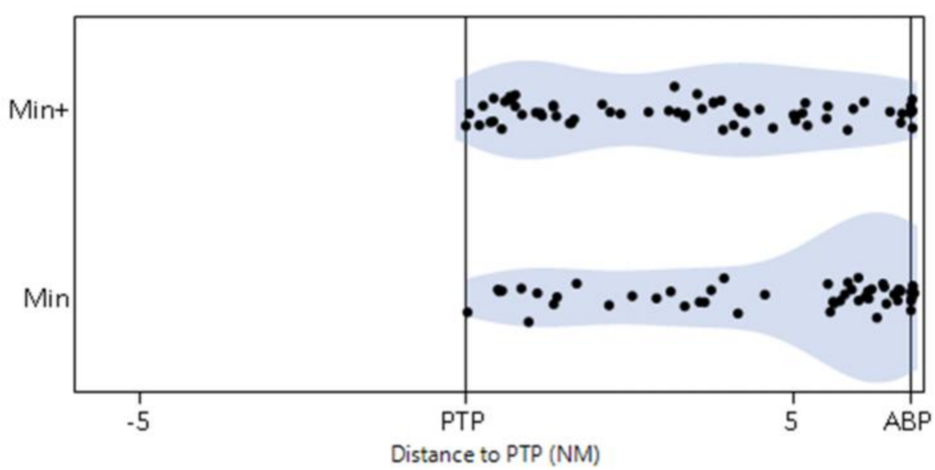

Figure 4-21. Distribution of IM Speeds for Maintain Stage

4.4.5.2 Magnitude of IM speeds

The average magnitude difference between IM speeds was 6.4 knots (SD=2.3) (Table 4-22). As noted in Section 3.1.2, the algorithm was designed to present the IM speeds in 10 kt increments when greater than 10 NM from the ABP, and in 5 kt increments when less than 10 NM from the ABP and when in the maintain stage. As would be expected then, the magnitude changes were higher for the achieve-by stage (M=6.6; SD=2.3) with 5 and 10-knot increments than the maintain stage (M=5.0; SD=0.0) with only 5-knot increments. The magnitude changes were similar for the two tool sets. Figure 4-22 shows the distribution of the speed changes and the transitions at 10 miles from the ABP for the two different ABPs. The 5 and 10-kt increment schedules can be clearly seen.

Table 4-22. Mean Speed Change Magnitude (SD) in Knots by Flight Crew Tool Set and Achieve-by then Maintain Stage

Flight crew tool set	Stage of achieve-by then maintain		
	Achieve-by	Maintain	Combined
Min	**6.6** (2.3)	**5.0** (0.0)	**6.5** (2.3)
Min+	**6.5** (2.3)	**5.0** (0.0)	**6.3** (2.2)
Combined	**6.6** (2.3)	**5.0** (0.0)	**6.4** (2.3)

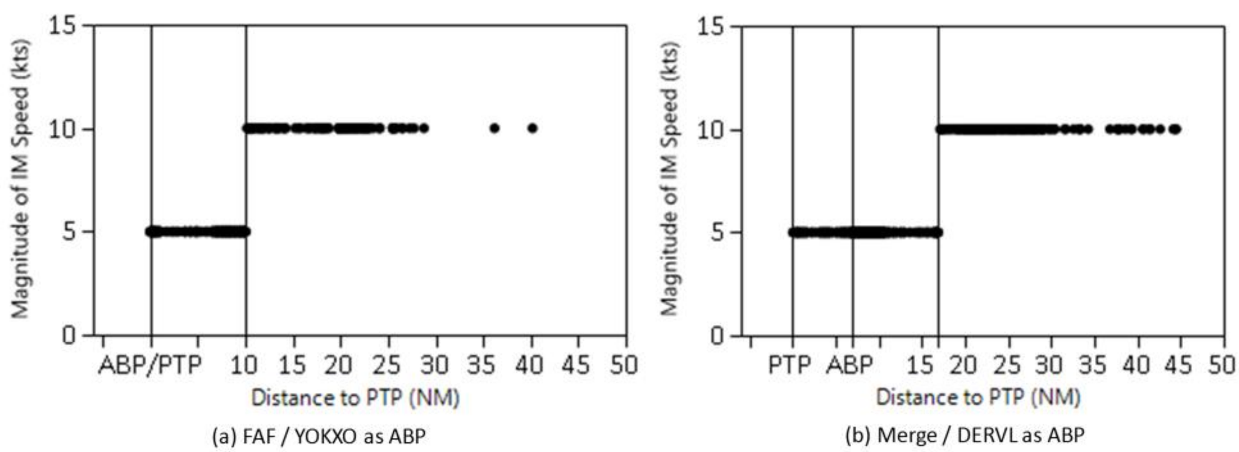

Figure 4-22. Distribution of IM Speed Change Magnitude with (a) FAF / YOKXO as ABP and (b) Merge / DERVL as ABP

4.4.5.3 IM Speed Reversals

Of the 1113 IM speed changes issued, 3% (31/1113) were speed reversals (i.e., the previous speed change was an increase followed by a decrease or vice versa). Of the 31 speed reversals, twenty-nine were a speed decrease followed by a speed increase. On average, 2% (24 of 1113) of IM speeds were speed reversals in the achieve stage of the IM operation and 0.6% (7/1113) in the maintain stage. However, when considering the percentage of speeds only associated with the stages, fewer speed reversals occurred with the achieve-by stage (24/995; 2.4%) as compared to the maintain stage (7/118; 5.9%) (Table 4-23). Additionally, fewer speed reversals occurred with the min+ tool set (31/534; 2.6%) as compared to the min tool set (17/579; 2.9%). Figure 4-23 and Figure 4-24 show the locations of the reversals for the tool sets and stages.

Table 4-23. Percentage of Speed Reversals

Flight crew tool set	Stage of achieve-by then maintain		
	Achieve-by (n =995)	**Maintain** (n=118)	**Combined** (n =1113)
Min (n = 579)	2.3	9.4	2.9
Min+ (n = 534)	2.6	3.1	2.6
Combined (n = 1113)	2.4	5.9	2.8

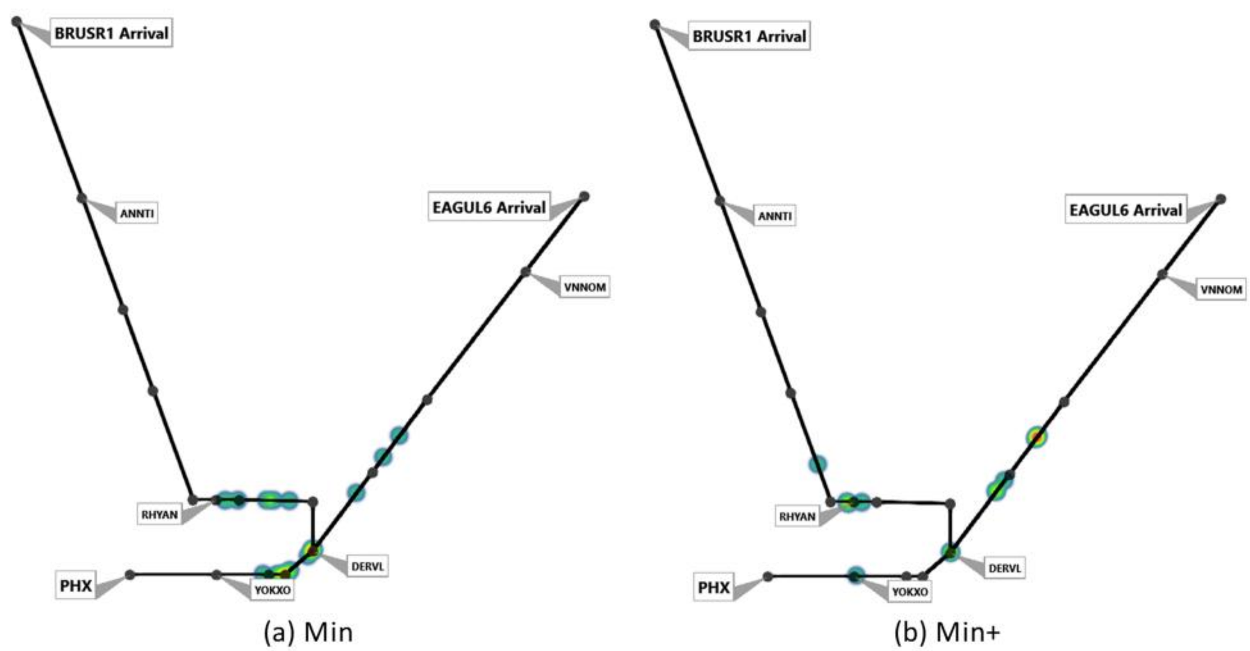

Figure 4-23. IM Speed Reversal Locations for (a) the Min and (b) the Min+ Tool Sets

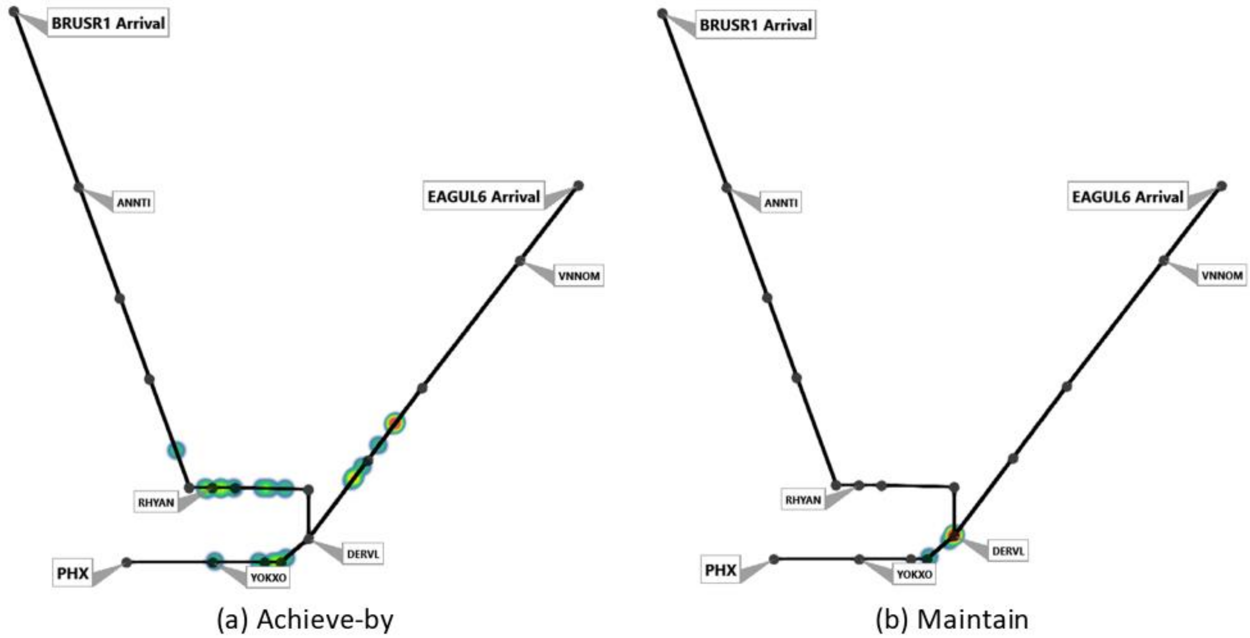

Figure 4-24. IM Speed Reversal Locations for (a) Achieve-by and (b) Maintain Stages

4.4.5.4 IM Speed Increases

Of the 1113 IM speeds changes, seventeen percent (194/1113) were speed increases and required acceleration (Table 4-24). When considering the percentage of speeds only associated with the stages, fewer speed increases occurred with achieve-by stage (150/995; 15.1%) as compared to maintain stage (44/118; 37.3%). Additionally, fewer speed increases occurred for the Min+ tool set (86/534; 16.1%) as compared to the min tool set (108/579; 18.7%)

Table 4-24. Percentage of Speed Increases

	Stage of achieve-by then maintain		
Flight crew tool set	**Achieve-by**	**Maintain**	**Combined**
Min	14.3	62.3	18.7
Min+	16.0	16.9	16.1
Combined	15.1	37.3	17.4

4.4.5.5 Time Between IM Speed Changes and DTG

On average, the time between IM speeds was 29.2 sec (SD=34.8) (Table 4-25). Most of the times between IM speeds were between 6 second (10^{th} percentile) and 87.9 second (90^{th} percentile). There was more time between IM speeds for the achieve-by stage (32.3) than for the maintain stage (26.1). There was also more time between speed changes for the min+ tool set (32.7) than there was for the min tool set (25.7).

Table 4-25. Mean Time in Seconds (SD) Between IM Speeds

	Stage of achieve-by then maintain		
Flight crew tool set	**Achieve-by**	**Maintain**	**Combined**
Min	**31.5** (38.7)	**19.9** (28.2)	**25.7** (33.5)
Min+	**33.1** (45.1)	**32.3** (27.3)	**32.7** (36.2)
Combined	**32.3** (41.9)	**26.1** (27.8)	**29.2** (34.8)

Most IM speed changes occurred between 3.6 NM (10 percentile) and 27.4 NM (90 percentile) from the PTP. Figure 4-25 and Figure 4-26 show the relationship between the time between IM speeds and the distance to the ABP and PTP. The dots show specific events and the blue line is a curved of best fit. The bars on top and right side of the graph show frequencies of events for distance to the PTP (top) and time between IM speeds (right).

Figure 4-25 shows that relationship when the participant flight crew flew the achieve-by IM clearance with YOKXO as the ABP (and PTP). Figure 4-26 shows that relationship when the participant flight crew flew the achieve-by then maintain IM clearance with DERVL as the ABP (and YOKXO as the PTP). As can be seen in both figures, IM speeds were generally closer together and occurred more often when close to the ABP. The speeds were closest in time and most frequent when the aircraft was about 10 miles to the ABP for the achieve-by IM clearance and about 5 miles from the ABP for the achieve-by then maintain IM clearance.

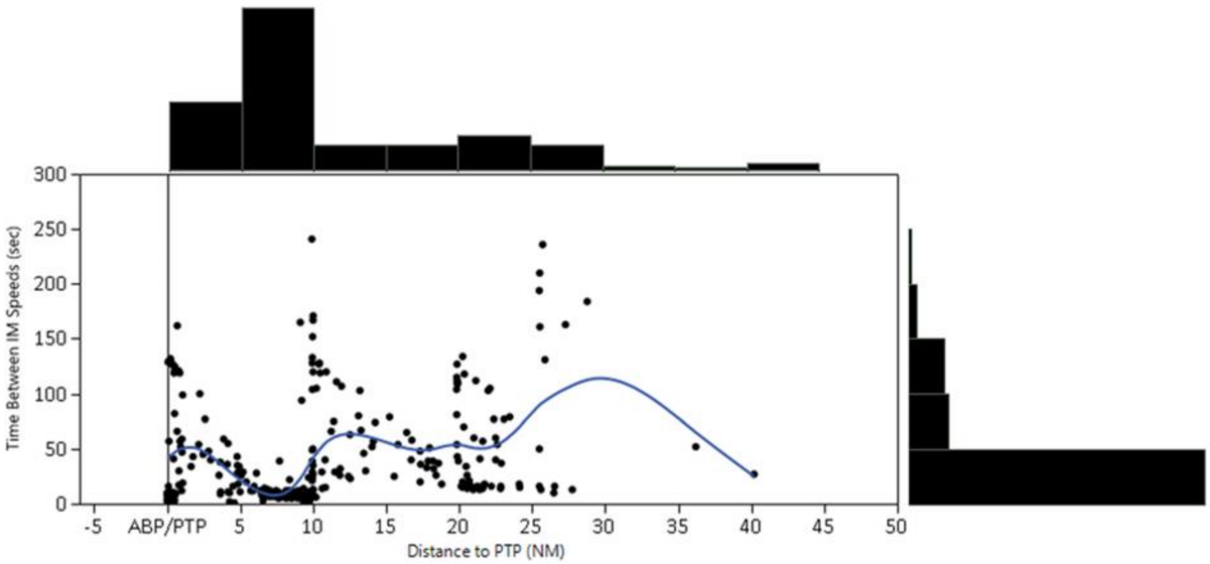

Figure 4-25. Scatterplot of Time Between IM Speeds and Distance to the PTP with FAF / YOKXO as ABP (Achieve-by Clearance Type)

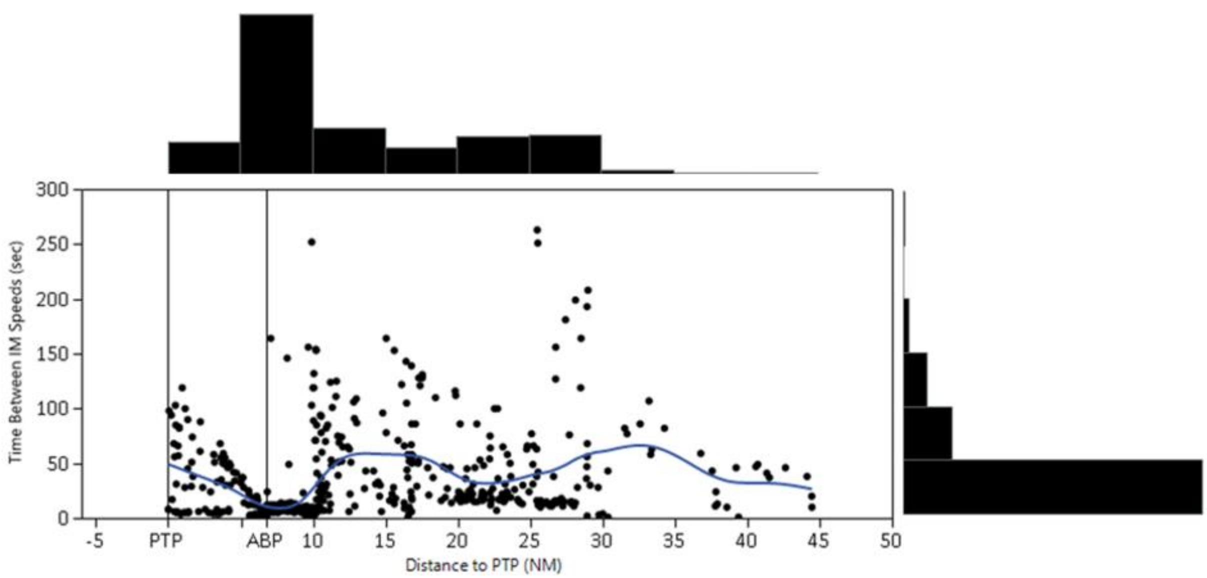

Figure 4-26. Scatterplot of Time between IM Speeds and Distance to the PTP with Merge / DERVL as ABP (Achieve-by then Maintain Clearance Type)

4.4.5.6 Compliance with IM Speeds

Compliance with IM speeds is defined as the participant flight crew dialing in the IM speed in the MCP speed window. For the simulation, the flight crew was considered to be in compliance with the IM speed if the speed set in the MCP speed window was within 2 kts of the IM speed[14].

As shown in Table 4-26, flight crews complied with more IM speeds when in the achieve-by stage (76.6%) than when in the maintain stage (70.3%) and with the min+ tool set (79.2%) than the min tool set (72.9%). However, the statistical test noted in Section 4.1.3.2, did not reveal a statistically significant difference between the two tool sets.

When flight crews complied with IM speeds, the IM speeds had been presented for a longer period of time (M=40.6; SD=41.4) (Table 4-27 and Figure 4-27). When flight crews did not comply with IM speeds, the IM speeds had been presented for a shorter period of time (M=7.9; SD=10.2).

Table 4-26. Percentage of IM Speed Compliance

	Stage of achieve-by then maintain		
Flight crew tool set	**Achieve-by**	**Maintain**	**Combined**
Min	74.1	60.4	72.9
Min+	79.3	78.5	79.2
Combined	76.6	70.3	75.9

Table 4-27. Mean Duration (SD) of IM Speed Presentation Time (in Seconds) as Related to Compliance

	Stage of achieve-by then maintain					
	Achieve-by		Maintain		Combined	
Flight crew tool set	**Complied**	**Not complied**	**Complied**	**Not complied**	**Complied**	**Not complied**
Min	**34.1** (39.1)	**8.5** (8.4)	**45.5** (40.6)	**8.4** (21.1)	**39.8** (39.9)	**8.5** (14.8)
Min+	**38.1** (48.7)	**8.1** (4.7)	**44.6** (37.0)	**6.7** (6.5)	**41.4** (42.9)	**7.4** (5.6)
Combined	**36.1** (43.9)	**8.3** (6.6)	**45.1** (38.8)	**7.6** (13.8)	**40.6** (41.4)	**7.9** (10.2)

[14] The MCP speed knob in the flight deck simulator sometimes made it difficult to dial in the speed to the exact kt, so some latitude was allowed.

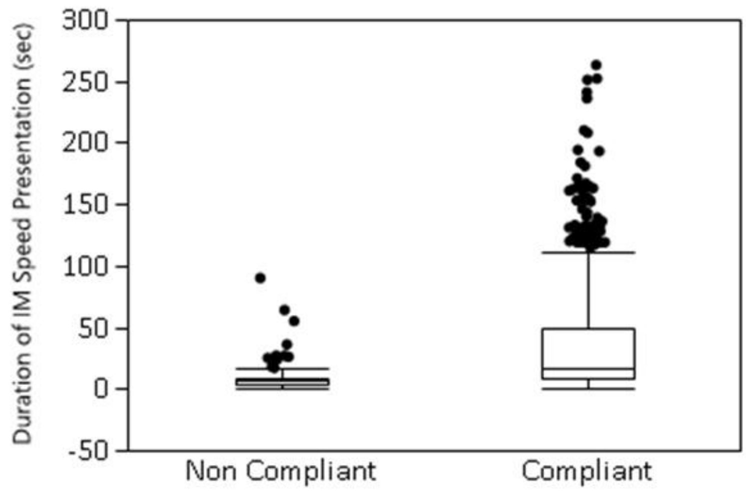

Figure 4-27. Mean Duration of IM Speed Presentation Time as Related to Compliance

4.4.5.7 IM Speed Conformance Monitoring Advisory

Out of 73 runs, thirty-eight (52%) had at least one IM speed conformance monitoring advisory. There were a total of 160 advisories accounting for 14% (160 of 1113) of IM speeds. The 160 advisories were associated with 119 IM speeds: 86 (72.3%) were for one IM speed and 33 (27.7%) were for the same IM speed[15].

For all advisories, fewer occurred with the min+ tool set (61/534; 11.4%) as compared to the min tool set (99/579; 17.1%) (Table 4-28). Figure 4-28 shows the location of the advisories for the individual tool sets. Additionally, fewer advisories occurred with the achieve-by stage (136/995; 13.7%) as compared to the maintain stage (24/118; 20.3%). Figure 4-29 shows the location of the advisories for the stages of the achieve-by then maintain clearance type.

Table 4-28. Percentage of IM Speed Conformance Monitoring Advisories

	Stage of achieve-by then maintain		
Flight crew tool set	**Achieve-by**	**Maintain**	**Combined**
Min	16.9	18.9	17.1
Min+	10.0	21.5	11.4
Combined	13.7	20.3	14.4

[15] As noted previously, the implementation for this simulation allowed for multiple alerts for one IM speed. This is not required / specified in DO-361 (RTCA, 2015a).

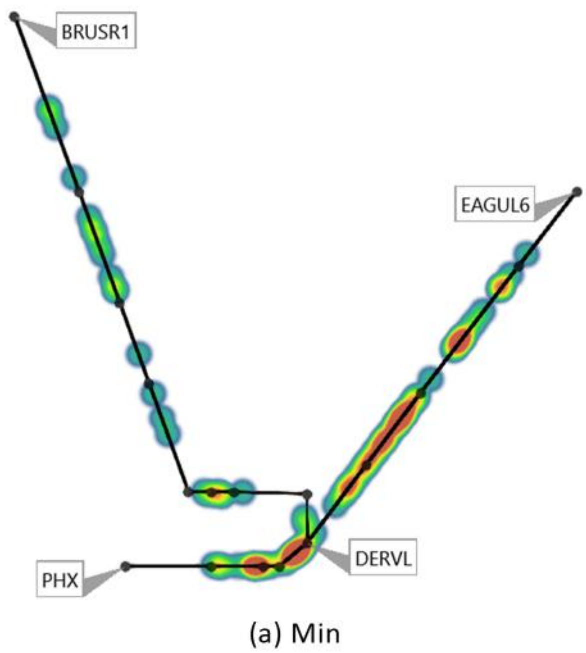

Figure 4-28. IM Speed Conformance Monitoring Advisory Locations for the (a) Min Tool Set and (b) Min+ Tool Set

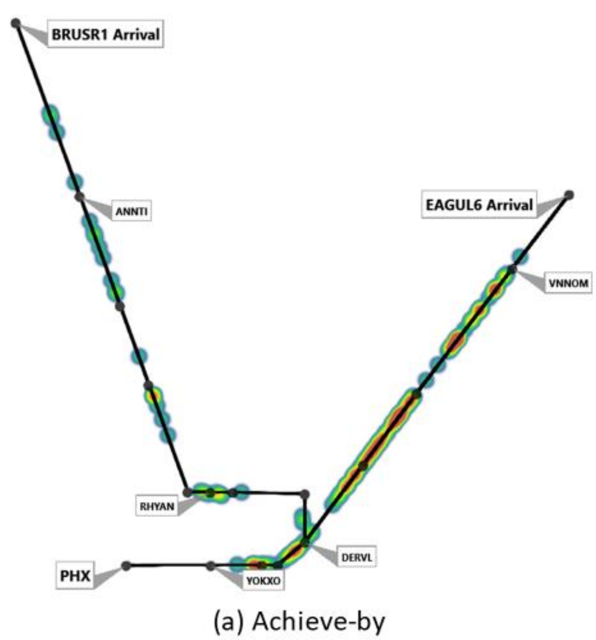

Figure 4-29. IM Speed Conformance Monitoring Advisory Locations for the (a) Achieve-by and (b) Maintain Stages of the Achieve-by then Maintain Clearance Type

Of the 160 advisories, 67 (41.9%) were inside the MOPS no advisory threshold (i.e., should not have been triggered) and 93 (58.1%) were outside the MOPS no advisory threshold[16]. As seen for all advisories combined, fewer advisories occurred with the min+ tool set (18/534; 3.4%) as compared to the min tool set (49/579; 8.5%) when the alert should not have been triggered (Table 4-29). Additionally, fewer advisories occurred with the min+ tool set (43/534; 8.1%) as compared to the min tool set (50/579; 8.6%), but the difference is greatly reduced when the alert should have been triggered (Table 4-30).

The average number of advisories for the achieve-by stage (60/995; 6.0%) are very similar to the maintain stage (7/118; 5.9%) when the alert should not have been triggered. However, fewer advisories occurred with the achieve-by stage (77/995; 7.7%) as compared to the maintain stage (16/118; 13.6%) when the alert should have been triggered.

Table 4-29. Percentage of IM Speed Conformance Monitoring Advisories Inside the MOPS No Advisory Threshold (Should Not have been Triggered per DO-316 [RTCA, 2015a])

	Stage of achieve-by then maintain		
Flight crew tool set	Achieve-by	Maintain	Combined
Min	8.9	3.8	8.5
Min+	2.8	7.7	3.4
Combined	6.0	5.9	6.0

Table 4-30. Percentage of IM Speed Conformance Monitoring Advisories Outside the MOPS No Advisory Threshold (Should have been Triggered per DO-316 [RTCA, 2015a])

	Stage of achieve-by then maintain		
Flight crew tool set	Achieve-by	Maintain	Combined
Min	8.2	13.2	8.6
Min+	7.2	13.8	8.1
Combined	7.7	13.6	8.4

4.5 Aircraft Spacing and Separation

This section reports data related to aircraft spacing and separation. It includes both pseudo-pilot and participant flight crew aircraft[17]. Measures in this section indicate how well the IM aircraft achieved or maintained the ASG, and also how well aircraft conformed to the underlying schedule and the associated slot markers. A detailed analysis of each of these measures is not conducted in this paper. The main purpose of reviewing these measures is to compare how IM aircraft behaved relative to non-IM aircraft and whether they generally behaved the same.

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[16] As noted previously, the implementation for this simulation alerted more often than specified in DO-361 (RTCA, 2015a).

[17] The participant flight crews only flew the achieve-by then maintain IM clearance (i.e., no capture then maintain). Pseudo-pilot aircraft flew all clearances.

4.5.1 Schedule Conformance

Schedule conformance measures how well aircraft met the original schedule at the various constraint points (including the ABPs and PTP for IM). The measure, termed schedule deviation, is the difference between the STA and the ATA of an aircraft.

Table 4-31 and Figure 4-30 show the schedule deviation at the constraint points. The first two data columns are the meter fixes. IM aircraft were not included at these points because it was difficult to determine whether or not aircraft had started IM. The non-IM aircraft are representative of the spacing of IM aircraft upon entering the TRACON. Aircraft, on average, reached the meter fix ahead of schedule (by design, as described in Section 3.1.6).

At the merge / DERVL, IM aircraft (M= -2.4; SD=11.9) had more schedule deviation and slightly more variance as compared to non-IM aircraft (M=0.0; SD=10.4). At the FAF / YOKXO, IM aircraft (M= -7.1; SD=10.9) had more schedule deviation and about the same variance as compared to non-IM aircraft (M= -4.9; SD=11.2).

At the merge / DERVL, IM aircraft had a mean deviation from schedule of less than 6 seconds and similar variances but the achieve-by type (M= -5.3; SD=12.1), had more schedule deviation than the achieve-by then maintain (M= -1.1; SD=12.1) or the capture then maintain (M= -2.3; SD=10.9). At the FAF / YOKXO, all IM aircraft terminated IM. IM aircraft had a mean deviation from schedule within 1 second of each other and similar variances.

All aircraft were ahead of schedule, on average, at YOKXO (the FAF).

Table 4-31. Schedule Deviation in Seconds (SD) at Constraint Points

Aircraft role - IM clearance type	Constraint point				
	BRUSR (BRUSR1 meter fix)	HOMRR (EAGUL6 meter fix)	DERVL (merge)	RHYAN (RNP RF turn)	YOKXO (FAF)
IM trail - Achieve-by	--	--	**-5.3** (12.1)	**-0.3** (9.6)	**-6.5** (10.1) **ABP & PTP**
IM trail - Achieve-by then maintain	--	--	**-1.1** (12.1) **ABP**	**-4.4** (15.2)	**-7.5** (12.0) **PTP**
IM trail – Capture then maintain	--	--	**-2.3** (10.9)	**-2.0** (11.4)	**-7.1** (10.3) **PTP**
IM trail - Combined	--	--	**-2.4** (11.9)	**-2.4** (12.7)	**-7.1** (10.9)
Non-IM	**-8.8** (17.6)	**-3.3** (21.0)	**0.0** (10.4)	**-1.7** (9.1)	**-4.9** (11.2)

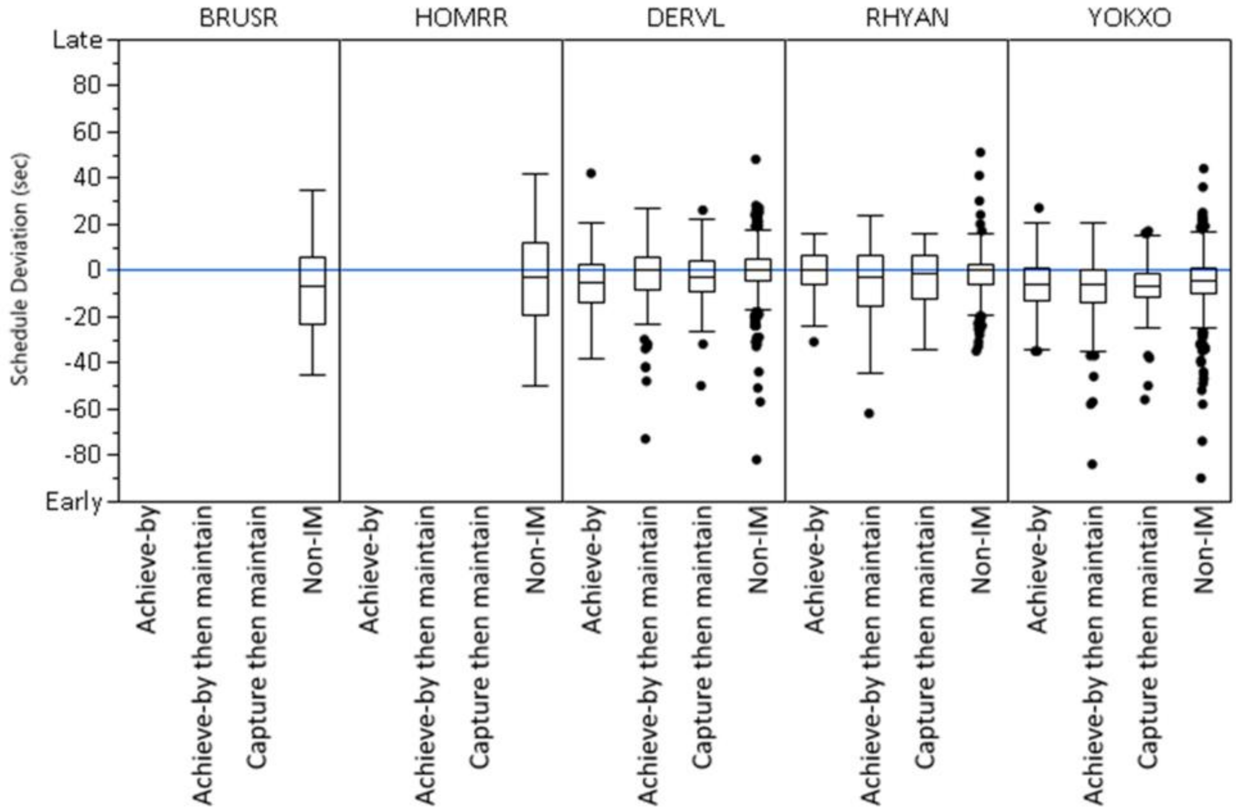

Figure 4-30. Schedule Deviation at Constraint Points

4.5.2 Aircraft Position as Related to Slot Markers

This section provides information on how each aircraft deviated from the center of the slot markers (Section 4.5.2.1 Absolute Slot Marker Deviation), the amount of time aircraft were in their slot markers (Section 4.5.2.2 Aircraft Time in Slot Markers), and the difference between the deviation from the center of the slot marker for a trail aircraft as compared to its lead aircraft (Section 4.5.2.3 Relative Slot Marker Deviation).

4.5.2.1 Absolute Slot Marker Deviation

The absolute slot marker deviation metric shows how close an individual aircraft was to the center of its slot marker. A positive value indicates the aircraft was (behind schedule and) behind the center of the slot marker. A negative value indicates the aircraft was (ahead of schedule and) ahead of the center of the slot marker. A zero value indicates the aircraft was centered in its slot marker (see Appendix D for examples).

Aircraft were delivered from en route into feeder airspace with a distribution around the slot markers. The feeder controller was expected to work to get non-IM aircraft on schedule / into their slot markers before handing off to the final controller. IM aircraft were working toward achieving or maintaining the ASG, regardless of slot marker position. The final controller received the aircraft and was expected to get non-IM aircraft on schedule / into their slot markers (until around the final approach path where the controller is likely more concerned about the relative spacing between aircraft than the schedule).

Table 4-32 shows both time and distance (shaded gray) for deviations from the center of the slot marker by overall time in feeder and final airspace and at the handoff from final to feeder. Distance is included for a general reference, while time is discussed for the results. Figure 4-31, Figure 4-32, and Figure 4-33 show the distributions of the time deviation. Lines are shown in these figures for the slot marker radius for the feeder (15 seconds) and the final (5 seconds) controllers.

Table 4-32. Aircraft Slot Marker Center Deviation in Mean Seconds (SD) and NM (SD)

	Aircraft role – IM clearance type							
	IM trail - Both achieve-by		IM trail - Capture then maintain		IM trail - Combined		Non-IM	
Airspace location	**sec**	**NM**	**sec**	**NM**	**sec**	**NM**	**sec**	**NM**
Feeder	**-15.7** (20.0)	-1.2 (1.6)	**-12.5** (16.4)	-1.0 (1.3)	**-14.1** (18.2)	-1.1 (1.5)	**-14.6** (13.5)	-1.1 (1.1)
Handoff to final	**2.0** (6.4)	0.2 (0.5)	**1.8** (5.5)	0.2 (0.4)	**1.9** (6.0)	0.2 (0.5)	**0.1** (4.7)	0.0 (0.4)
Final	**-13.6** (12.8)	-0.8 (0.8)	**-12.2** (12.4)	-0.7 (0.8)	**-12.9** (12.6)	-0.8 (0.8)	**-11.1** (9.3)	-0.7 (0.6)

IM (M= -14.1; SD=18.2) and non-IM aircraft (M= -14.6; SD=13.5) had similar deviations ahead of the slot marker center in the feeder's airspace. At the handoff, the IM aircraft (M=1.9; SD=6.0) were further behind schedule and further behind the slot marker center as compared to the non-IM aircraft (M=0.1; SD=4.7). In final controller's airspace, IM (M= -12.9; SD=12.6) and non-IM aircraft (M= -11.1; SD=9.3) had similar deviations from the slot marker center and were ahead of schedule.

In the feeder's airspace, aircraft with the achieve-by clearance types (M= -15.7; SD=20.0) were further behind the slot marker center as compared to aircraft with the capture then maintain clearance type (M= -12.5; SD=16.4). At the handoff, aircraft with the achieve-by clearance types (M=2.0; SD=6.4) and aircraft with capture then maintain clearance type (M=1.8; SD=5.5) had similar deviations behind the slot marker center. In the final controller's airspace, aircraft with the achieve-by clearance types (M= -13.6; SD=12.8) and aircraft with capture then maintain clearance type (M= -12.2; SD=12.4) had similar deviations ahead of the slot marker center.

The general trend appears to be that all aircraft in the feeder airspace were ahead of schedule, on average. This is, in part, based on the distribution of aircraft around the slot marker center when received from en route airspace as more aircraft were delivered ahead of schedule (as described in Section 3.1.6). Then, all aircraft were delivered by the feeder to final controller on average within 2 seconds of their slot marker centers. In the final controller's airspace, all aircraft were, on average, ahead of the slot marker centers. Most differences between IM and non-IM aircraft, and the two IM clearance types, were minor.

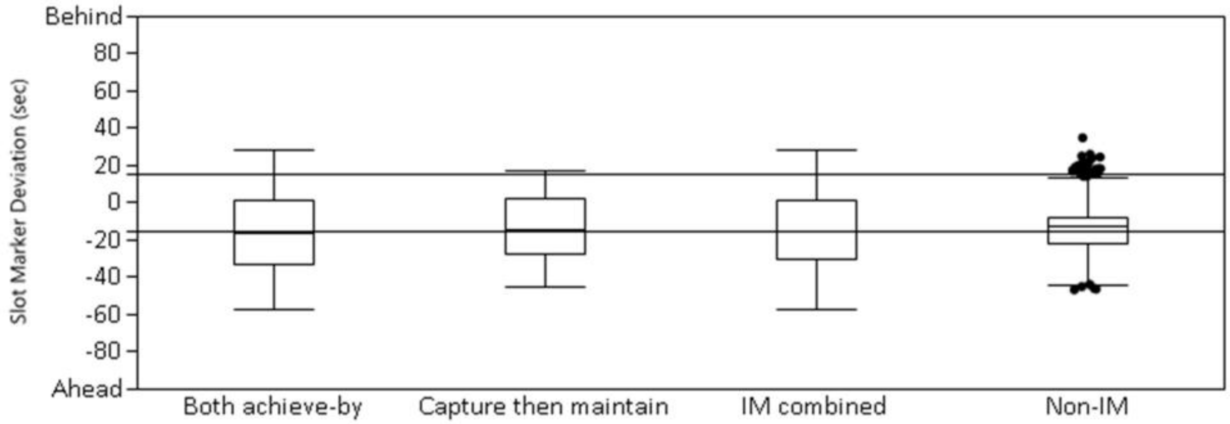

Figure 4-31. Aircraft Slot Marker Center Deviation in Mean Seconds for Feeder Controller Airspace

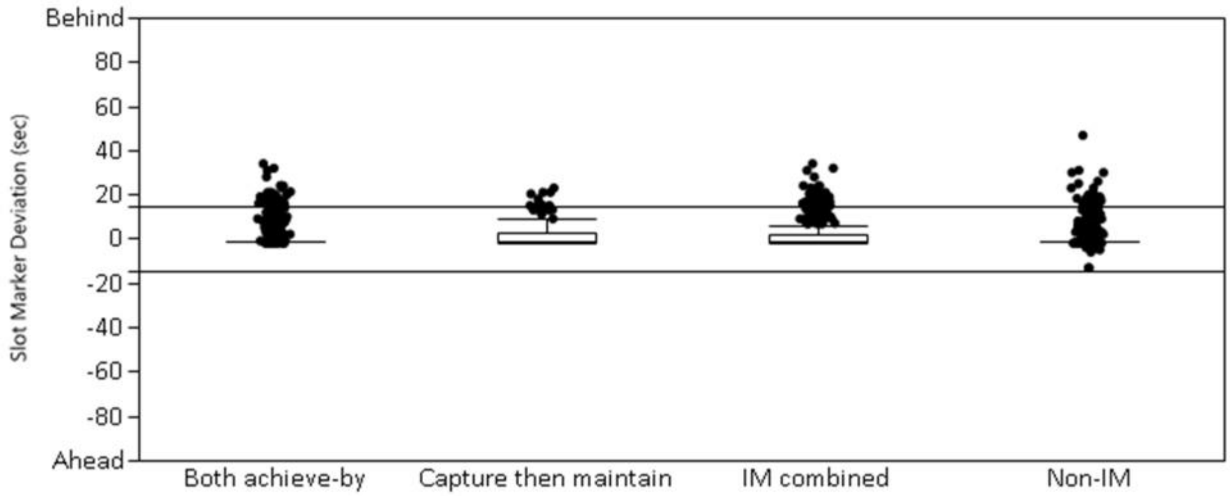

Figure 4-32. Aircraft Slot Marker Center Deviation in Mean Seconds at Handoff from Feeder to Final Controller

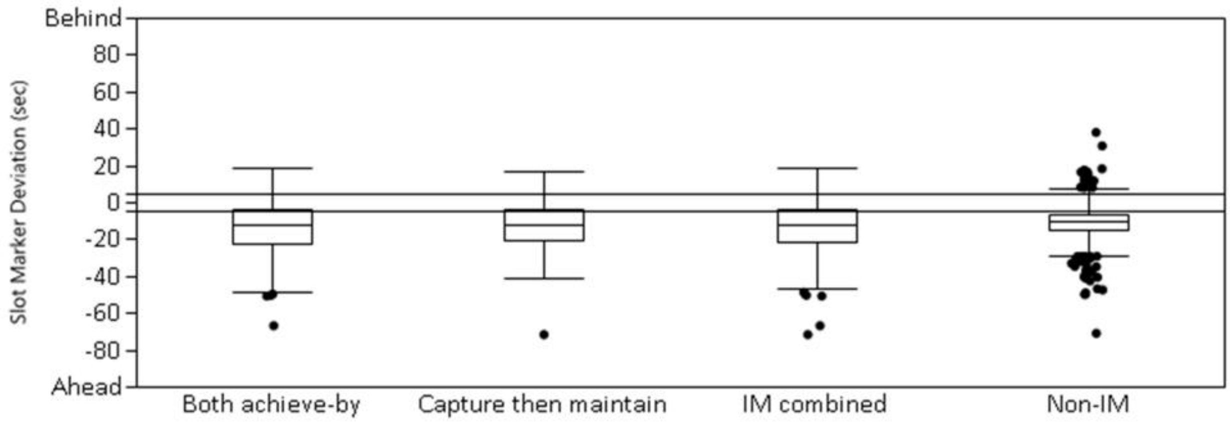

Figure 4-33. Aircraft Slot Marker Center Deviation in Mean Seconds for Final Controller Airspace

4.5.2.2 Aircraft Time in Slot Markers

Slot markers have a 15-second radius for the feeder controller and a 5-second radius for the final controller. Therefore, the absolute slot marker deviation metric can be used to determine whether aircraft were in their slot markers. Table 4-33 shows the percentage of time aircraft were in their slot markers while in the feeder and final controller's airspace. From the previous section, Figure 4-31, Figure 4-32, and Figure 4-33 show the distributions of the time deviation as well as the radius of the slot markers (as the lines drawn at 5 and 15 seconds).

Table 4-33. Percentage of Time Aircraft were in Slot Markers

	Aircraft role – IM clearance type			
Airspace location	IM Trail - Both achieve-by	IM Trail - capture then maintain	IM trail - Combined	Non-IM
Feeder	41.2	50.5	45.9	54.2
Final	17.2	16.9	17.1	19.1

Overall, all aircraft were in their slot markers less often in the feeder's airspace as compared to the final's airspace. IM aircraft (45.9%) were in the slot markers for less time in the feeder's airspace as compared to non-IM aircraft (54.2%). Both achieve-by clearance type aircraft (41.2%) spent less time in their slot marker in the feeder's airspace as compared to the capture then maintain aircraft (50.5%). All aircraft had similar amount of time (approximately 17.5%) spent in their slot markers in the final controller's airspace.

In summary, IM aircraft (particularly those flying the achieve-by clearance types) appeared to spend more time outside the slot markers than non-IM aircraft in the feeder controller's sector. This is likely because the controller was working to get non-IM aircraft into their slot markers prior to the handoff to the final controller, while the achieve-by aircraft were still working toward the ASG at a later point (DERVL and YOKXO) in the final controller's airspace. All aircraft ended up spending similar amounts of time in the slot markers in the final controller's airspace. As seen with the slot marker deviation data, the final controller appeared to let aircraft run ahead of schedule after receiving aircraft very close to the slot marker centers.

4.5.2.3 Relative Slot Marker Deviation

The relative slot marker deviation measure provides information on where the trail aircraft was relative to its slot marker based on the lead aircraft position relative to its slot marker (see Appendix D for sample configurations). The relative slot marker deviation is broken into conditions where the lead aircraft was either ahead of the center of the slot marker or it was behind the center of the slot marker[18]. The reason to examine the relative slot marker deviation is to determine whether the behavior of an aircraft performing IM has an unexpected position for its own slot marker relative to the lead aircraft.

The figures in this section portray the results of this measure for the various possible relative trail and lead aircraft positions. The lead aircraft is used as the reference. The figures show the slot marker (scaled to the appropriate size for both feeder [15-second radius] and final [5-second radius] controller's airspace), the mean (as a dot), and the standard deviation (as the dashed bar). The figures are intended to show the relative position of the aircraft. The slot marker radius and aircraft distance from the slot marker center are to scale, but the time / distance between the slot markers is not. Additional details on the compilation of this data are available in Appendix E.

Figure 4-34 and Figure 4-35 show the average relative positions of the lead and trail aircraft to their slot markers when the lead was ahead of its slot marker center. The figures show that 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. IM pairs and non-IM pairs also look very similar across all conditions.

[18] The number of events where the lead aircraft was perfectly in the center of the slot marker (i.e., 0 deviation) were too rare to include.

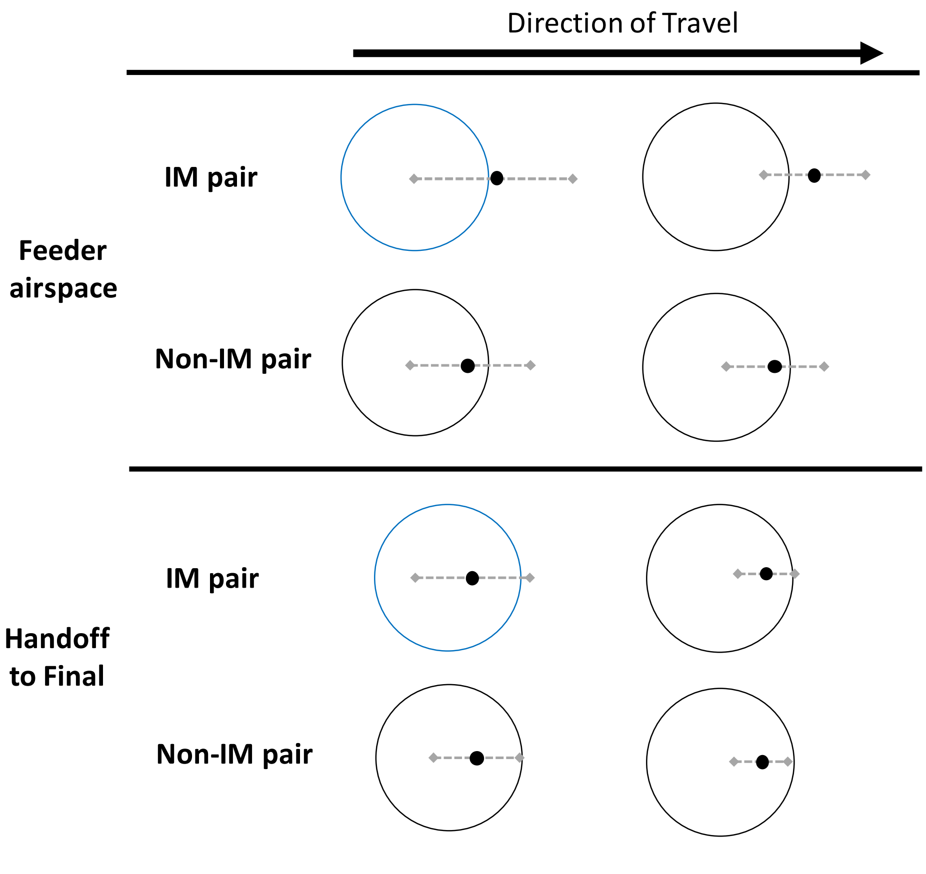

Figure 4-34. Lead and Trail Position Relative to Slot Markers When the Lead Aircraft was Ahead of its Slot Marker Center (Feeder Airspace and Handoff)

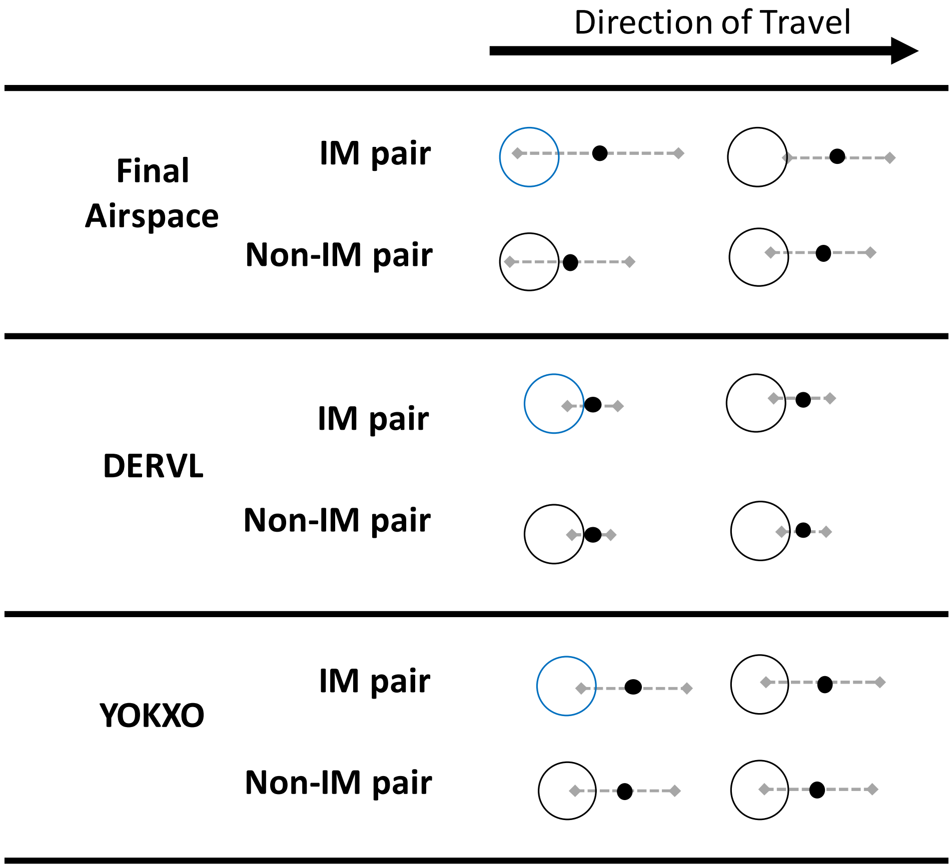

Figure 4-35. Lead and Trail Position Relative to Slot Markers When the Lead Aircraft was Ahead of its Slot Marker Center (Final Airspace, DERVL, and YOKXO)

Figure 4-36 and Figure 4-37 show the relative positions of the lead and trail aircraft to their slot markers when the lead was behind its slot marker center.

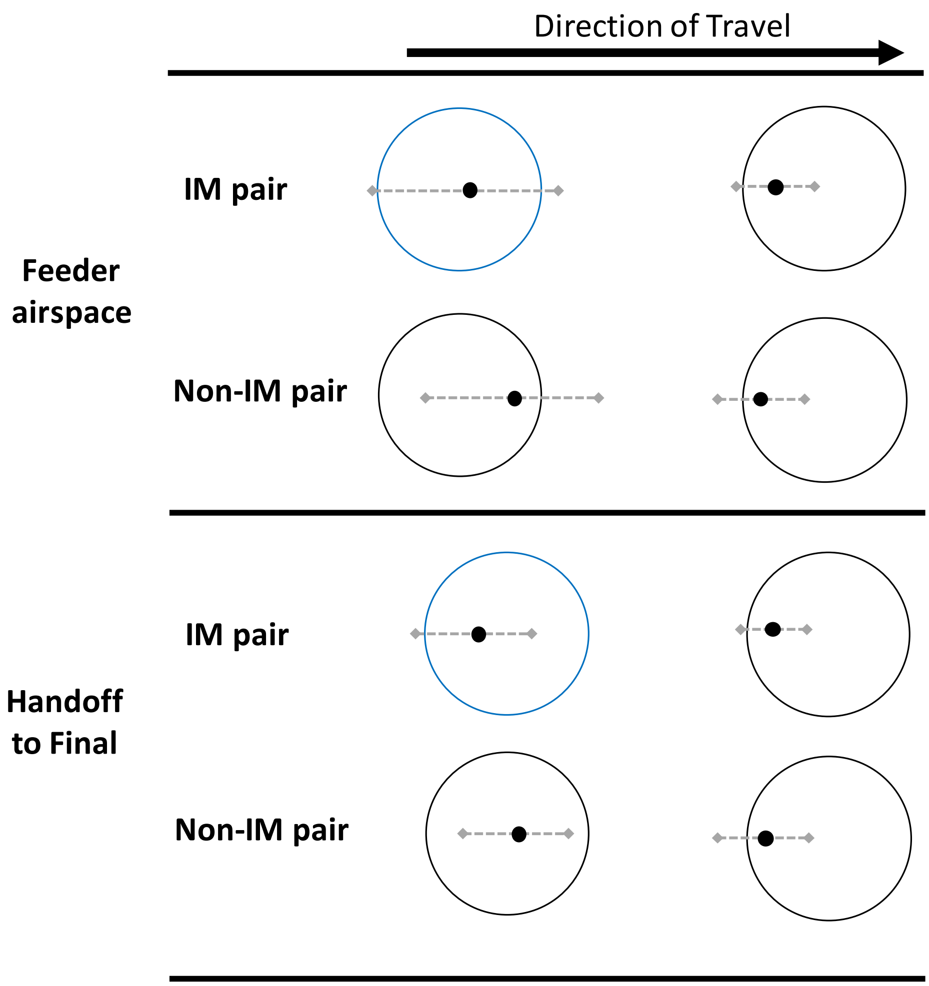

Figure 4-36. Lead and Trail Position Relative to Slot Markers When the Lead Aircraft was Behind its Slot Marker Center (Feeder Airspace and Handoff)

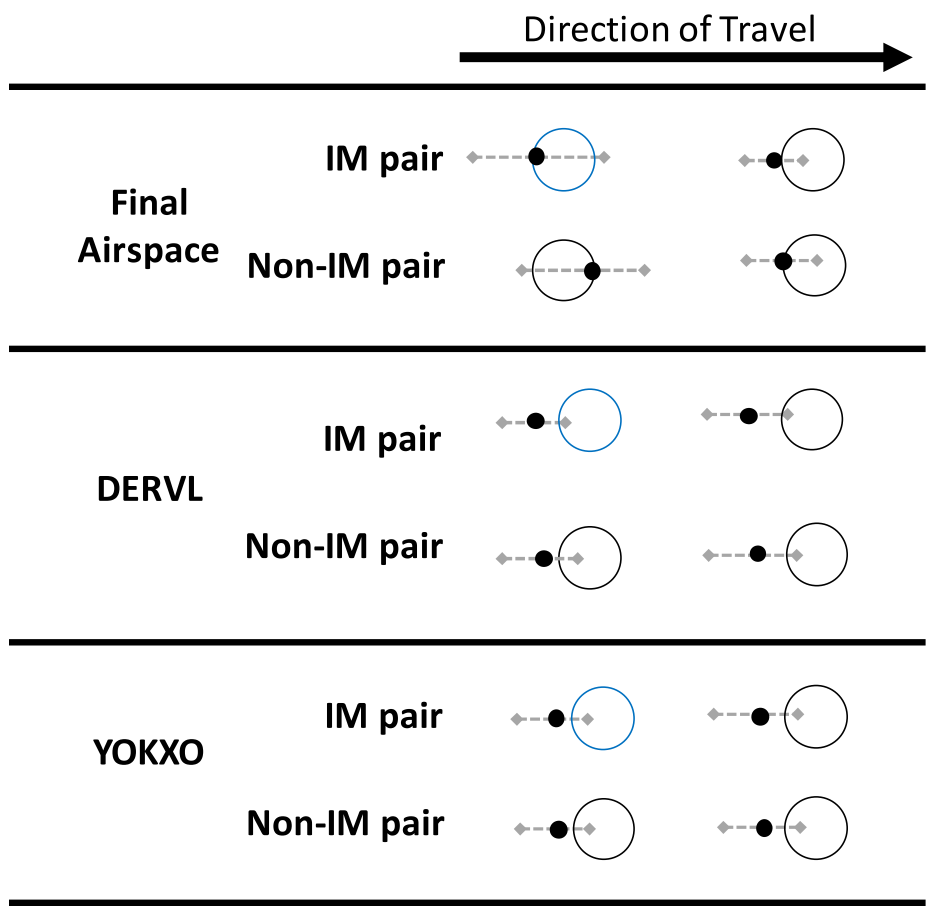

Figure 4-37. Lead and Trail Aircraft Position Relative to Slot Markers When the Lead Aircraft was Behind its Slot Marker Center (Final Airspace, DERVL, and YOKXO)

Figure 4-36 shows (when the lead was behind the slot marker center) that the situations were similar, but the IM aircraft pairs were often further apart than the non-IM pairs in the feeder airspace and at the handoff to the final controller. Figure 4-37 shows the same was true over the course of time that the aircraft were in the final controller's airspace. However, at both DERVL and YOKXO, the IM trail aircraft is also behind with similar variance. IM pairs and non-IM pairs also look very similar for both DERVL and YOKXO.

Overall, the figures show few differences between IM and non-IM aircraft.

4.5.3 Spacing Error

The following reviews the spacing error (the difference between the planned interval and the achieved interval) in seconds measured at DERVL and YOKXO. For all aircraft, the planned interval was the STA of the trail aircraft minus the STA of the lead aircraft at the same point. For IM aircraft, the planned interval became the ASG at the ABP. For IM aircraft the spacing error is a direct measure of how close the IM aircraft were to the ASG. For non-IM aircraft, it is a measure of how well the aircraft met the planned interval. (see Appendix D for further detail). For both IM and non-IM aircraft, this is not a measure of schedule conformance.

Trail IM aircraft that did achieve-by only operations and those that did capture then maintain did not have a specified spacing goal at DERVL so the aircraft are excluded for measurement at that point. Those aircraft are included, along with all other aircraft for the spacing error at YOKXO (also the PTP and FAF). Table 4-34 shows the spacing errors by aircraft role and operation at the two points.

Table 4-34. Mean Spacing Error in Seconds (SD) at Two Points

Waypoint	Aircraft role - IM clearance type				
	IM trail - Achieve-by (no maintain)	IM trail - Achieve-by then maintain	IM trail – Capture then maintain	IM trail – Total	Non-IM
DERVL	---	**0.2** (4.5) **ABP**	---	**0.2** (4.5)	**1.0** (8.5)
YOKXO	**-1.0** (4.9) **ABP & PTP**	**0.2** (3.0) **PTP**	**0.6** (5.1) **PTP**	**0.4** (4.1)	**0.4** (8.2)

The IM aircraft that achieved at DERVL (M=0.2; SD=4.5) had less spacing error and less variance than the non-IM aircraft (M=1.0; SD=8.5). With respect to meeting performance baseline / goal discussed in Section 2.2.2.1, IM aircraft that achieved at DERVL met the performance goal (Table 4-35). The non-IM aircraft also met their performance baseline. When aircraft reached YOKXO, all aircraft had similar spacing errors, though non-IM aircraft had the largest variance. All IM aircraft and non-IM aircraft met the performance baseline / goals at YOKXO.

Table 4-35. Aircraft Role and Performance Baseline / Goal Achievement

Waypoint	Aircraft role - IM clearance type						
	IM trail - Achieve-by		IM trail - Achieve-by then maintain		IM trail – Capture then maintain		Non-IM
	95% 10 secs	68% 5 secs	95% 10 secs	68% 5 secs	95% 10 secs	68% 5 secs	68% 12 secs
DERVL	---	---	Yes 95.8% **ABP**	Yes 88.4% **ABP**	---	---	Yes 75.6%
YOKXO	Yes 97.4% **ABP & PTP**	Yes 89.5% **ABP & PTP**	Yes 98.5% **PTP**	Yes 93.5% **PTP**	Yes 100% **PTP**	Yes 100% **PTP**	Yes 77.1%

See Figure 4-38 and Figure 4-39 for the spacing error for IM and non-IM aircraft for the two points. See Figure 4-40 and Figure 4-41 for more detail[19] on the spacing error of only the IM aircraft. The blue horizontal lines in the figures show the IM performance goal of 5 seconds and the gray horizontal lines show the TSAS performance baseline of 12 seconds. Overall, IM and non-IM aircraft met the performance baseline / goals expected for the operations.

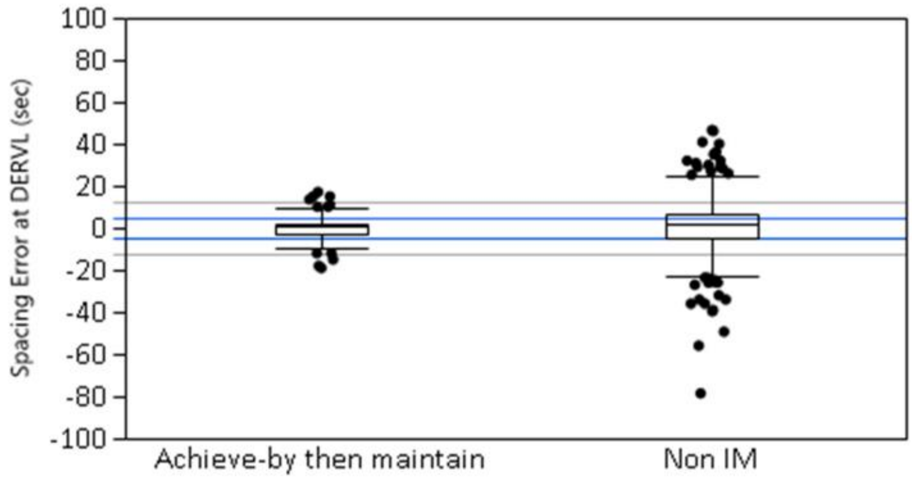

Figure 4-38. Spacing Error Distribution for IM and Non-IM Aircraft at DERVL

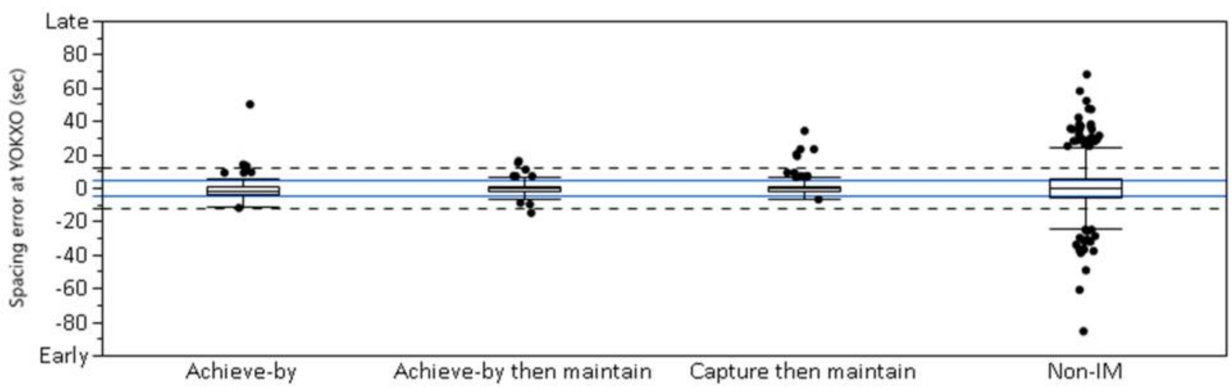

Figure 4-39. Spacing Error Distribution for IM Aircraft by IM Clearance Type and Non-IM at YOKXO

[19] One event during for capture then maintain clearance type was late by 55 seconds and was removed. This allowed greater detail to be portrayed for the remaining events.

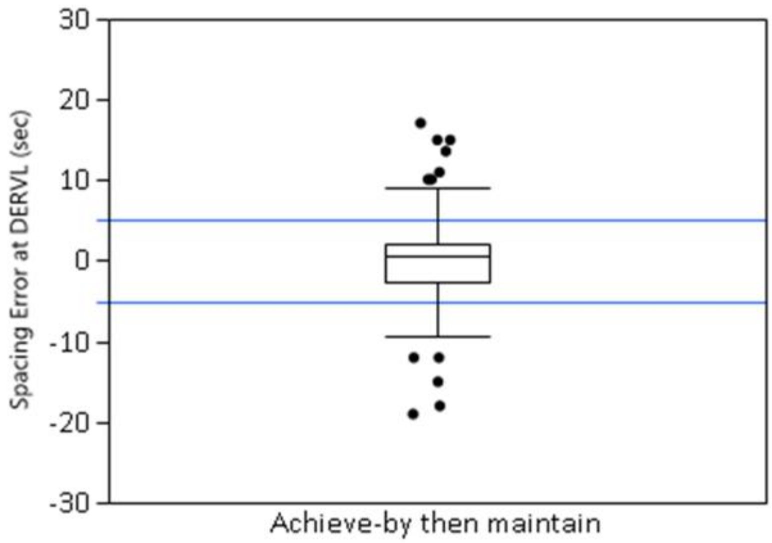

Figure 4-40. Spacing Error Distribution for IM Aircraft at DERVL

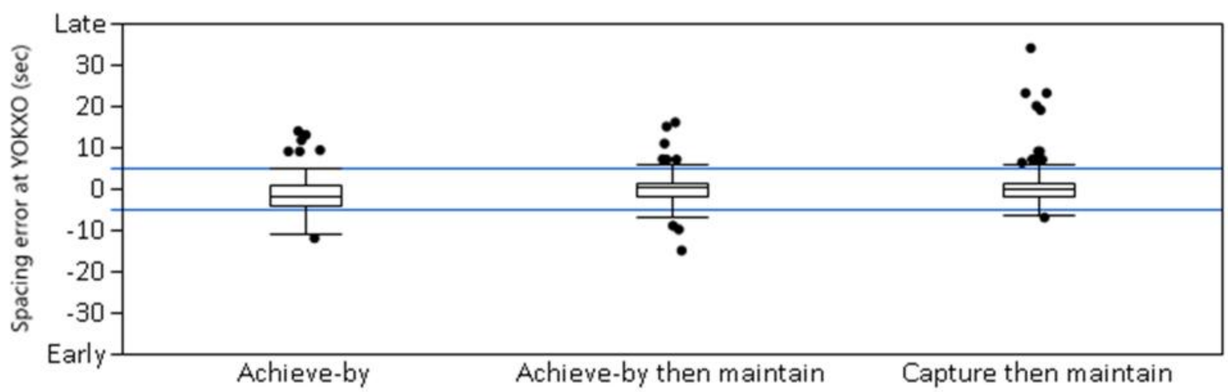

Figure 4-41. Spacing Error Distribution for IM Aircraft by IM Clearance Type at YOKXO

4.5.4 Maintenance of the ASG

While aircraft performing achieve operations reach the ASG at a point, aircraft in the maintain stage are required to maintain the ASG throughout. The maintain stage began (1) at the ABP (DERVL) for achieve-by then maintain operations and (2) when the MSI was within 10 seconds of the ASG for capture then maintain operations.

Achieve-by clearance types when in the maintain stage were within 10 seconds of the ASG (the 95% tolerance performance goal) on average 97.7% of the time, which met the performance goal. Capture then maintain operations that were in the maintain stage were within tolerance 100% of the time.

Table 4-36. Percentage of Time IM Aircraft were within 10 Seconds of the ASG (95% Performance Goal) During the Maintain Stage

IM clearance type	
Achieve-by then maintain	97.7
Capture then maintain	100

In summary, the maintain stage of the achieve-by then maintain clearance type met the performance goal over the course of the maintain stage as well as at the PTP of YOKXO (as shown in Section 4.5.3). For the capture then maintain clearance type, the performance goal was met over the course of the maintain stage and at the merge point of DERVL and at the PTP of YOKXO (as shown in Section 4.5.3).

4.5.5 Events Below Separation Standard

Five events occurred where an aircraft was below the applicable separation standard[20]. None of the events were for trail aircraft conducting IM. One event was an aircraft that had started IM but then subsequently terminated IM. The controller stated that the reason for the termination was so he could speed the trail aircraft up beyond the IM speeds, so IM was unrelated to the separation issue. There were no specific causes determined for the other events. Figure 4-42 shows the locations of the events.

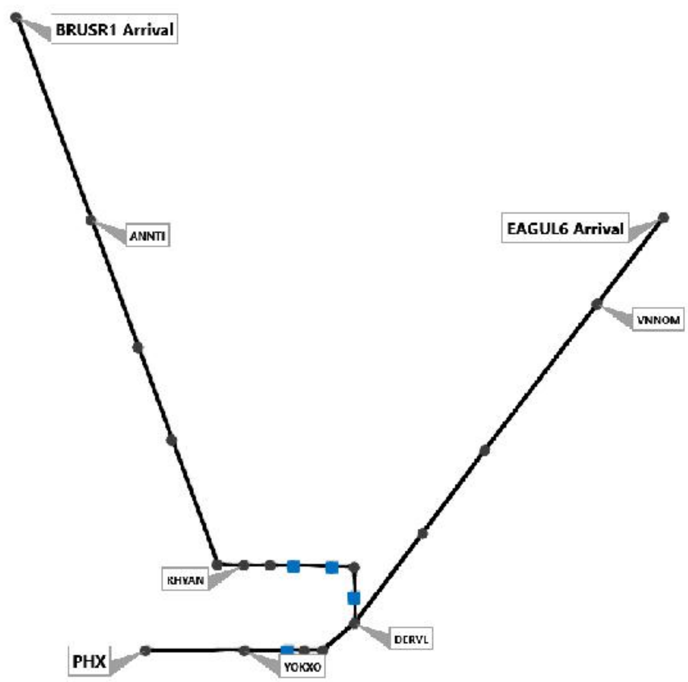

Figure 4-42. Location Where an Aircraft was Below the Applicable Separation Standard

Note: Two events occur just prior to DERVL and overlap on the figure.

[20] No events inside of YOKXO were considered as the was no tower controller in the simulation.

4.6 IM During Terminal Metering Acceptability

In the post-scenario questionnaires, controllers were asked whether IM is operationally acceptable (Table 4-37 and Figure 4-43). Controllers, on average, agreed regardless of role or tool set.

Table 4-37. Mean (SD) Controller Response to Post-Scenario Statement "Given the appropriate training, IM during terminal metering is operationally acceptable" for TRACON IM Initiation

Controller tool set	Controller role	
	Feeder	Final
Basic	**79.6** (20.0)	**77.3** (20.4)
Basic+ cue	**73.5** (21.9)	**77.4** (20.1)
Basic+ cue and prediction	**71.9** (22.8)	**76.5** (18.9)

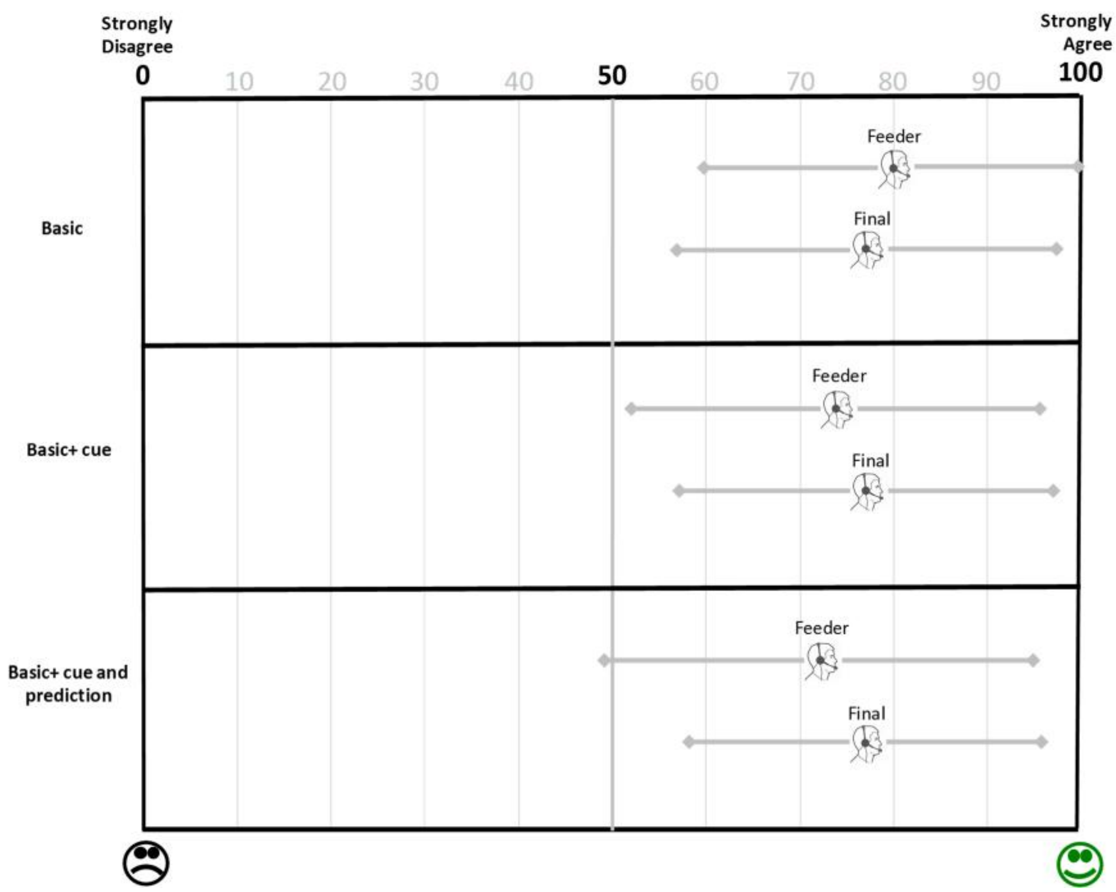

Figure 4-43. Controller Responses to Post-Scenario Statement "Given the appropriate training, IM during terminal metering is operationally acceptable"

In the post-scenario questionnaires, pilots were also asked whether IM is operationally acceptable (Table 4-38 and Figure 4-44). The pilots, on average, agreed regardless of position or tool set.

Table 4-38. Mean (SD) Pilot Response to Post-Scenario Statement "Given the appropriate training, IM is operationally acceptable"

Flight crew tool set	Pilot role	
	PF	PM
Min	**88.0** (12.7)	**81.8** (23.9)
Min+	**87.3** (15.8)	**82.1** (22.7)

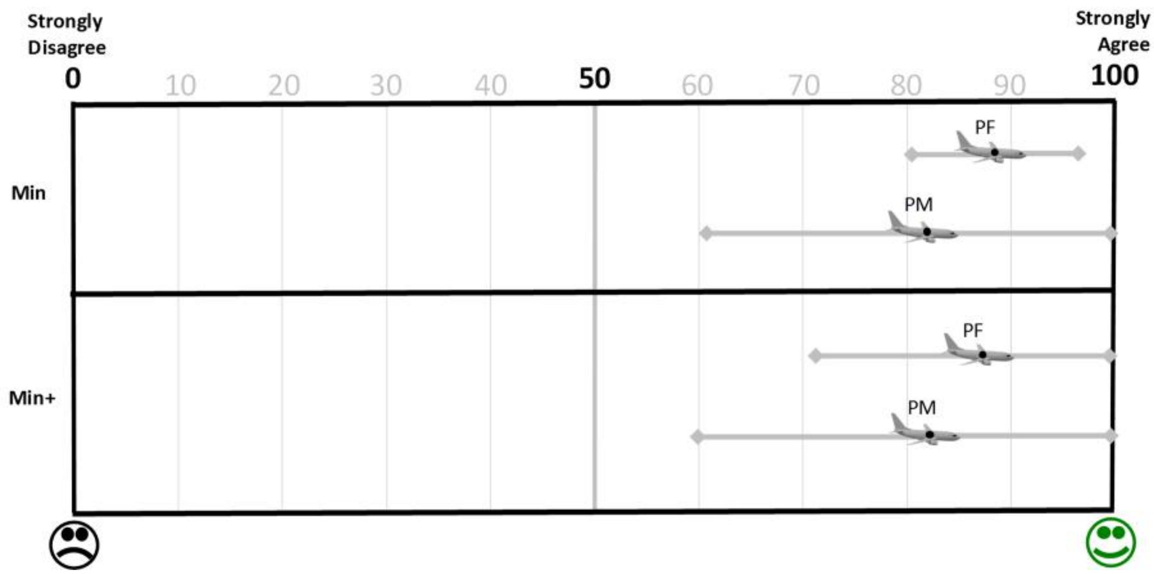

Figure 4-44. Pilot Responses to Post-Scenario Statement "Given the appropriate training, IM is operationally acceptable"

Participants were asked (in the post-simulation questionnaire too) whether IM is operationally acceptable, the majority (7/9; 78%) of controllers agreed (M=65.0; SD=22.4) and the majority of pilots (16/18; 89%) also agreed (M=82.9; SD=23.4). Participants were asked whether IM is operationally desirable. The majority (7/9; 78%) of controllers agreed (M=67.3; SD=24.7) and the majority (15/18; 83%) of pilots also agreed (M=79.7; SD=23.7). All controllers reported both achieve-by and capture than maintain clearances to be acceptable. Controllers were asked whether it was acceptable to receive aircraft already performing IM when handed off from the feeder controller and when handed off from the en route environment. All controllers agreed when receiving aircraft from the feeder controller (M=88.7; SD=12.3) and the majority (8/9; 89%) of controllers agreed when receiving aircraft from the (simulated) en route controller (M=78.8; SD=3.7). Figure 4-45 depicts these results.

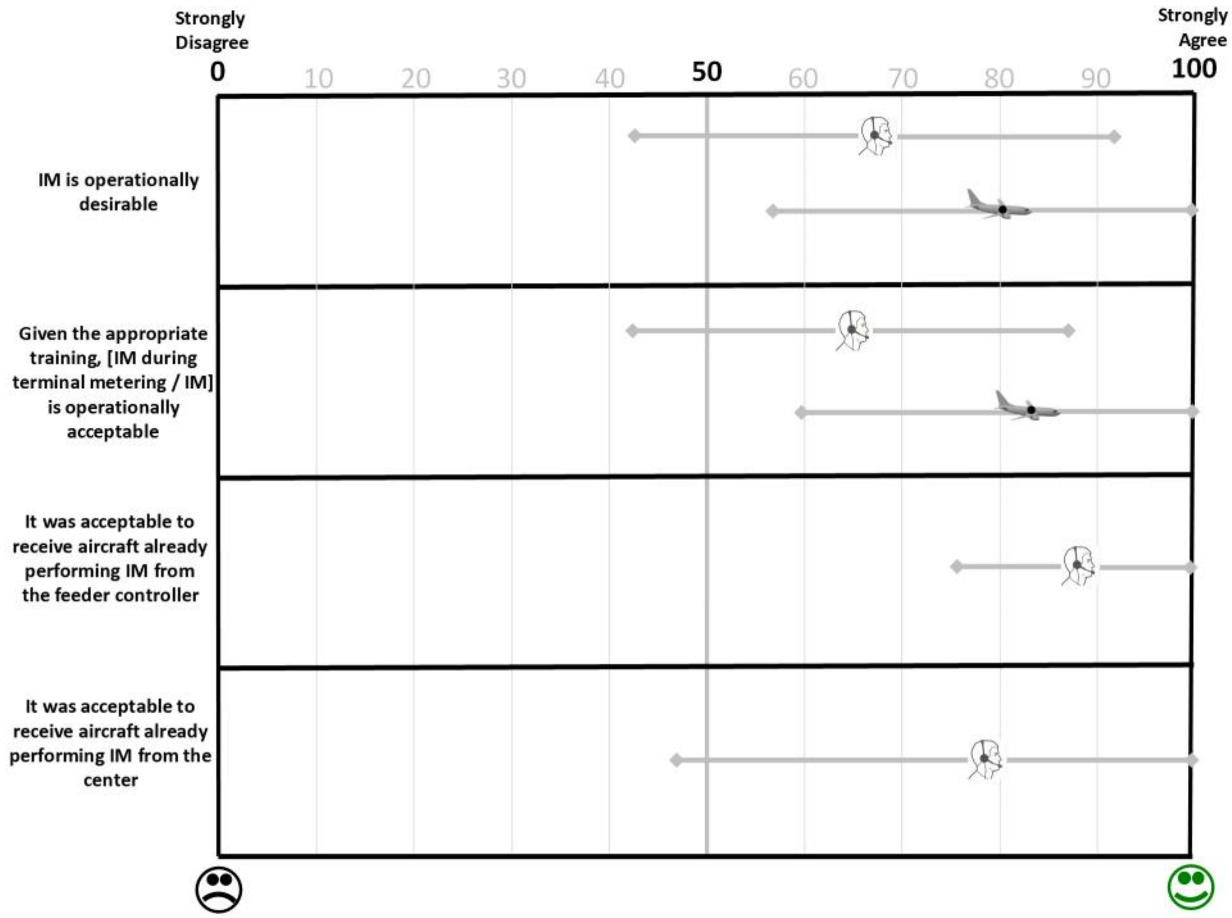

Figure 4-45. Summary of Controller and Pilot Responses on IM Desirability and Acceptability Statements

4.6.1 Traffic Spacing Awareness and Acceptability

Participants were asked whether their level of traffic awareness was acceptable. Responses are shown next and in Figure 4-46.

- Controllers
  - IM trail aircraft
    - All controllers agreed (M=86.6; SD=10.5)
  - Non-IM aircraft
    - All controllers agreed (M=91.8; SD=7.6)
- Pilots
  - Lead aircraft for IM
    - All pilots agreed (M=90.3; SD=9.6)
  - Aircraft other than lead aircraft
    - The majority (16/18; 89%) of pilots agreed (M=83.6; SD=20.2)

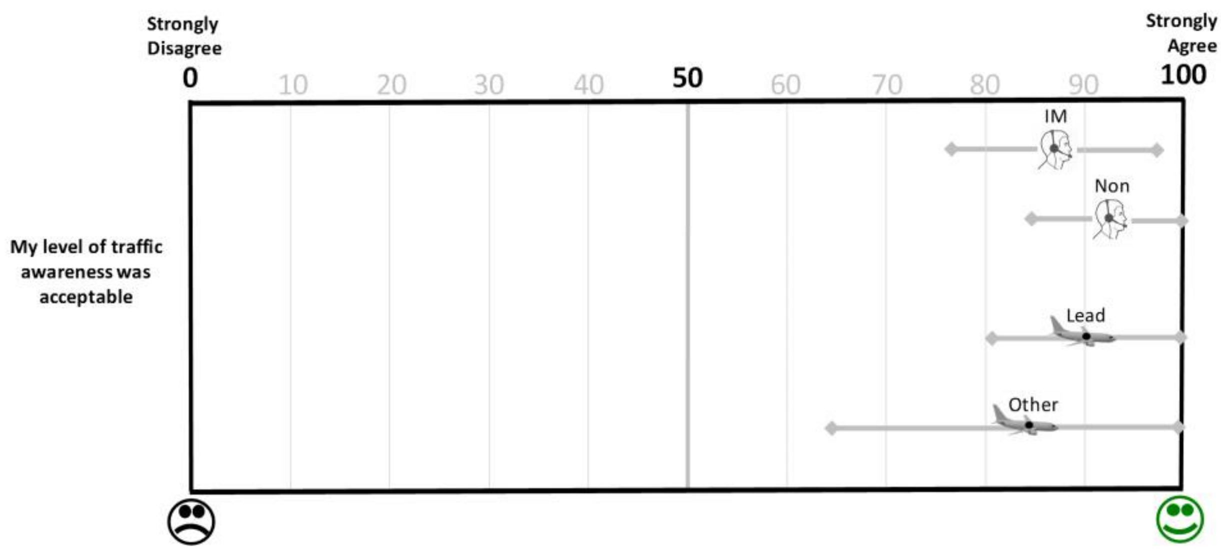

Figure 4-46. Controller and Pilot Responses to "My level of traffic awareness was acceptable"

In the post-scenario questionnaire, controllers were asked whether they were confident the spacing of the aircraft would remain outside their separation requirement. The results are shown in Table 4-39 and Figure 4-47. The controllers, on average, agreed regardless of role, tool set, or aircraft role. Higher variability was exhibited in the feeder and final replies for IM aircraft with the basic+ cue and prediction tool set. As mentioned in Section 0, a statistical test was run on this measure and no statistically significant difference was found.

Table 4-39. Mean (SD) Controller Response to Post-Scenario Statement "I was confident that the spacing of the aircraft would remain outside my separation requirement"

	Controller role			
	Feeder		Final	
Controller tool set	IM	Non-IM	IM	Non-IM
Basic	**79.7** (24.2)	**83.3** (24.9)	**77.9** (20.8)	**85.1** (15.3)
Basic+ cue	**81.6** (22.8)	**86.0** (13.3)	**80.1** (24.6)	**89.1** (16.1)
Basic+ cue and prediction	**75.7** (26.7)	**80.3** (21.5)	**75.9** (28.0)	**88.5** (14.6)

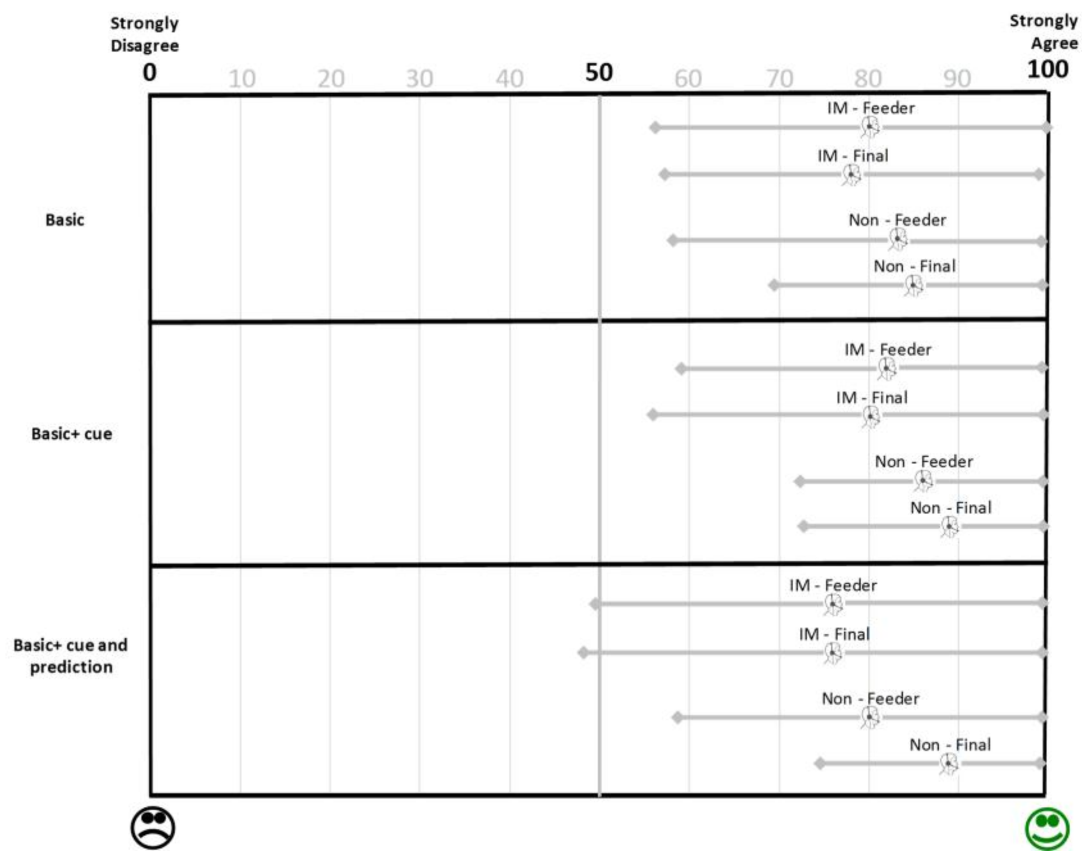

Figure 4-47. Controller Responses to Post-Scenario Statement "I was confident that the spacing of the aircraft would remain outside my separation requirement"

In the post-scenario questionnaire, controllers were asked whether they could detect spacing or separation issues. The results are shown in Table 4-40 and Figure 4-48. 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 4-40. Mean (SD) Controller Response to Post-Scenario Statement "I was able to detect when spacing / separation issues were developing for aircraft"

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

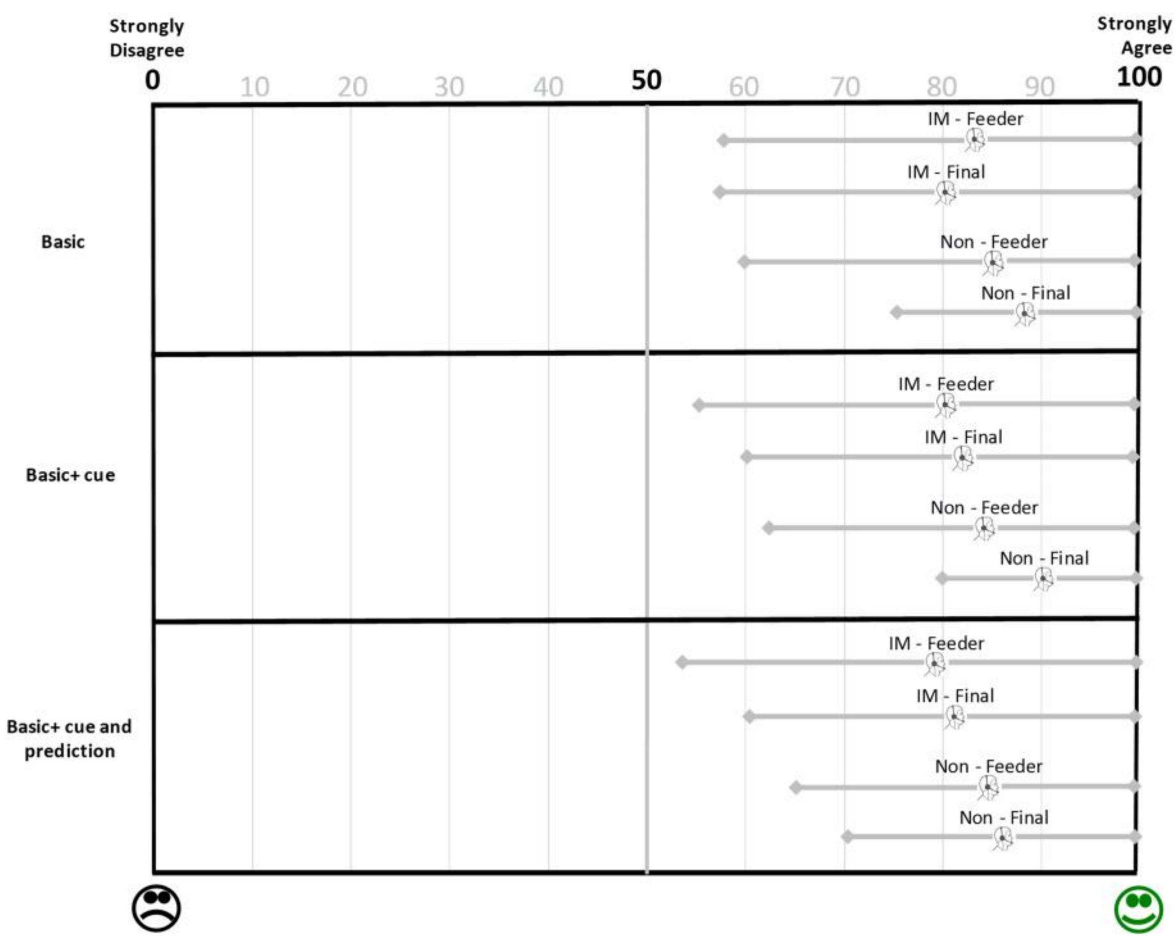

Figure 4-48. Controller Responses to Post-Scenario Statement "I was able to detect when spacing / separation issues were developing for aircraft"

In the post-scenario questionnaire, pilots were asked whether they could determine if they would remain within tolerances of the ASG. The results are shown in Figure 4-49. Pilots, on average, agreed regardless of role or tool set.

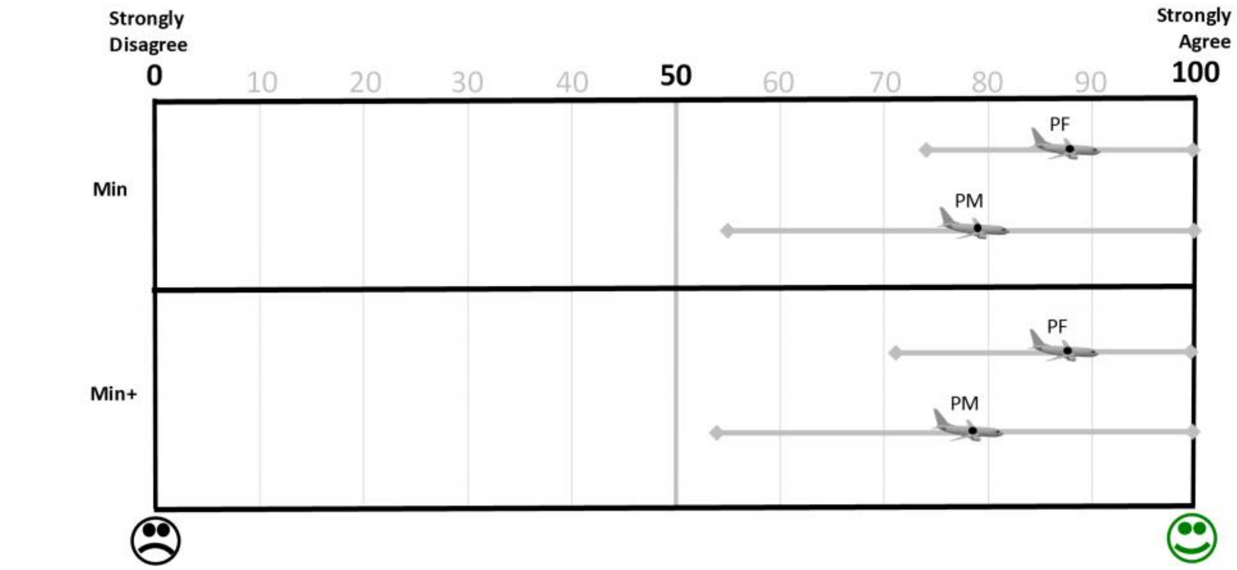

Figure 4-49. Pilot Responses to Post-Scenario Statement "I could detect whether I would remain within tolerances to achieve and maintain the assigned spacing goal"

The following questions are from the post-simulation questionnaire and are summarized in Figure 4-50. Participants were asked whether they could detect spacing or separation issues during IM. The responses were:

- Controllers
  - IM aircraft
    - Controller responses were variable but the majority (6/9; 67%) agreed (M= 64.8; SD= 26.7)
  - Non-IM aircraft
    - The majority (8/9; 89%) of controllers agreed (M= 85.7; SD= 18.8)
- Pilots
  - Min
    - The majority (16/18; 89%) of pilots agreed (M= 72.6; SD= 22.7)
  - Min+
    - The majority (17/18; 94%) of pilots agreed (M= 86.2; SD= 15.8)

Controllers were asked if the spacing of the aircraft would remain outside their separation requirement. The majority (7/9; 78%) of the controllers agreed for IM aircraft (M=63.1; SD=27.7) and all controllers agreed for non-IM aircraft (M= 80.3; SD=14.6). Participants were asked whether the spacing when conducting IM was acceptable. The majority (7/9; 78%) of controllers agreed for IM aircraft (M=68.7; SD=22.7) and the majority (7/8; 88%; missing=1) agreed for non-IM aircraft (M=82.1; SD=16.5). The majority (17/18; 94%) of pilots agreed (M=85.1; SD=22.4).

Several comments were made on the questions related to controller confidence in monitoring and predicting spacing and separation. A majority (approximately 7/9; 78%) of controllers expressed issues with not "knowing what the [IM aircraft / flight crew] is doing" / not knowing the speeds to be flown and when. Controllers reported trusting the flight crew and letting it "play out," but 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, e.g., two aircraft (one acting as an IM trail aircraft) on one route with an aircraft between them (acting as the IM lead aircraft) on the other route.

When controllers were asked whether the handed-off aircraft would be accepted with minimal problems, the majority (8/9; 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 by the controllers. Since the situation was created by speed alone, the overtake took a long time to evolve and appear to the controllers as problematic. However, by the time the trail aircraft was in the final controller's airspace, the situation became apparent and the final controller terminated the IM operation. This was a point where the "no speed" alerts were no longer provided, so the controller needed to detect the situations without an alert.

Pilots were asked whether they could determine if they would remain within tolerances of the ASG. The majority (15/18; 83%) agreed (M= 75.7; SD=24.4). As mentioned in Section 0, a statistical test was run on this measure and no statistically significant difference was found. However, comments for this question and other similar ones indicate that the tolerances were unclear, especially without the graphical progress indicator. Figure 4-50 depicts the results for this line of questioning for pilots and controllers.

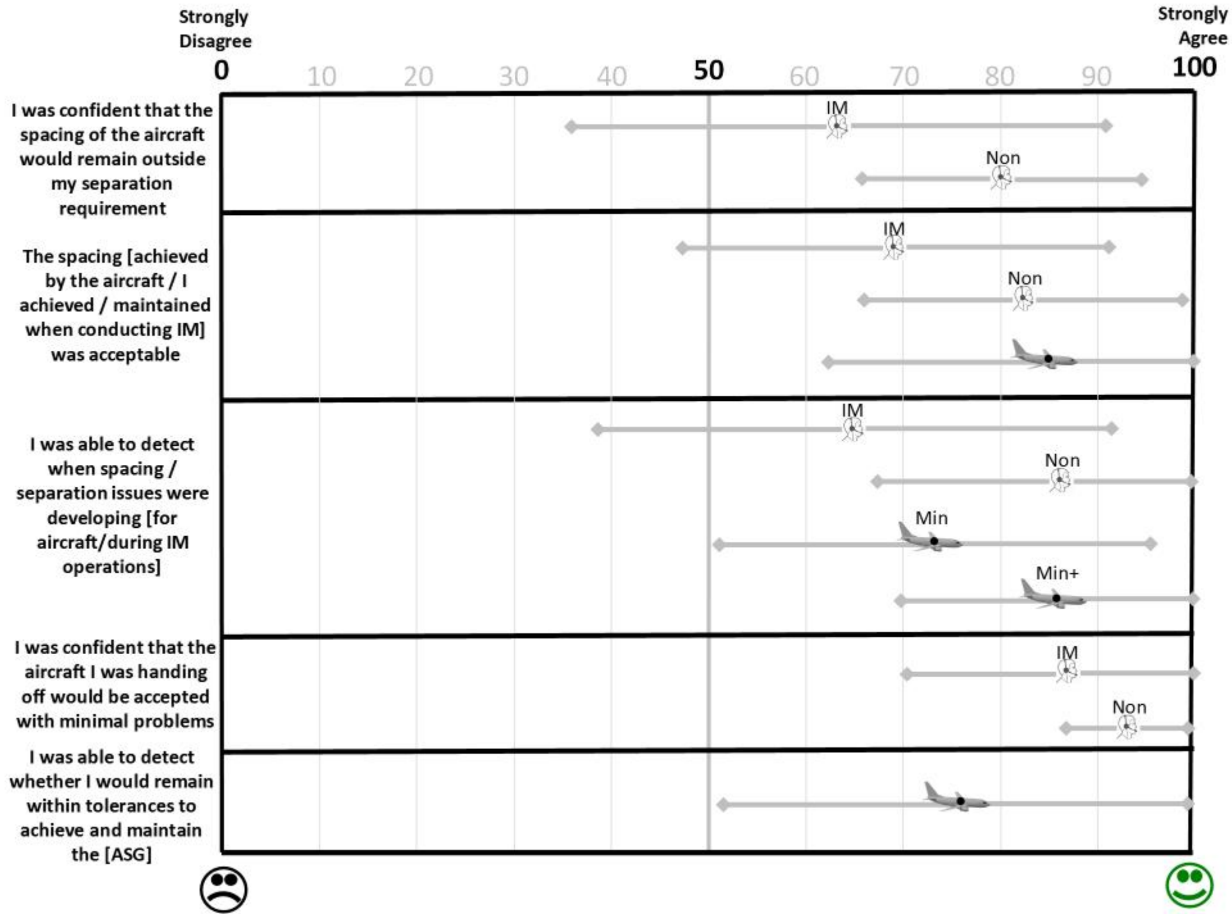

Figure 4-50. Summary of Controller and Pilot Responses on Spacing Acceptability Statements

The majority (8/9; 89%) of controllers agreed that there were an acceptable number of aircraft performing IM (M=77.2; SD=27.6) (Figure 4-51). Controllers reported on average that 78.6% (SD=19.7; missing=2) aircraft performing IM and above was / would be reasonable (Figure 4-52).

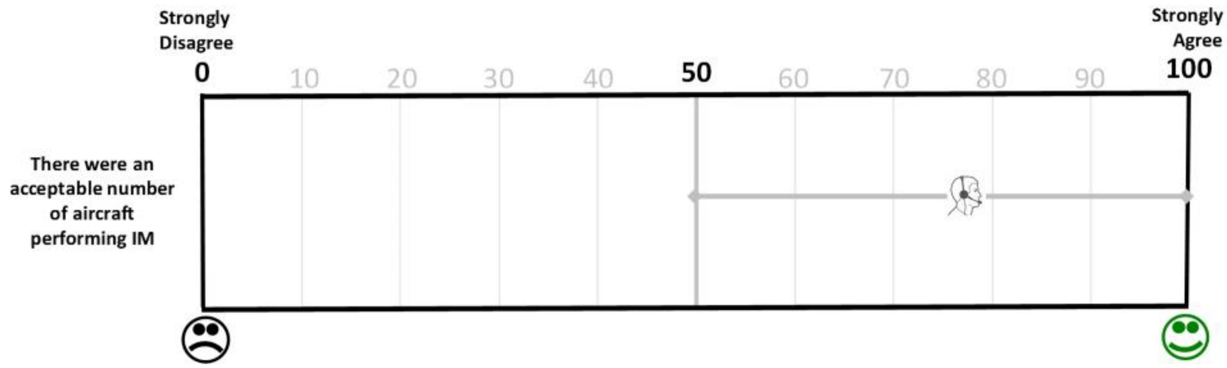

Figure 4-51. Controller Responses to "There were an acceptable number of aircraft performing IM"

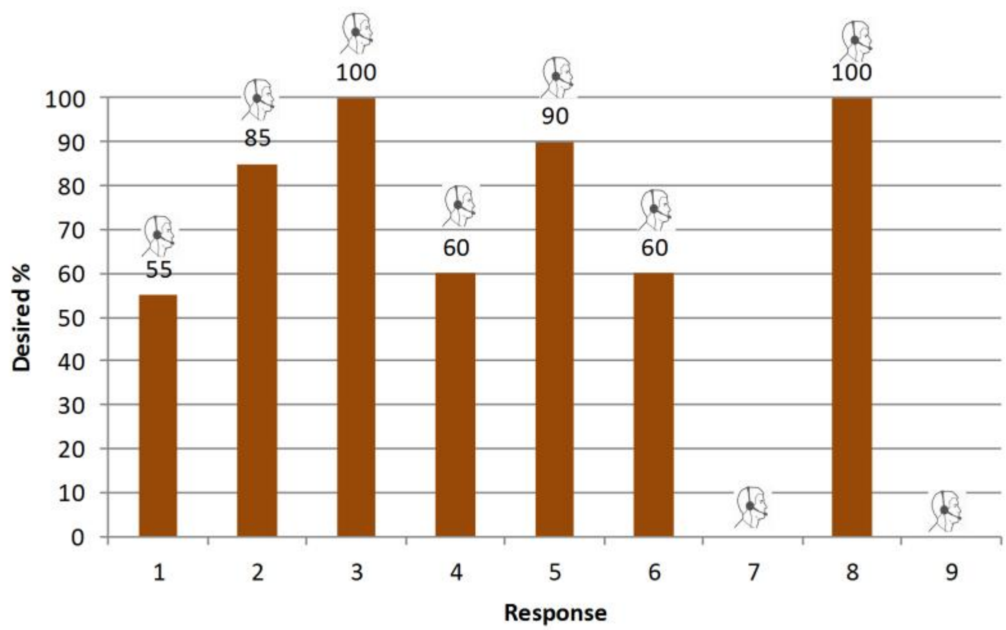

Figure 4-52. Controller Responses to "There were an acceptable number of aircraft performing IM… What percentage and above is reasonable?"

Participants were asked whether it was clear that IM was driving toward appropriate spacing. Controller responses were variable but the majority (7/9; 78%) of controllers agreed for IM aircraft (M=62.9; SD=33.9) and all (8/8; 100%; missing=1) agreed for non-IM aircraft (M=89.8; SD=12.0). Pilot responses were variable but the majority (15/18; 83%) of pilots agreed (M=76.5; SD=27.9). Pilots were asked whether they trusted that the IM algorithm was providing the appropriate speeds. Their responses were variable but the majority (15/17; 88%; missing=1) agreed (M=73.4; SD=26.0). However, six pilots, regardless of whether they agreed or not, reported some level of distrust. The observer noted several pilot comments indicating confusion about IM speeds. For example, if aircraft had a large amount of time to make up and could fly 250 kts, some pilots reported being confused about not receiving an IM speed of 250 kts. The reason for this could have been that the IM speed was limited (as described in Section 3.1.2) but still acceptable, or because the IM speed provided was the speed necessary, regardless of speed limiting. The limiting was not annunciated to the flight crew. Figure 4-53 depicts these results.

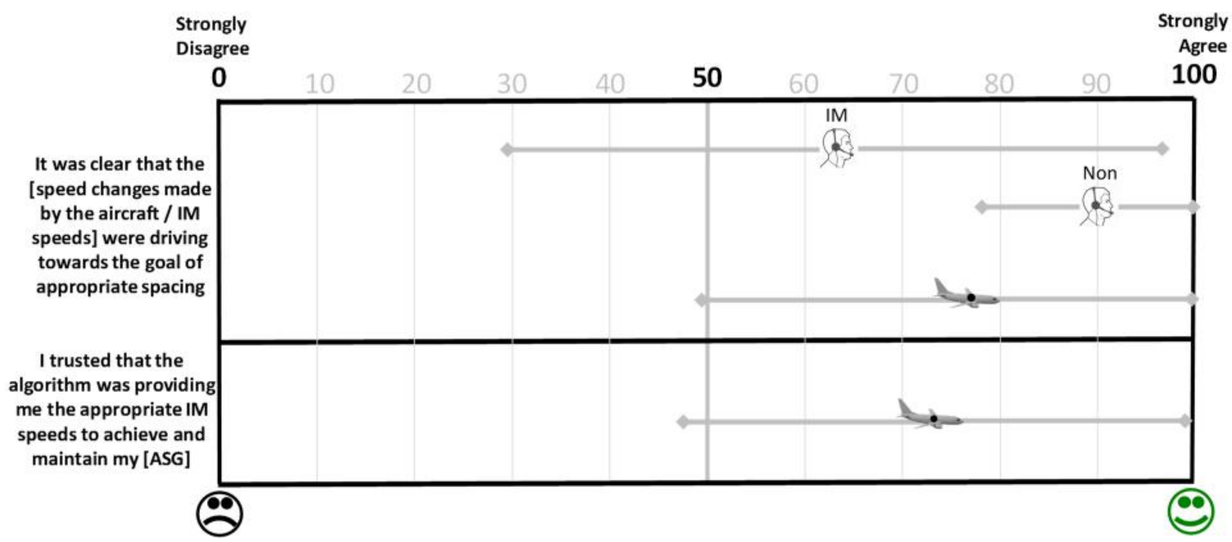

Figure 4-53. Summary of Controller and Pilot Responses on IM Trust Statements

Pilots were asked whether they tried to out-guess the algorithm. Forty-seven percent (8/17; missing=1) provided "yes" responses (Figure 4-54). However, the majority (15/18; 83%) of pilots reported they did not choose to ignore an IM speed (Figure 4-55).

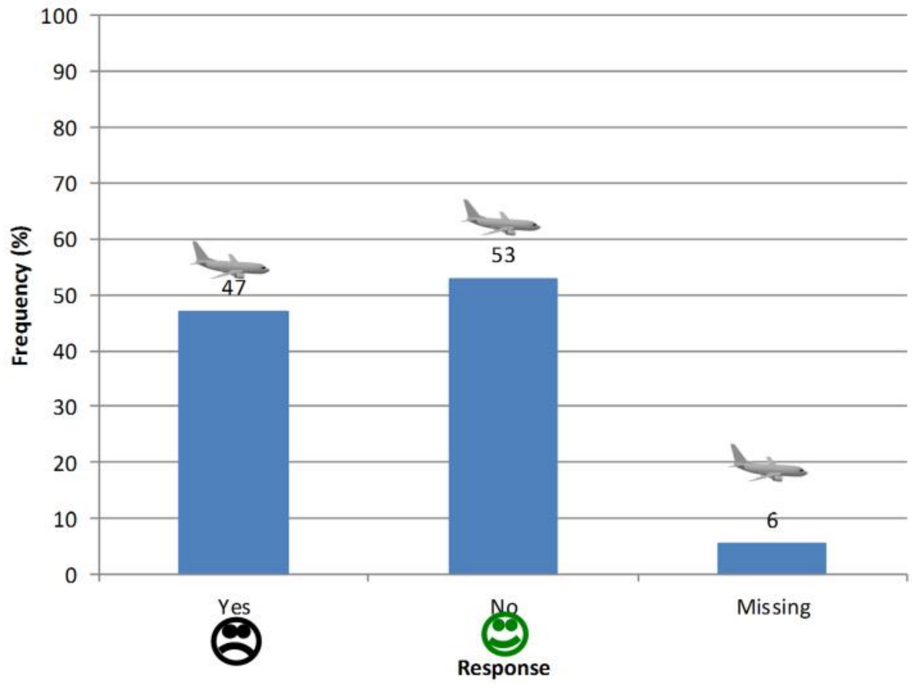

Figure 4-54. Pilot Responses to "Did you ever try to "out-guess" the IM algorithm and the IM speeds?"

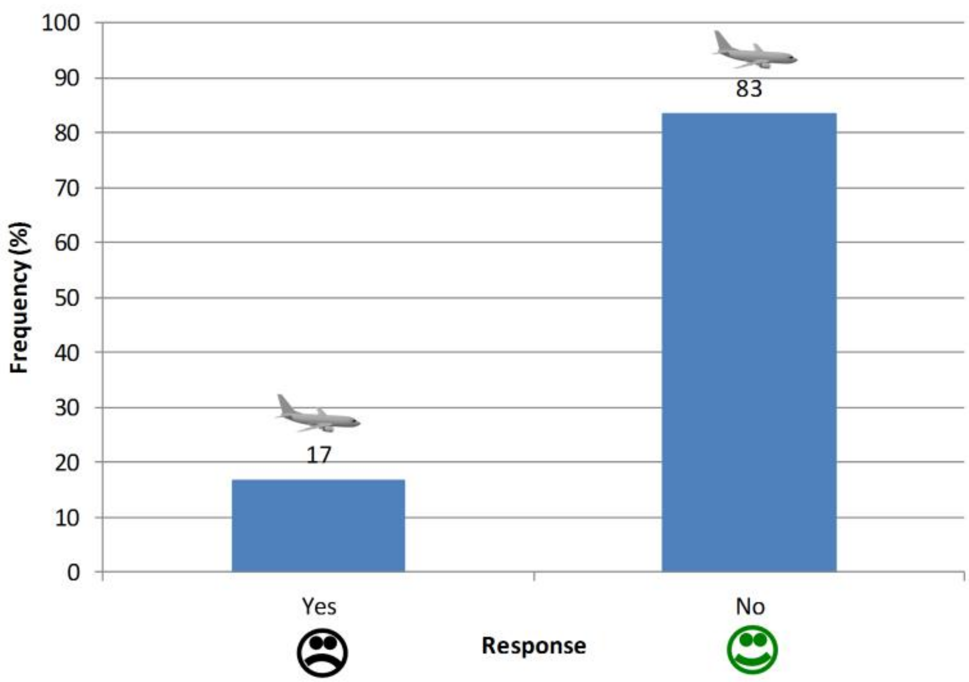

Figure 4-55. Pilot Responses to "Did you choose not to fly an IM speed?"

4.6.2 Workload

In the post-scenario questionnaire, controllers and pilots were asked to rate their average overall workload on the Bedford Workload Rating Scale. Table 4-41, Table 4-42, and Figure 4-56 show the ratings for both controllers and pilots. As can be seen, controllers and pilots generally found workload to be acceptable.

Table 4-41. Mean (SD) Pilot Response to Post-Scenario Bedford Workload Rating Scale

Flight crew tool set	Pilot role	
	PF	PM
Min	**2.7** (1.2)	**2.4** (1.0)
Min+	**2.7** (1.1)	**2.5** (1.0)

Table 4-42. Mean (SD) Controller Response to Post-Scenario Bedford Workload Rating Scale

Controller tool set	Controller role	
	Feeder	Final
Basic	**2.8** (1.4)	**2.6** (1.3)
Basic+ cue	**2.7** (1.2)	**2.6** (1.2)
Basic+ cue and prediction	**2.8** (1.3)	**2.5** (1.1)

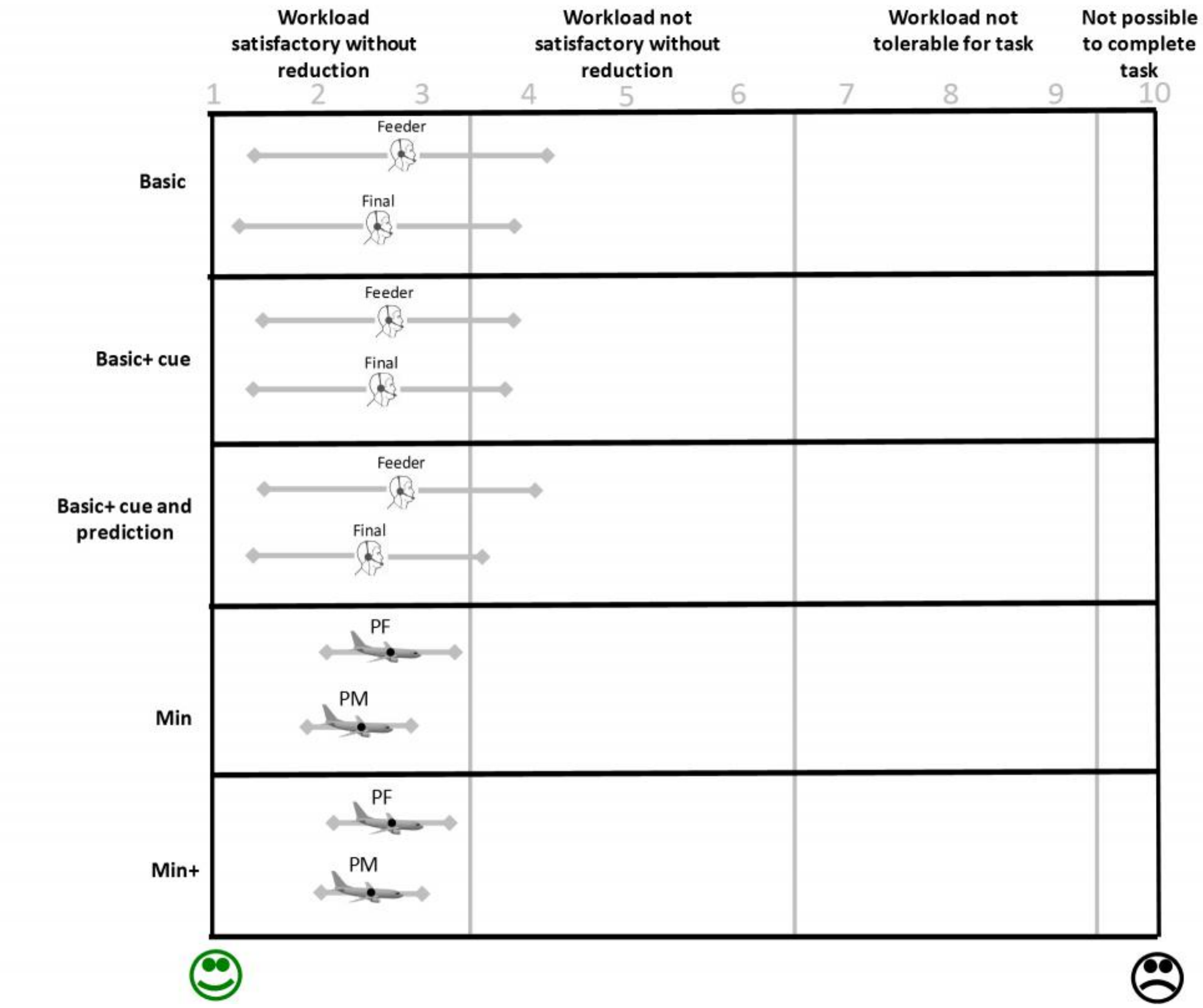

Figure 4-56. Controller and Pilot Response Means to the Bedford Workload Rating

When asked about the acceptability of their overall workload, all controllers agreed that it was acceptable (M=88.1; SD=10.2). The pilot responses were variable (M=80.5; SD=26.2), but the majority (15/18; 83%) agreed. The majority (15/18; 83%) of the pilots also agreed they received an acceptable number of IM speeds (M= 75.4; SD=24.9). However, at least four pilots, regardless of whether they agreed or not, reported that the IM speeds could be too frequent at times. Figure 4-57 depicts these results.

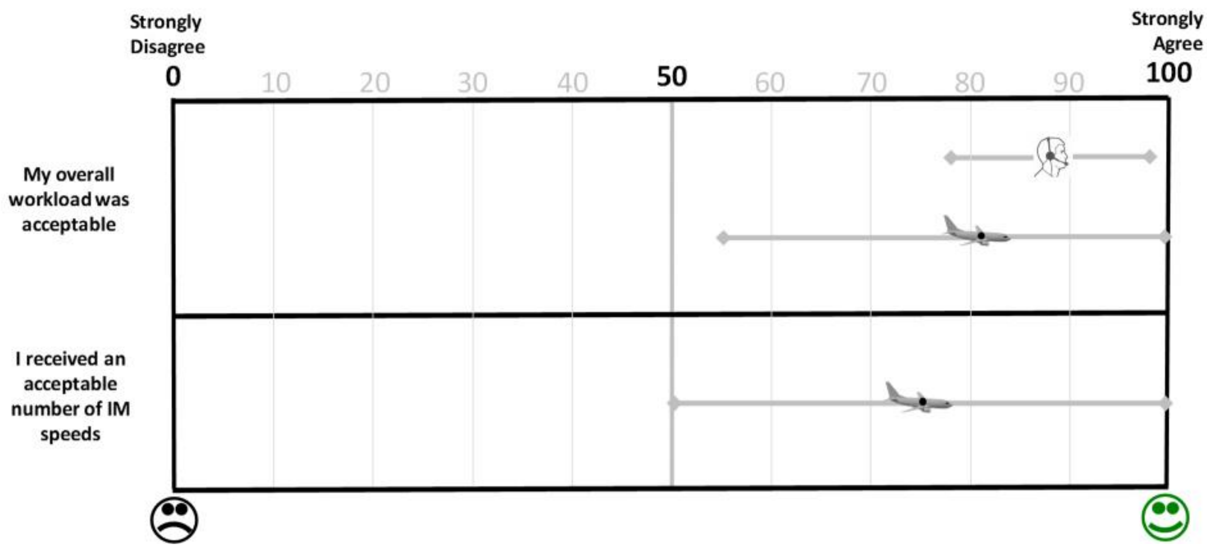

Figure 4-57. Summary of Pilot Responses on Workload Statements

4.6.3 Controller Acceptability Rating Scale

In the post-scenario questionnaire, controllers were asked to rate their acceptability of IM with Controller Acceptance Rating Scale (Table 4-43 and Figure 4-58). As can be seen, controllers generally found the system to be acceptable.

Table 4-43. Mean (SD) Controller Response to Post-Scenario Controller Acceptance Rating Scale

Controller tool set	Controller role	
	Feeder	Final
Basic	**7.8** (1.6)	**8.0** (1.2)
Basic+ cue	**7.9** (1.6)	**7.8** (1.8)
Basic+ cue and prediction	**7.5** (1.9)	**7.6** (1.5)

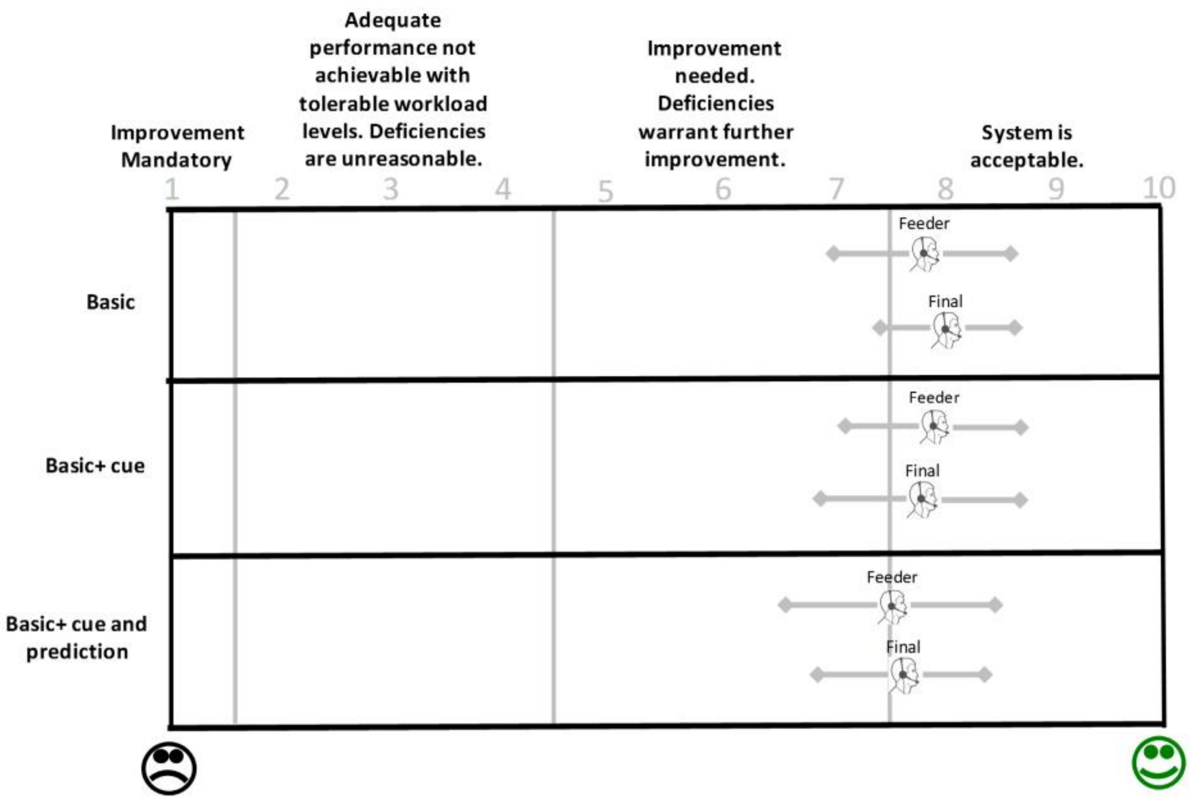

Figure 4-58. Controller Response Means to Controller Acceptance Rating Scale

The following comments were captured in the questionnaires or were made to the observers. They are not directly tied to one question, but are included for completeness.

- The environment of terminal metering and IM during nominal conditions created a relatively low workload environment.
- Controllers sometimes mentioned worries about becoming "monitors" and being less engaged in this environment.

4.7 Displays

4.7.1 Air Traffic Controllers

In the post-scenario questionnaire, controllers were asked whether they had the necessary display elements to conduct IM. The results are shown in Table 4-44 and Figure 4-59. 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. As mentioned in Section 0, a statistical test was run on this measure and no statistically significant difference was found.

Table 4-44. Mean (SD) Controller Response to Post-Scenario Statement "I had the necessary display elements for conducting IM operations"

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

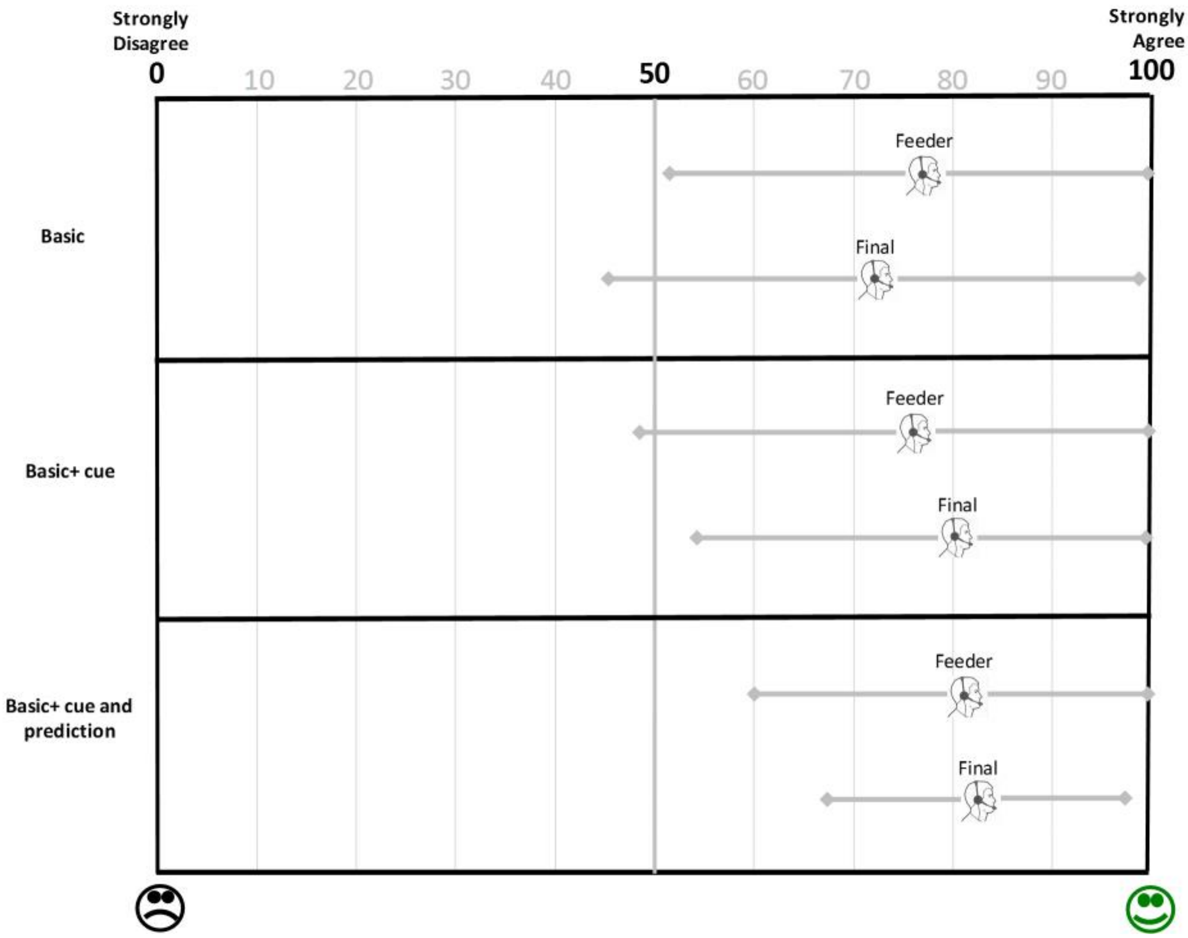

Figure 4-59. Controller Responses to Post-Scenario Statement "I had the necessary display elements for conducting IM operations"

In order to understand the impact of terminal metering elements on IM operations, controllers were asked whether the elements were helpful for IM and non-IM aircraft (Figure 4-60).

The majority of controllers agreed for the following elements (some with higher variability):

- (Non-blue) Slot markers
  - Non-IM aircraft (6/9; 67%) (M= 79.8; SD= 22.7)
- Speed advisories
  - IM aircraft (6/9; 67%; missing n= 1) (M= 66.1; SD= 31.2)
    - Note: Large variance driven by one 0 rating
  - Non-IM aircraft (6/9; 67%) (M = 69.1; SD= 25.4)
- Slot marker speeds
  - IM aircraft (8/9; 89%) (M= 76.9; SD= 28.0)
  - Non-IM aircraft (8/9; 89%) (M= 80.0; SD= 28.4)
- Aircraft indicated airspeed
  - IM aircraft (8/9; 89%) (M= 77.2; SD= 28.2)
  - Non-IM aircraft (8/9; 89%) (M= 78.4; SD= 28.3)
- Runway sequence number
  - IM aircraft (8/9; 89%) (M= 82.1; SD= 19.6)
  - Non-IM aircraft (8/9; 89%) (M= 82.0; SD= 19.6)

Controller responses were variable for the following elements.

- (Non-blue) Slot Markers
  - IM Aircraft (M= 52.8; SD= 35.0)
- Early / Late indicator
  - IM aircraft (M= 35.9; SD= 34.1)
  - Non-IM aircraft (M= 30.2; SD= 24.9)
- Runway assignment
  - IM aircraft (M= 71.0; SD= 26.1)
  - Non-IM aircraft (M= 70.9; SD= 26.2)
- Timeline
  - IM aircraft (M= 40.7; SD= 38.9)
  - Non-IM aircraft (M= 34.1; SD= 36.4)

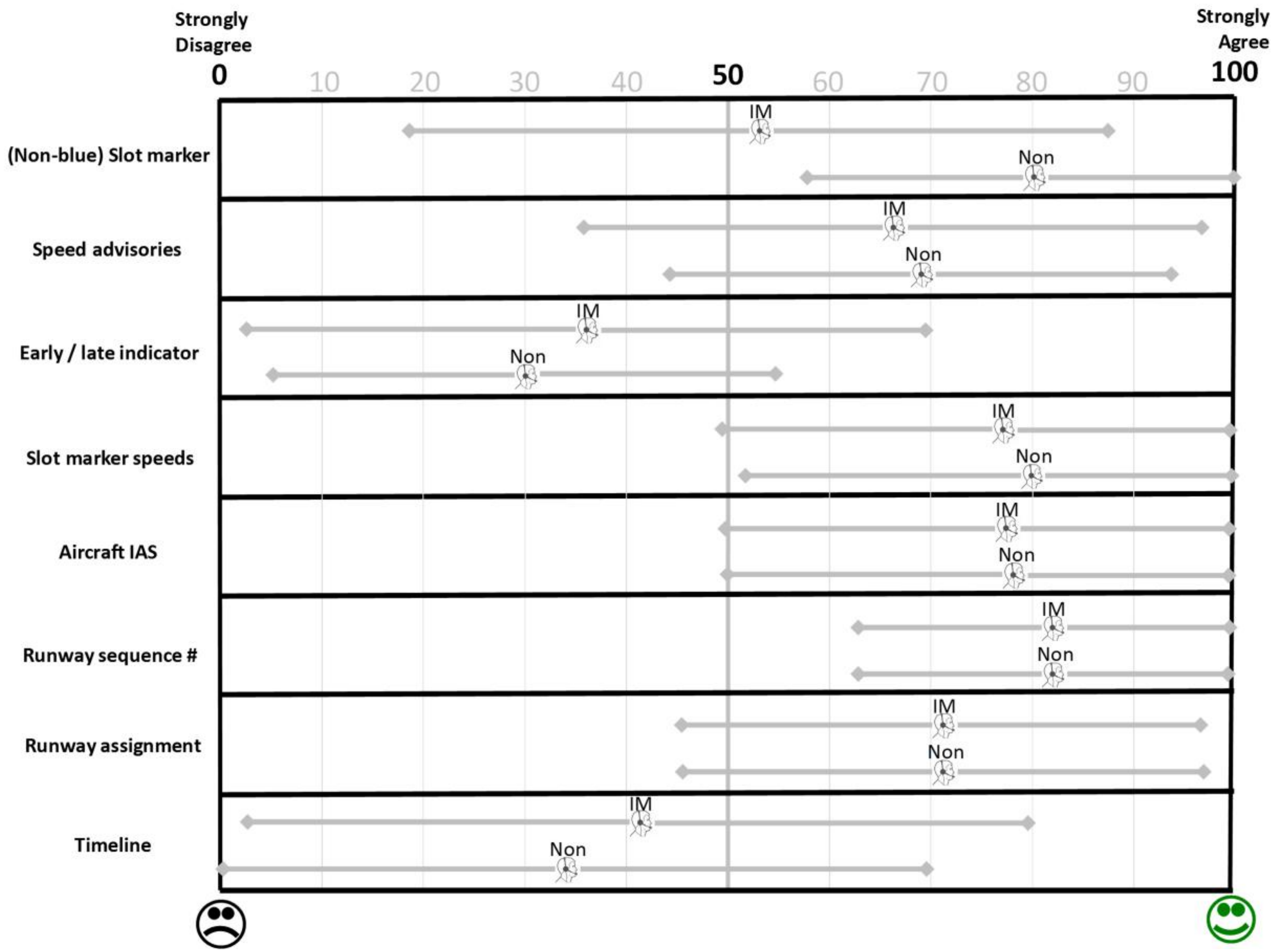

Figure 4-60. Controller Responses to "The terminal metering elements were helpful for the IM and non-IM aircraft"

The majority (7/9; 78%) of controllers agreed that the position of IM aircraft relative to the slot markers was logical (M= 74.4; SD=24.6). The majority (7/9; 78%) of controllers also agreed that the behavior of the slot markers relative to IM aircraft was logical (M= 67.7; SD=25.6).

Controllers were also asked about the new IM elements and if they were useful for IM. The results were:

- Trail aircraft status
  - The majority (8/9; 89%) of controllers agreed (M= 82.1; SD= 16.8)
- Lead aircraft status
  - The majority (8/9; 89%) of controllers agreed (M= 81.9; SD= 16.9)
- Blue slot marker
  - Controller responses were variable (M= 66.7; SD= 33.7)

While the controllers were not asked about the ATPA features, it was noted by some that ATPA distance information covered the trail aircraft status information (e.g., T(A)) in the aircraft data block. This was reported as an issue. Controllers reportedly like the status information in the data block and did not want it to be removed near and on final. If this occurred and the controllers did not have the blue slot markers for the run, the only way they knew the aircraft was doing IM was via the IM clearance window.

Controllers were asked if the information in the IM clearance window was helpful for IM. The majority (7/9; 78%) of the controllers agreed for the IM status information (M=71.1; SD=30.8). The majority (7/9; 78%) of the controllers agreed for the projected spacing / ETA differential (M=75.1; SD=21.2). The majority (8/9; 89%) of controllers also reported that it was helpful to be informed when there was no speed solution for IM (M=82.4; SD=17.9). Figure 4-61 depicts the results.

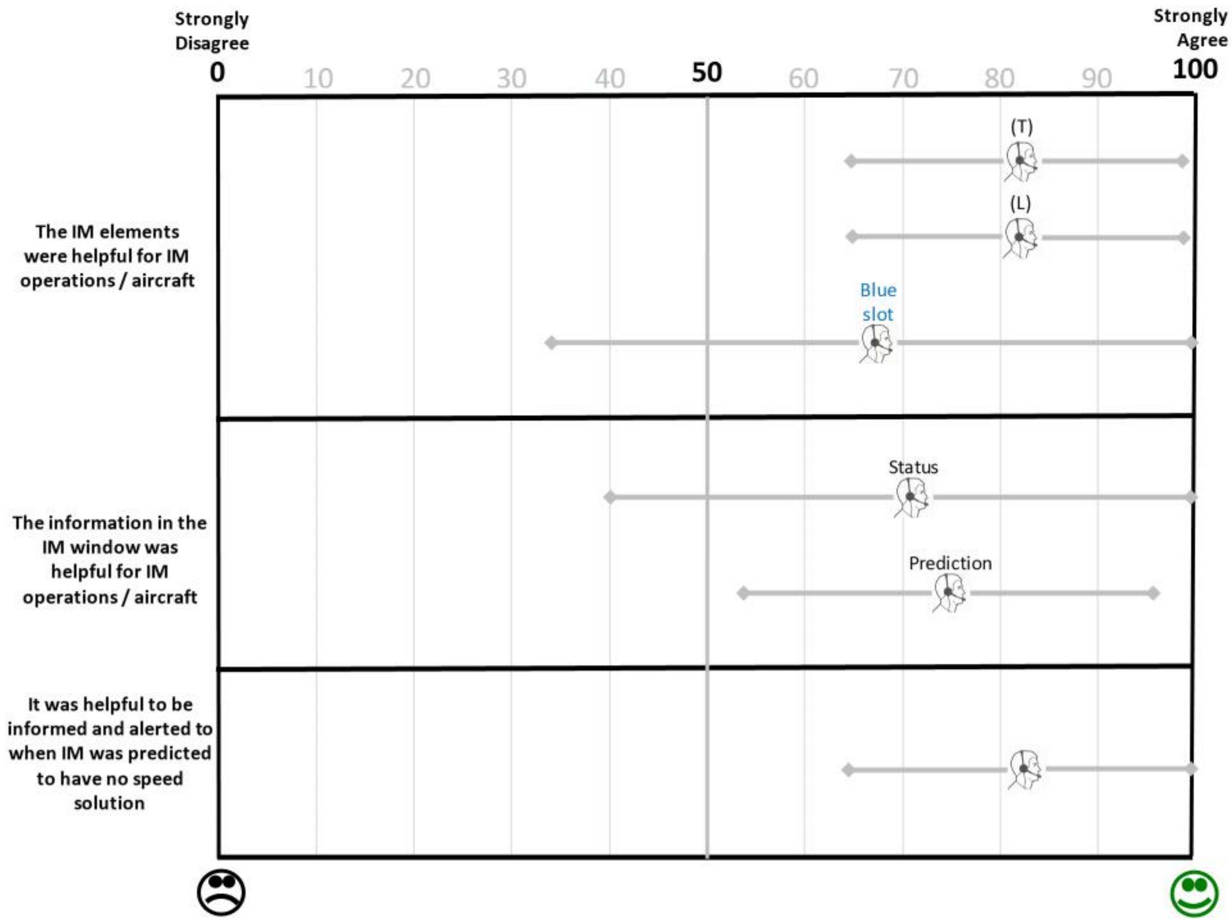

Figure 4-61. Summary of Controller Responses on IM Display Element Statements

When asked about the necessary monitoring of traffic, controller responses were variable but the majority of controllers (7/9; 78%) reported that the monitoring of IM traffic was increased (M=3.2; SD=2.0) and the controller replies were variable for non-IM traffic (M=3.8; SD=1.9) (Figure 4-62). When asked whether the necessary monitoring was acceptable, the majority (8/9; 89%) of controllers agreed for IM aircraft (M=77.6; SD=17.4) and all controllers agreed for non-IM aircraft (M=85.2; SD=12.1) (Figure 4-63).

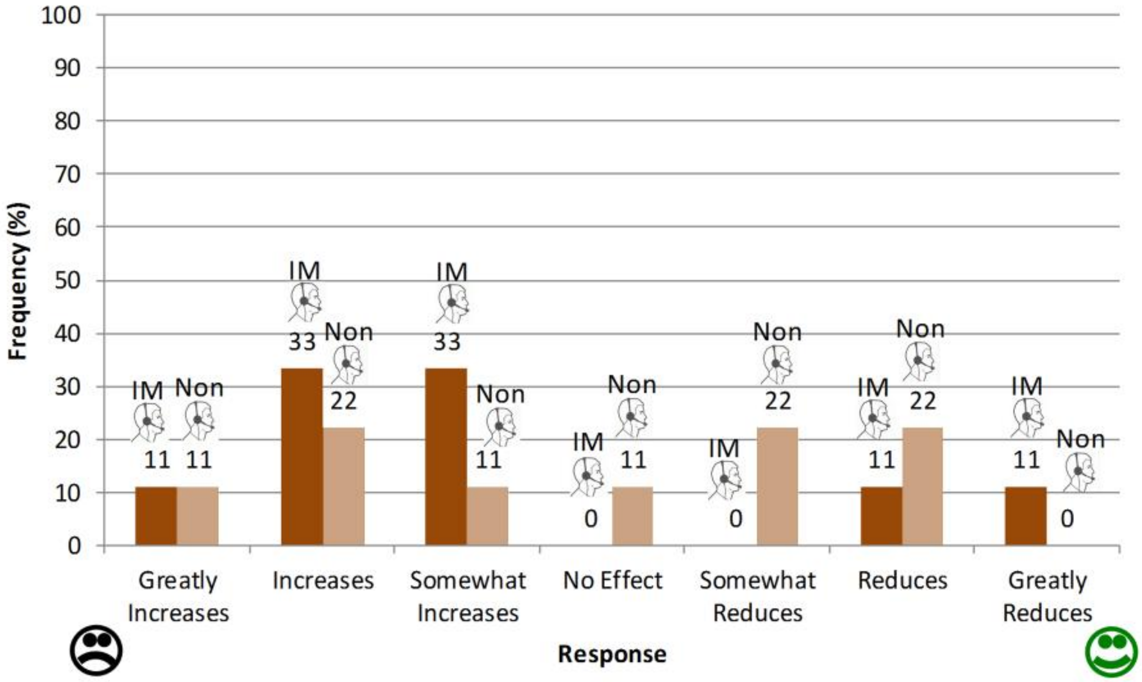

Figure 4-62. Controller Responses to "How did aircraft conducting IM during terminal metering effect your need to monitor traffic?"

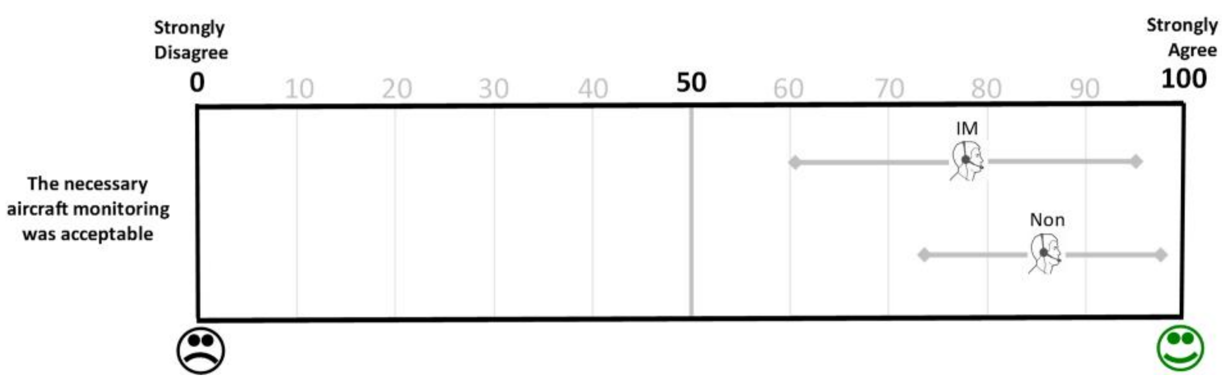

Figure 4-63. Controller Responses to "The necessary aircraft monitoring was acceptable"

4.7.2 Flight Crew

The pilots were asked about select, key min elements as well as the min+ IM elements. For the min elements, the majority (14/18; 78%) of pilots agreed the IM speed change advisory was sufficient to detect the presence of a new speed (M=71.4; SD=23.5). All pilots agreed that the IM speed conformance monitoring alert was useful (M=85.4; SD=8.6) and the majority (17/18; 94%) agreed that it is a minimum requirement (M=84.2; SD=18.4). Figure 4-64 depicts the results.

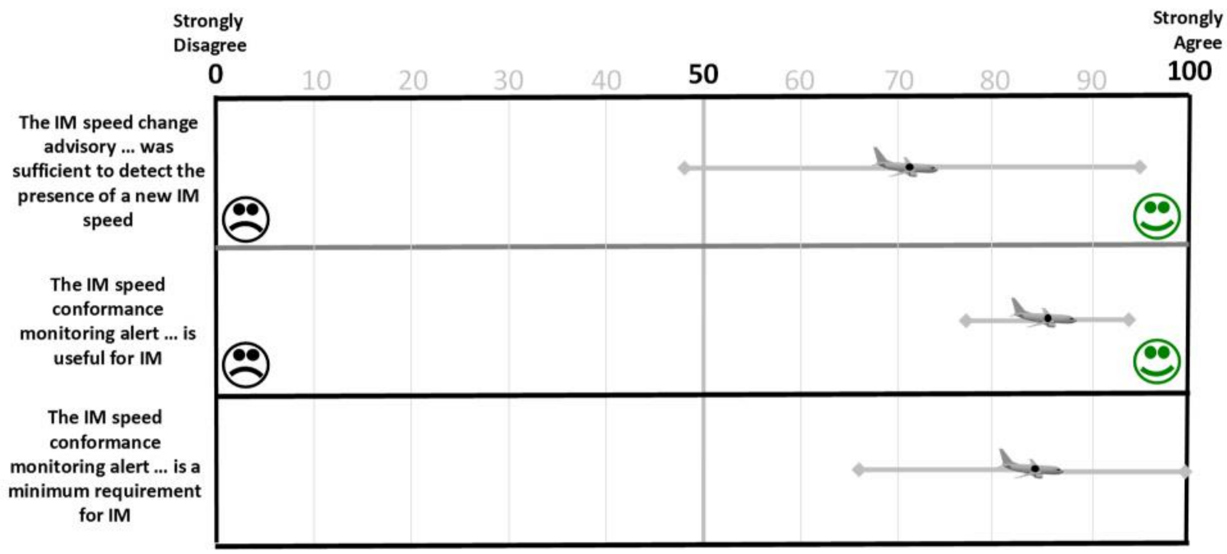

Figure 4-64. Summary of Pilot Responses on Min Display Element Statements

For the min+ elements, the majority (14/18; 78%) of pilots reported that the graphical progress indicator was useful (M=81.8; SD=20.1). However, pilot responses were variable as to whether it was a minimum requirement (M=59.2; SD=30.3). Pilots were then asked whether the graphical progress indicator was unnecessary. Responses were variable (M=59.3; SD=31.8).

The following was captured in comments made to the observer, or were in notes from the observer. The graphical progress indicator was generally preferred (over only the ASG and SI) to determine whether or not the ASG would be achieved or maintained. Without the graphical progress indicator, pilots had no clear information on the tolerances. Even with the graphical progress indicator, the situation could change as the operation evolved. A situation that was, at one point, out of tolerance, could get within tolerance at a future point. Pilots wanted clear guidance from the avionics on when to report “unable interval spacing.”

Pilot responses were variable about whether the speed tape was useful (M=59.3; SD=31.8). Three pilots commented that they wanted it on or near the PFD. The responses were variable as to whether it was a minimum requirement (M=32.9; SD=27.6), though the majority disagreed that it was a minimum requirement (13/18; 72%). Figure 4-65 depicts these results.

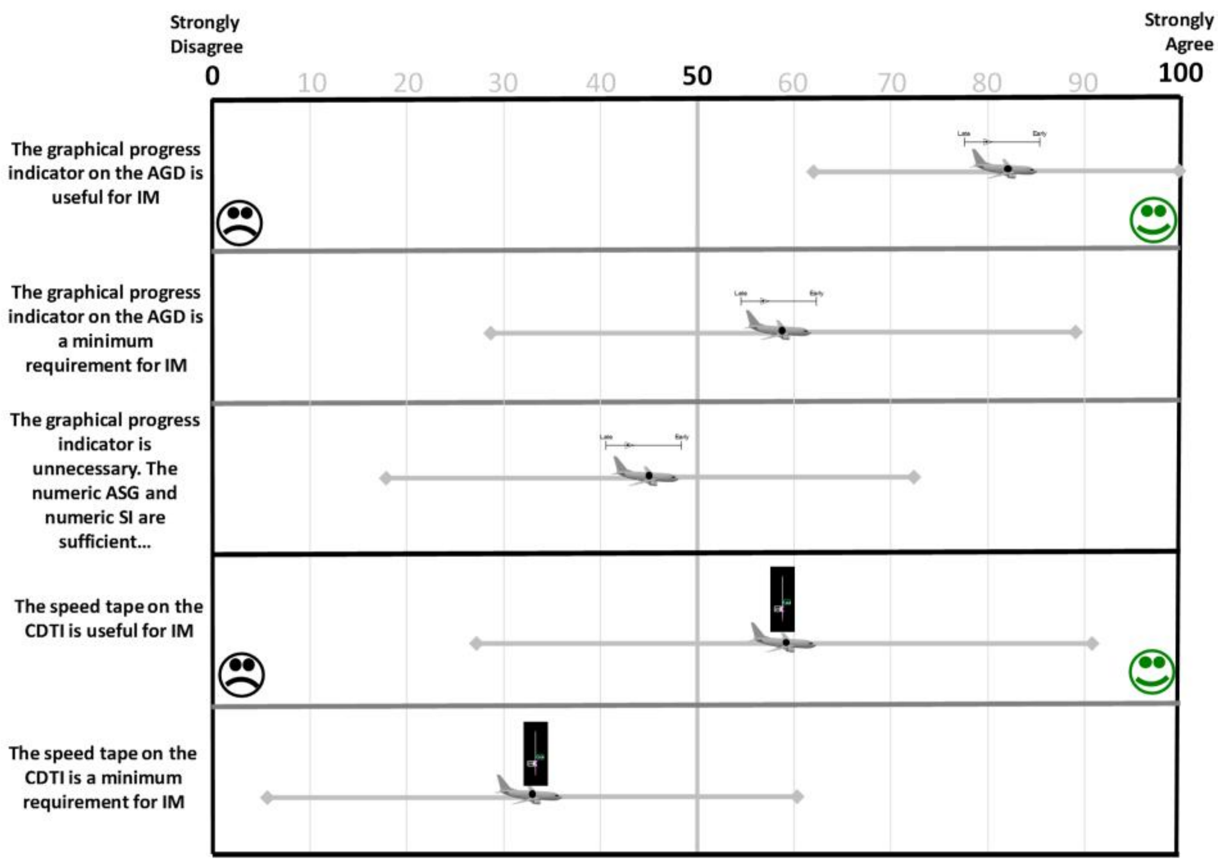

Figure 4-65. Summary of Pilot Responses on Min+ Display Element Statements

In the post-scenario questionnaire, pilots were asked whether they had the necessary display elements to conduct IM. Table 4-45 and Figure 4-66 shows pilots, on average, agreed, regardless of role or tool set. As mentioned in Section 4.1.3, a statistical test was run on this measure and no statistically significant difference was found.

Table 4-45. Mean (SD) Pilot Response to Post-Scenario Statement "I had the necessary display elements for conducting IM"

Flight crew tool set	Pilot role	
	PF	PM
Min	**83.8** (17.1)	**79.3** (22.4)
Min+	**89.2** (14.1)	**81.6** (21.9)

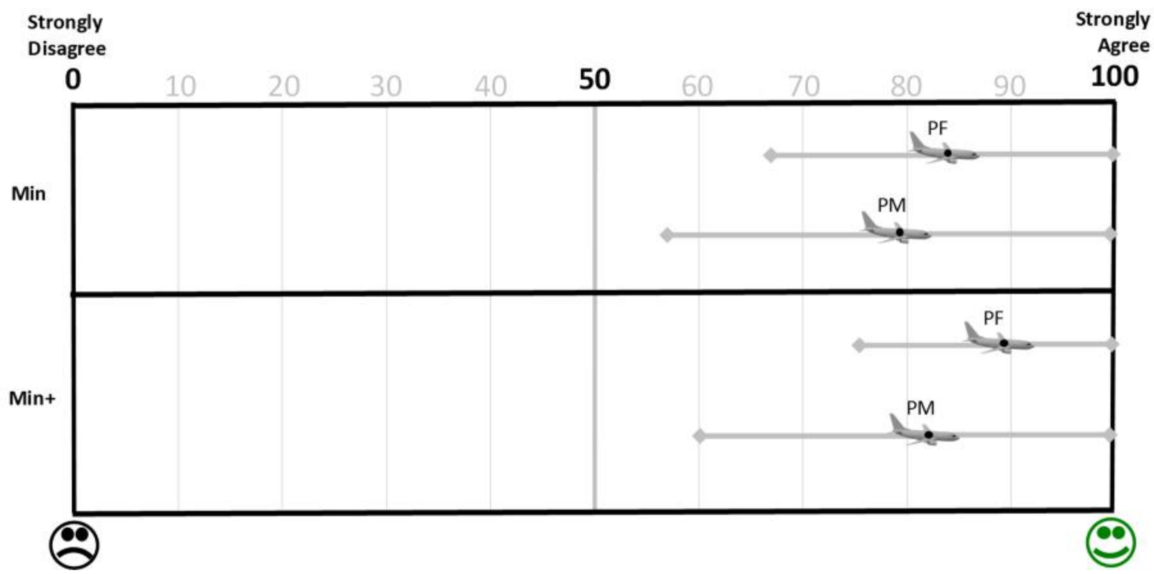

Figure 4-66. Pilot Responses to Post-Scenario Statement "I had the necessary display elements for conducting IM"

The majority of pilots reported the min (13/18; 72%) and the min+ (16/18; 89%) implementations included all the necessary information to conduct IM (Figure 4-67).

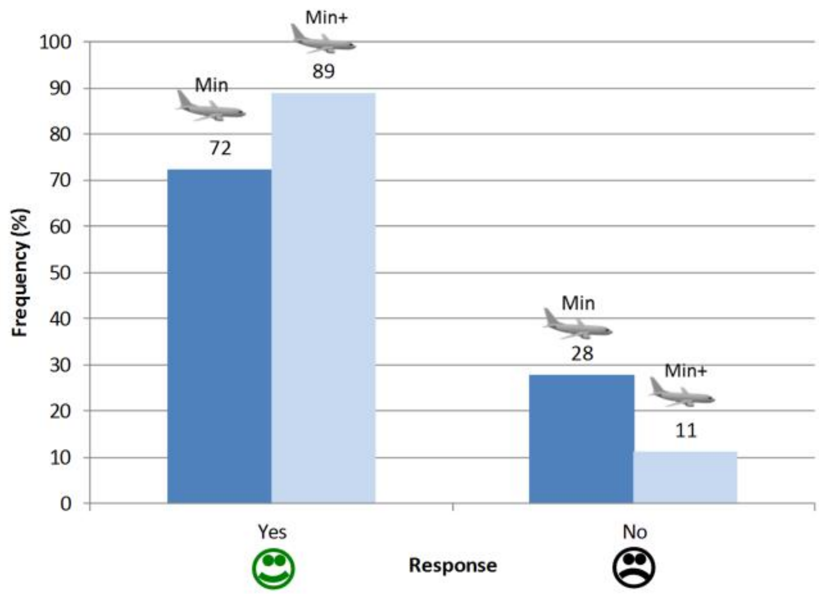

Figure 4-67. Pilot Responses to "Did the combination of both the AGD and CDTI implementations include all the information necessary for you to conduct IM?"

The majority of pilots reported that no display elements were confusing or misleading on neither the AGD (16/18; 89%) or CDTI traffic display (17/17; 100%; missing=1) (Figure 4-68). The reports of misleading information appeared to be due to initial misunderstandings or simulation issues (e.g., "didn't understand the box at first"), not on-going issues.

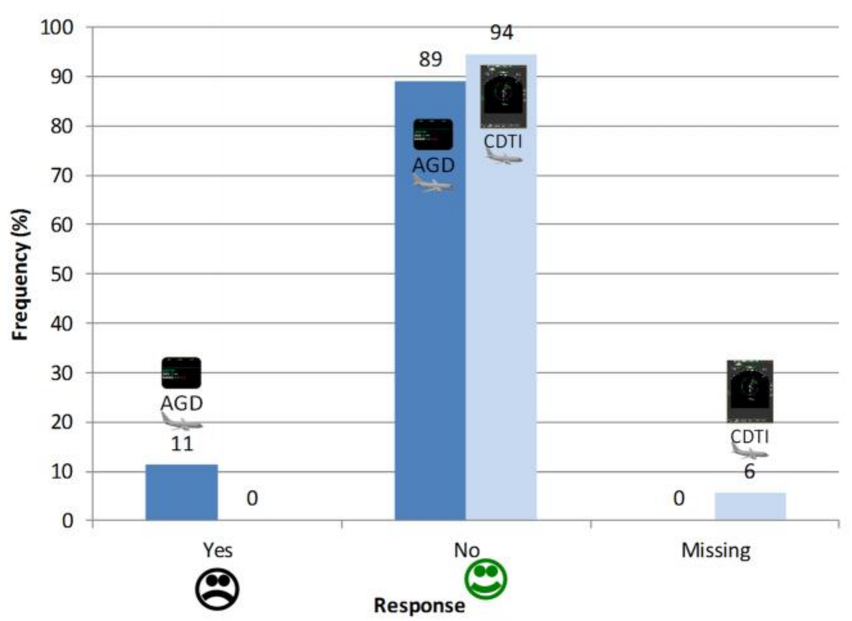

Figure 4-68. Pilot Responses to "Did you find any elements on the displays to be confusing or misleading?"

Pilots reported being able to focus more on the AGD than the CDTI. The PFs reported spending 83% of their time on the AGD while the PMs reported spending 67% of their time on the AGD (Figure 4-69).

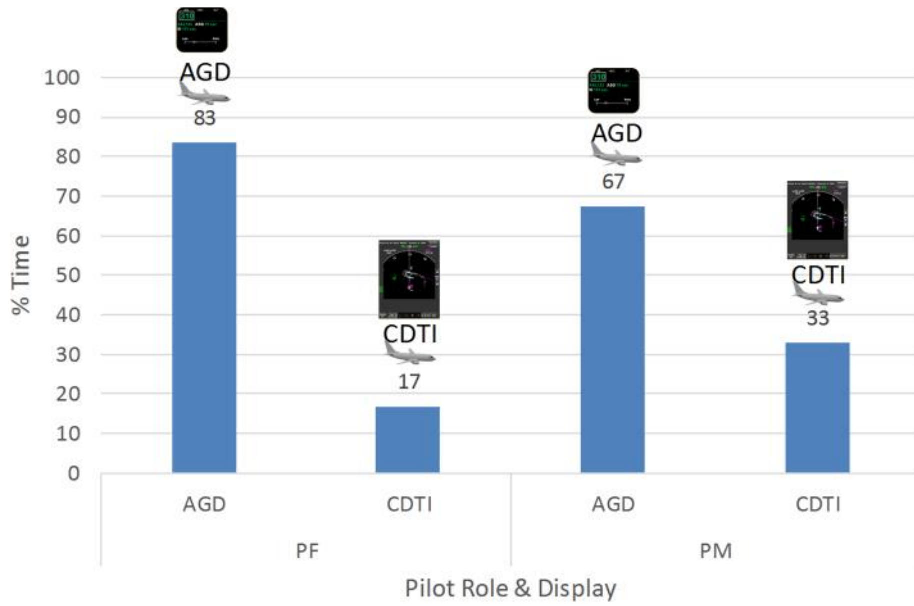

Figure 4-69. Pilot Responses to "Considering total time on the IM displays, estimate the total percentage of time using each display"

The majority (17/18; 94%) of pilots reported being able to perform IM by primarily focusing on the AGD (M=87.4; SD=14.1). When asked if they could integrate the displays into their normal scan, the majority (16/18; 89%) of the pilots agreed for the AGD (M= 75.1; SD=27.1) but the responses were variable for the CDTI (M=54.6; SD=32.8). The majority (16/18; 89%) of the pilots agreed that the necessary scan time was acceptable (M=74.4; SD=24.4). Pilot responses were variable (M=63.7; SD=30.1), but the majority (13/18; 72%) agreed that the amount of head down time was acceptable. Figure 4-70 depicts these results.

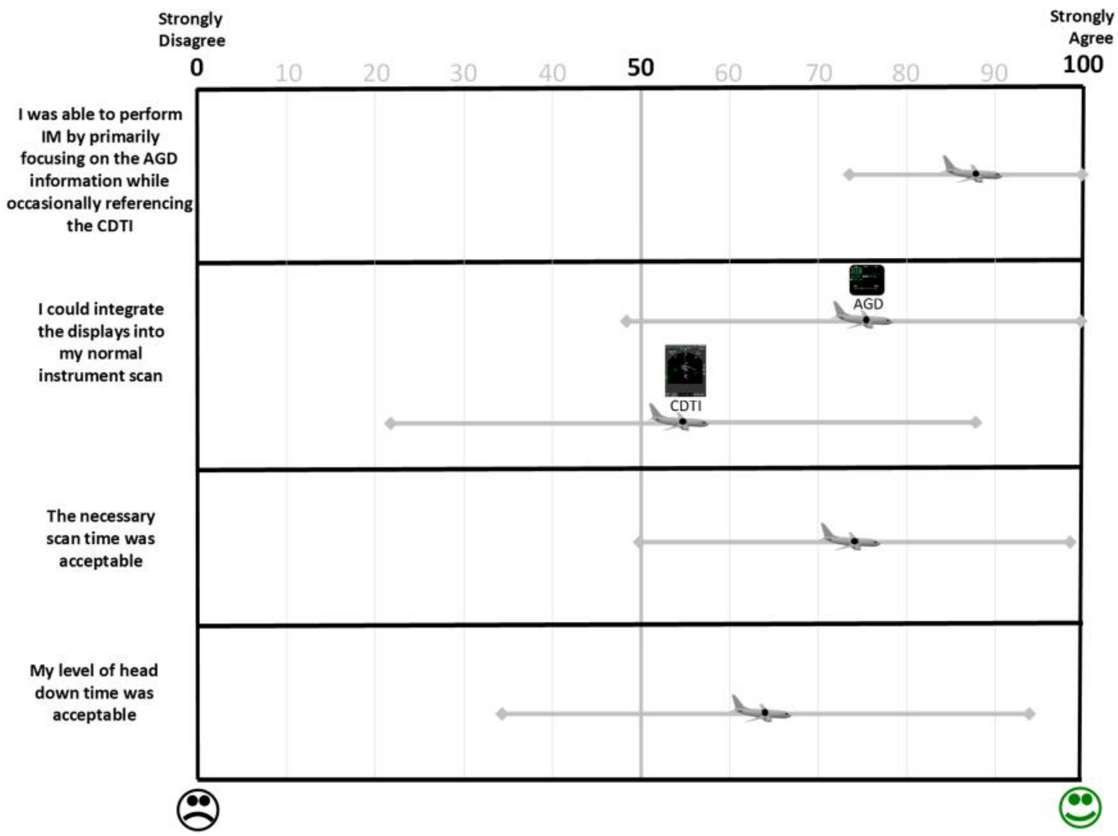

Figure 4-70. Summary of Pilot Responses on the Instrument Scan

Pilot were asked whether the display combination was acceptable for the CDTI states of clearance entry, entry evaluation, and execution. The majority of pilots agreed for all states.

- Clearance (awaiting) entry (15/18; 83%) (M= 79.1; SD= 23.7)
- Entry evaluation / cross flight deck coordination (16/18; 89%) (M= 83.4; SD= 18.5)
- Execution / IM conduct without graphical progress indicator (15/18; 83%) (M= 69.3; SD= 23.1)
- Execution / IM conduct with graphical progress indicator (16/18; 89%) (M= 83.0; SD= 18.9)

For the awaiting entry state, the research observer noted that participants often chose to type in the lead aircraft identification instead of selecting the lead aircraft and having the field automatically populated (as described in Section 3.1.1.2). This appeared to be due to the difficulty / burden associated with finding the lead aircraft on the CDTI traffic display.

Finally, when asked if they would be willing to perform IM with the tested displays, the majority (16/18; 89%) agreed for both the minimum (M= 74.9; SD=22.3) and the minimum+ (M= 79.1; SD=25.5) implementations. Figure 4-71 depicts the results.

As would be expected, pilot comments included ones stating a preference for having the IM information integrated into the PFD and navigation display.

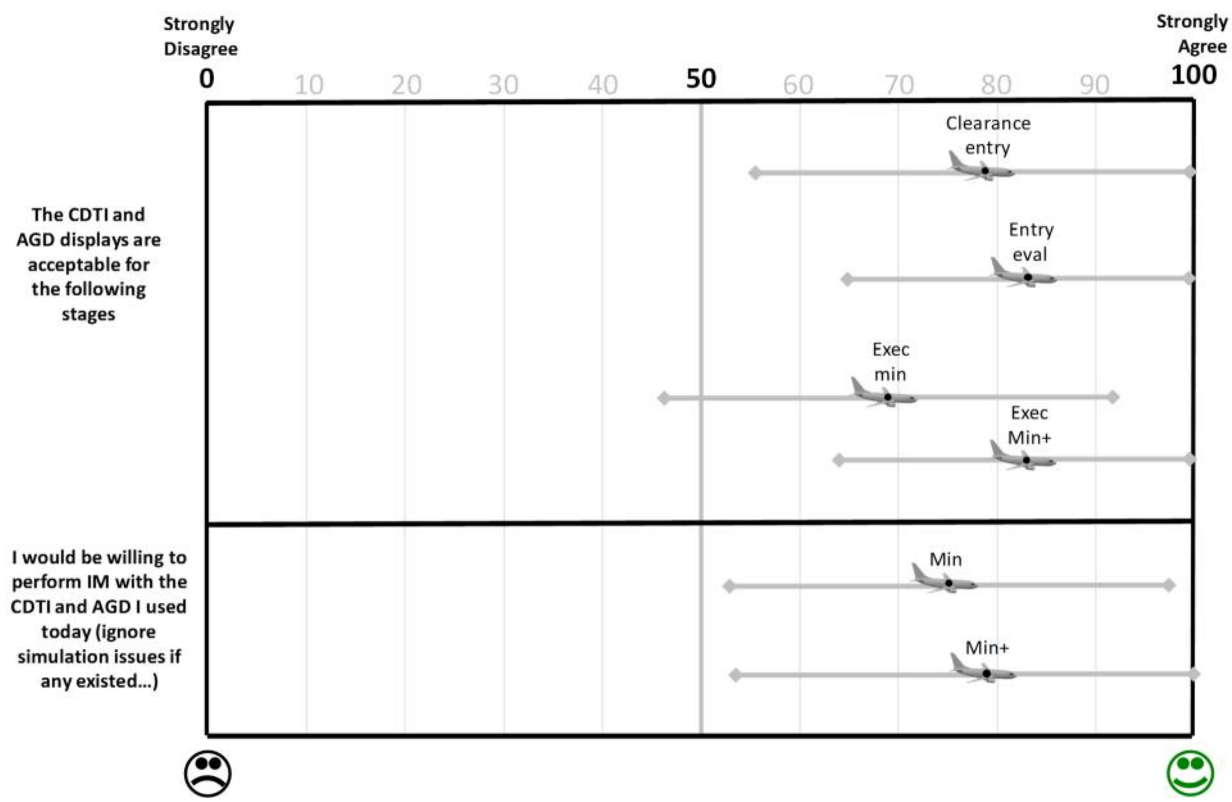

Figure 4-71. Summary of Pilot Responses to Display Acceptability Statements

4.8 Roles and Responsibilities

Participants were asked whether their roles and responsibilities were clear. The majority (8/9; 89%) of the controllers agreed for IM aircraft (M= 87.0; SD=17.8) and all controllers agreed for non-IM aircraft (M= 93.0; SD=7.9). The majority (17/18; 94%) of the pilots agreed (M= 87.1; SD=19.2). Figure 4-72 depicts the results.

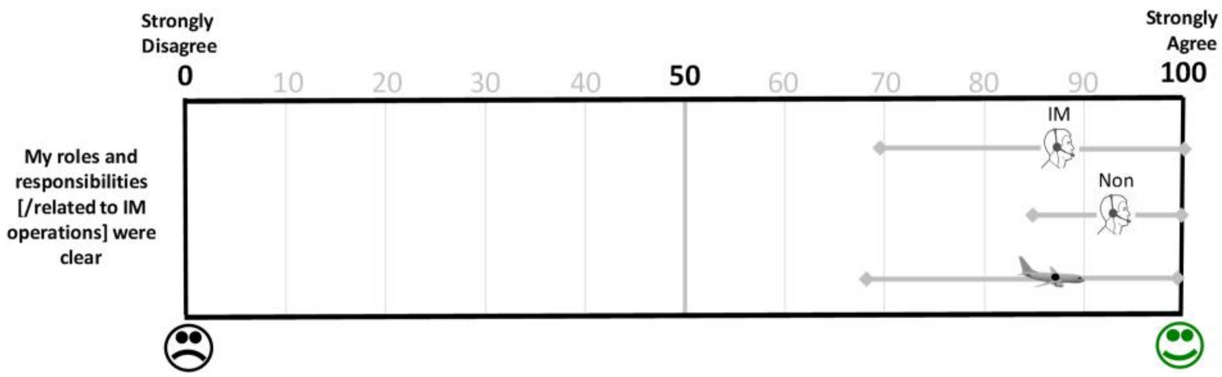

Figure 4-72. Summary of Controller and Pilot Responses on Role and Responsibilities Statements

4.9 Time on RNAV Arrival

When aircraft were conducting IM, they were on their RNAV procedure 98.2% of the time. Non-IM aircraft were on their RNAV procedure 93.8% of the time. IM aircraft were off the RNAV path on average 222.2 seconds (SD=187.0) and non-IM aircraft for 317.7 seconds (SD=182.0) (Table 4-46). As can be seen, less time was spent off the RNAV path for IM aircraft as compared to non-IM aircraft.

Table 4-46. Total Time in Seconds (SD) Aircraft were off the RNAV Path

Controller tool set	Aircraft role		
	IM	Non-IM	Combined
Basic	**245.6** (196.5)	**307.1** (164.9)	**276.4** (180.7)
Basic+ cue	**210.7** (181.5)	**339.4** (160.3)	**275.1** (170.9)
Basic+ cue and prediction	**210.2** (183.0)	**306.7** (220.7)	**258.5** (180.7)
Combined	**222.2** (187.0)	**317.7** (182.0)	**270.0** (177.4)

4.10 Communications

Participants were asked whether the IM clearance was acceptable. The majority (7/9; 78%) of controllers agreed for capture then maintain (M=80.4; SD=22.1) and controller responses were variable for achieve-by (M=57.9; SD=30.6) clearances. Four controllers reported wanting to keep the clearance concise. Two mentioned that data link communications would help.

Participant pilots only received achieve-by clearances and the majority (16/18; 89%) agreed that they were acceptable (M=84.6; SD=27.3). The majority (16/18; 89%) of the pilots reported that the necessary information was available in the clearance to detect and select the lead aircraft (M=82.8; SD=22.2).

Participants were asked whether the use of the lead aircraft identification in the IM clearance was acceptable. The majority (7/9; 78%) of controllers agreed (M=82.9; SD=19.9). Pilot responses were variable (M=79.4; SD=27.6) but the majority (14/17; 82%; missing=1) agreed. Figure 4-73 depicts these results.

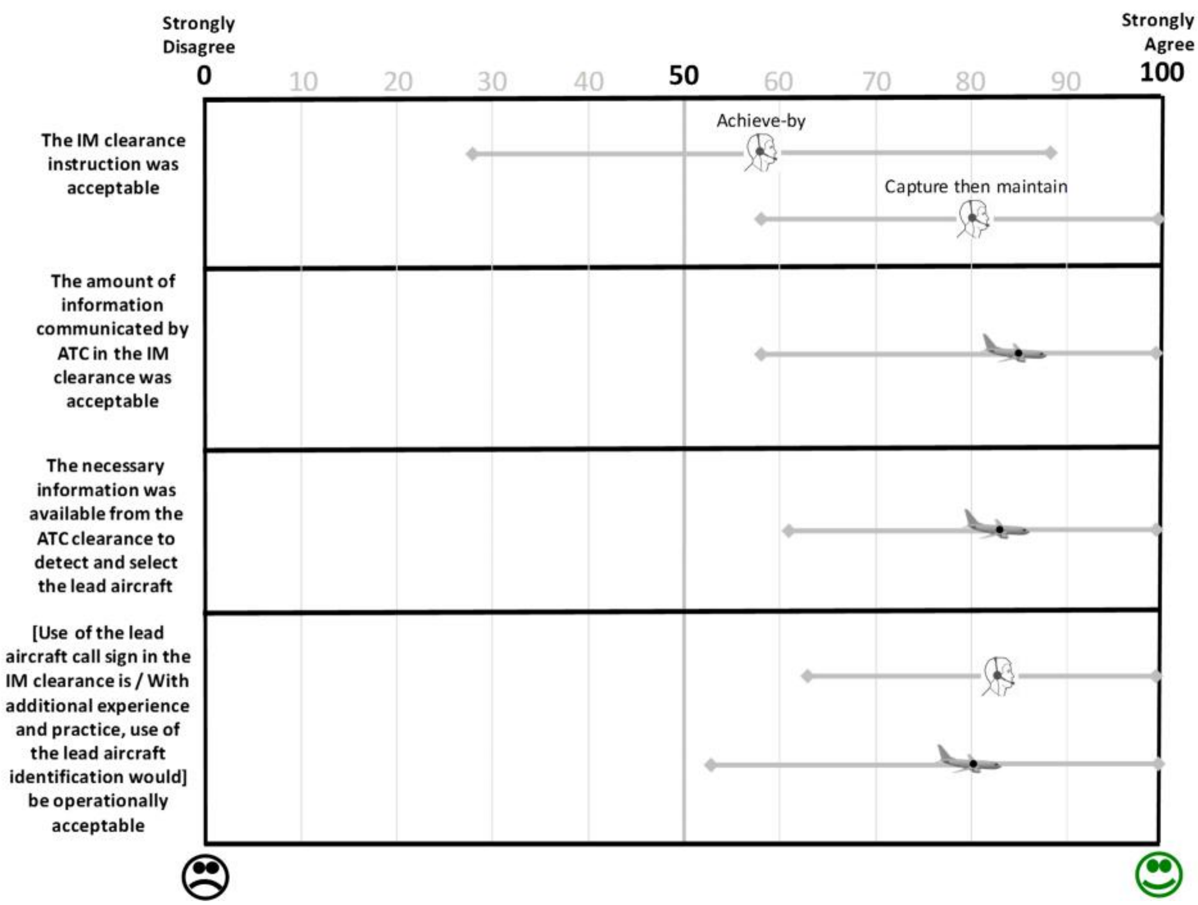

Figure 4-73. Summary of Controller and Pilot Responses on Phraseology Statements

When asked whether they had any issues when the lead aircraft identification was used in communications, the majority (8/9; 89%) of controllers and the majority (15/18; 83%) of pilots reported they did not (Figure 4-74).

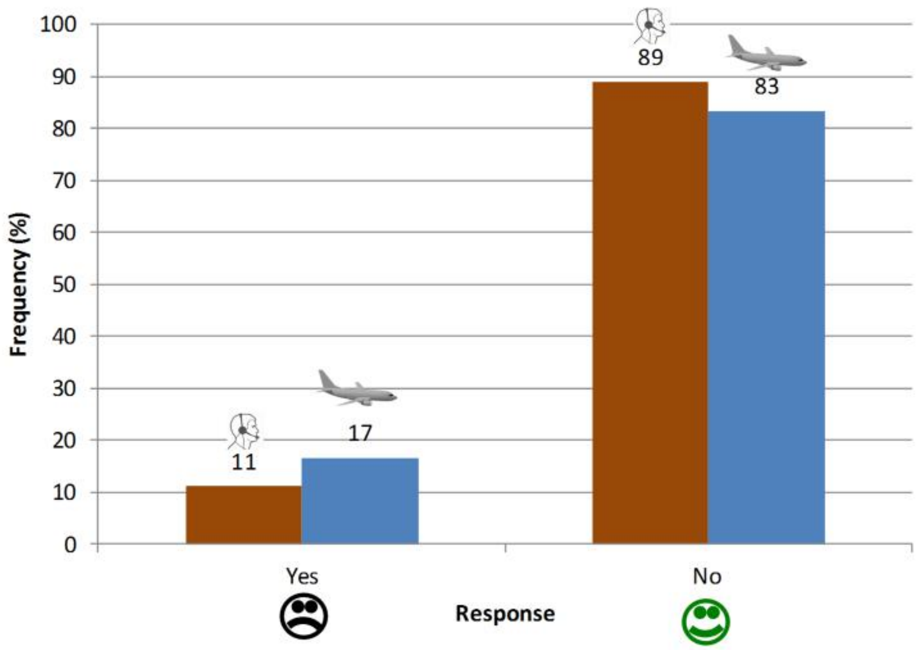

Figure 4-74. Controller and Pilot Responses to "Did you have any issues during communications when the lead aircraft call sign was used?"

4.11 En Route Initiation

The main topic to examine in the simulation was controllers initiating IM in the TRACON. However, some questions existed about receiving aircraft into the TRACON that were already conducting IM. Since the en route IM initiation scenarios were outside the main set of scenarios, the majority of the post-scenario results are presented separately in this section. The results are shown in Figure 4-75. Note that the post-simulation questionnaire did not distinguish between TRACON and en route initiation so the results are only from the post-scenario questionnaire.

In the post-scenario questionnaire, controllers, on average, agreed when there were asked whether they:

- Were confident the spacing of the aircraft would remain outside their separation requirement
  - Higher variability existed for IM aircraft for all tool sets and for non-IM aircraft for the basic+ cue tool set
- Could detect spacing or separation issues
  - Higher variability existed for IM aircraft for the basic+ cue and the basic+ cue and prediction tool sets
- IM is operationally acceptable
  - Higher variability existed for IM aircraft for the basic+ cue tool set
- Had the necessary display elements to conduct IM
  - Higher variability existed for IM aircraft for the basic+ cue tool set

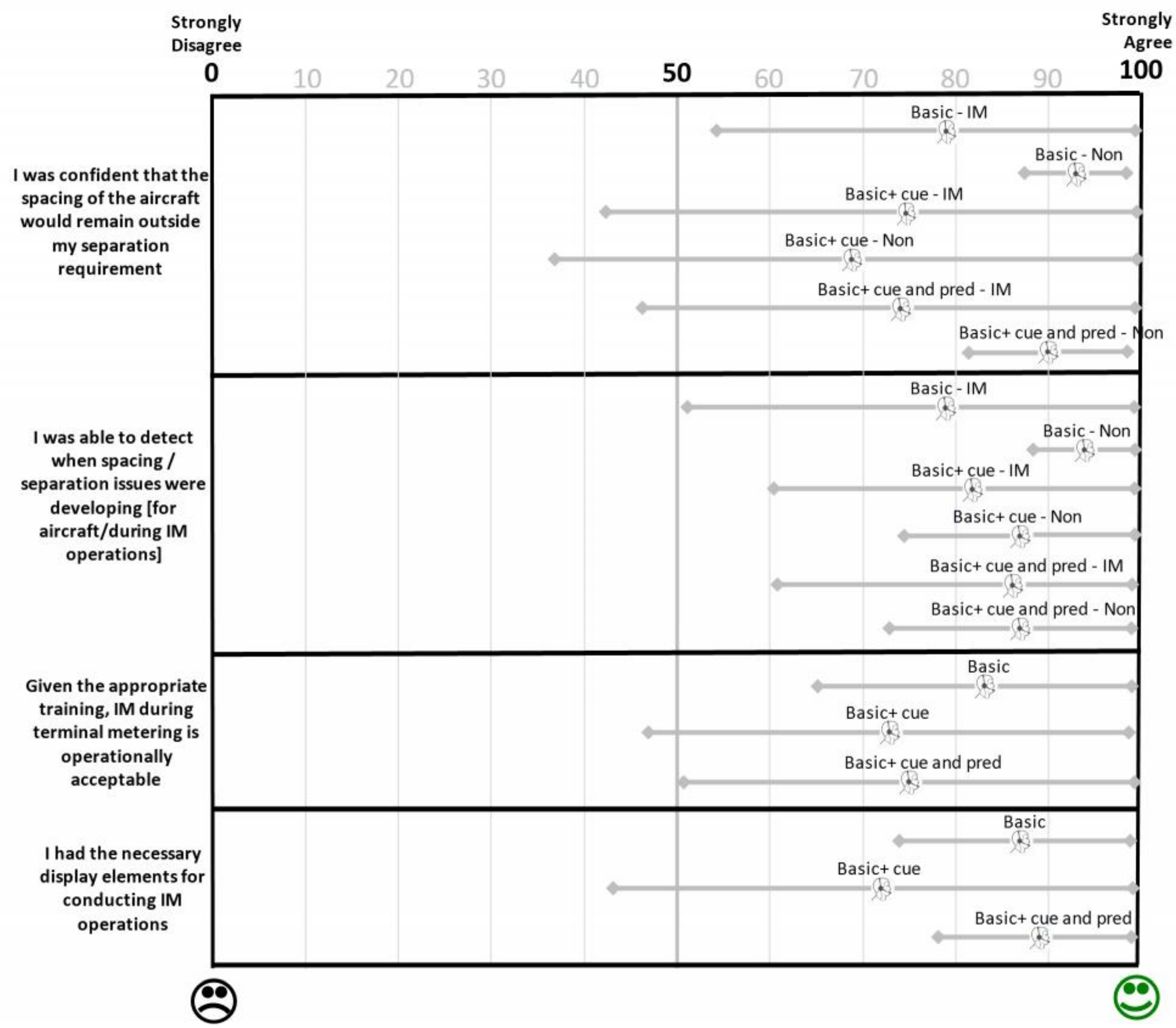

Figure 4-75. Controller Responses to Post-Scenario Statements on En Route Initiation

In the post-scenario questionnaire, controllers were asked to rate their average overall workload during en route initiation on the Bedford Workload Rating Scale. Figure 4-76 shows the ratings. Controllers generally found workload to be acceptable across the tool sets.

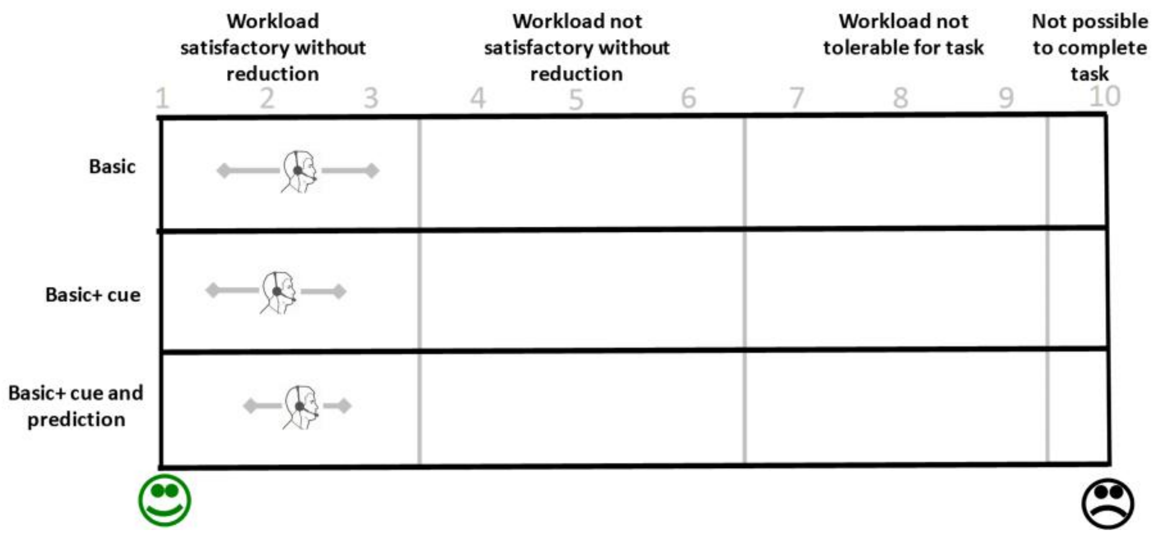

Figure 4-76. Controller Responses to the Bedford Workload Rating for En Route Initiation

In the post-scenario questionnaire, controllers were asked to rate their acceptability of IM during en route initiation with Controller Acceptance Rating Scale. Figure 4-77 shows the ratings. Controllers generally found IM operationally acceptable across the tool sets but the basic+ cue and prediction tool set average is in the "improvement needed" category.

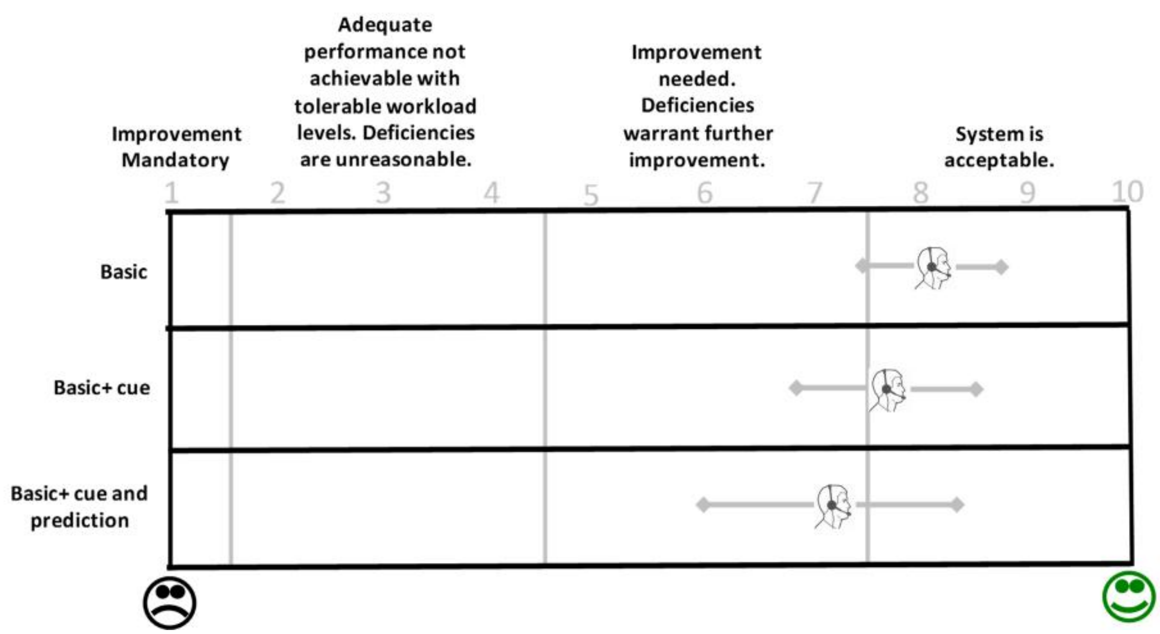

Figure 4-77. Controller Responses for Controller Acceptance Rating Scale for En Route Initiation

There were zero cases of aircraft spacing below the applicable separation and no IM terminations occurred.

4.12 Simulation Assessment

Participants were asked whether the training they received was adequate. All controllers agreed for IM (M=93.0; SD=7.4) and TSAS / terminal metering (M=93.1; SD=7.1). The majority (16/17; 94%; missing=1) of the pilots agreed (M=82.2; SD=14.0). Participants were also asked whether the overall activity was effective for evaluating IM during terminal metering. The majority (8/9; 89%) of controllers agreed (M=81.7; SD=18.3), and the majority (16/17; 94%; missing=1) of pilots agreed (M=85.8; SD=13.9). Figure 4-78 depicts these results.

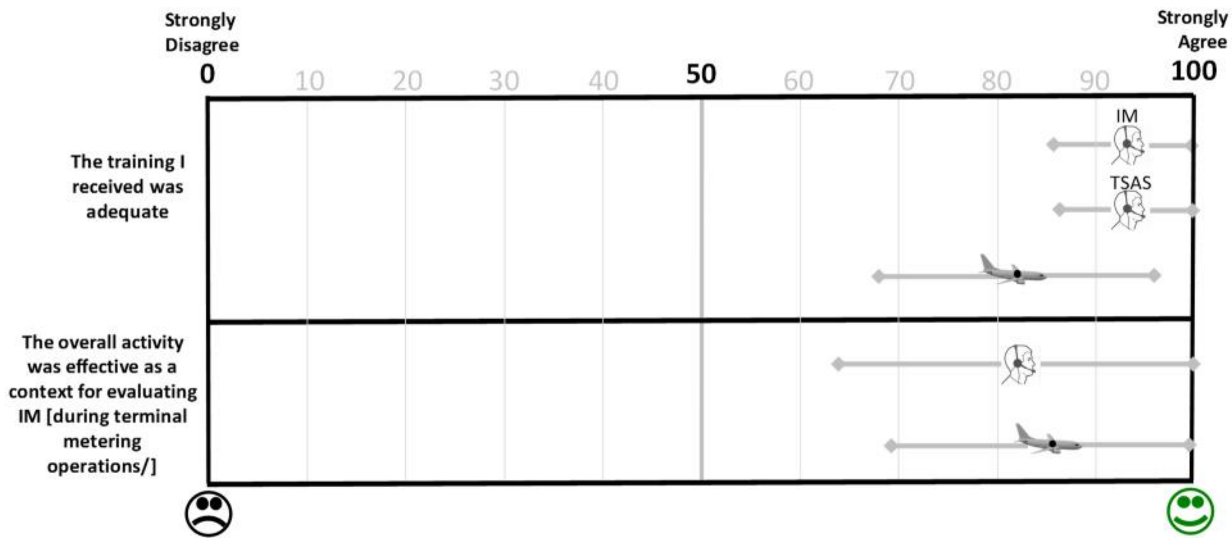

Figure 4-78. Summary of Controller and Pilot Responses on Simulation Assessment Statements

5 Discussion

5.1 IM During Terminal Metering

Terminal metering was of more interest (from a research perspective) for the controller participants, than the pilot participants, because it was new to them. Also, terminal metering was less of an issue for the flight crews because it was relatively transparent to them because they conduct IM operations in the same manner in and out of metering environments. Therefore, the flight crew questions and replies are more relevant in consideration of IM operations, while the controller replies cut across the entire environment of terminal metering, RNP RF turns, and IM.

Majorities of both controllers and pilots reported IM during terminal metering was operationally desirable and acceptable. A majority of controllers reported IM was compatible with terminal metering operations (as seen with: Rognin et al., 2005; Callantine et al., 2012; Peterson et al., 2012; Baxley et al., 2016). 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: Callantine et al., 2012).

Controllers also reported that it was acceptable to receive aircraft from both a (simulated) en route controller and a (participant) feeder controller. The majority of controllers reported they were confident both IM and non-IM aircraft would be handed off with minimal problems, though non-IM aircraft received higher / more positive ratings. Controllers did not appear to have issues with two different ABPs, nor spacing / separation issues with IM aircraft that were still in the achieve stage when passing the merge 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., Callantine et al., 2012). Therefore, this level as well as lower levels such as those seen in early NASA ATD-1 simulations (e.g., 3 aircraft per scenario, 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 and pilots reported that roles and responsibilities were clear. The majority of both groups also reported that overall workload was acceptable, though the pilot results were more variable. The majority of controllers and pilots reported acceptable traffic awareness, and associated monitoring, for IM and non-IM aircraft. However, though controller responses were variable, the majority reported 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, a few issues were noted about the overall metering environment with IM and structured arrivals that join the final approach course with speeds and altitudes for the flight crew to fly. 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. They also reported RNP RF turns as challenging in general based on an aircraft joining the final approach course late in the approach / at the FAF.

5.2 IM Conduct

5.2.1 Controllers

Of all the IM clearances proposed by the terminal metering system, 97% were initiated by the controllers. Of the 3% rejected, over half were by one controller. The capture then maintain clearances were rejected less often than the achieve-by clearance types, and were initiated approximately 11 seconds faster and earlier in the airspace. This seems likely due to the different geometries of the two clearance types. In the capture then maintain operations, aircraft are on the same path (likely easier to visualize) and the clearance information is reduced (likely easier to read and interpret[21]). Thipphavong et al. (2013) also found controllers were more likely to initiate IM when the IM trail aircraft and the lead were on the same route as is seen in the capture then maintain clearance type.

Less than 1% of IM operations were suspended and of those, less than half were resumed. Over half of the suspensions were from one controller. One quarter of the suspensions were due to spacing concerns. Other known reasons were related to increasing efficiency and vectoring the lead. Controller terminations of IM occurred in approximately 4% of the IM operations and the most frequent reasons were the same as those for suspensions. There were 4% fewer terminations for achieve-by operations and they occurred over 1.5 minutes later in the airspace as compared to capture then maintain operations. Few differences were found between the different controller tool sets.

The majority of controllers reported: (1) they were confident both IM and non-IM aircraft would remain outside their separation requirement, (2) the spacing achieved by IM and non-IM aircraft was acceptable, (3) they were able to detect spacing / separation issues developing, and (4) it was clear aircraft were working toward appropriate spacing. However, for all four statements, non-IM aircraft had more positive ratings and / or lower variability. Additionally, observations and comments showed controllers did not appear to feel entirely comfortable allowing aircraft to conduct IM, especially when close to the separation standard. Controllers reported some discomfort in not actively managing the aircraft speed and not knowing when aircraft would change speeds.

Few differences were found for controller actions or replies based on controller role. Overall, IM operations for controllers went well, with almost all clearances issued and initiated, and very few operations suspended or terminated. However, some level of discomfort in IM operations was observed. Based on reports from controllers, the issue seemed to be related to not actively issuing speeds to IM aircraft and thus not knowing what speeds would be flown and when.

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[21] This same situation is possibly seen when comparing the results noted in Bone et al. (2007) and Penhallegon and Bone (2008). See Section 2.5.1.2.

5.2.2 Flight Crew

The achieve-by operations had a rate of 1.5 speeds per minute while capture operations had a rate of approximately two per minute. The majority of pilots reported these rates as acceptable as was the case in past simulations (e.g., Swieringa et al., 2014; Kibler et al., 2015). About 6% fewer IM speed conformance advisories were issued for the achieve stage as compared to the maintain stage. For the achieve-by stage, IM speeds occurred more frequently the closer the aircraft was to the ABP. For the capture stage, IM speeds were fairly evenly distributed across the entirety of the stage.

IM speed reversals (a speed decrease followed by speed increase) can be challenging (i.e., confusing and annoying) for flight crews. Speed increases can also be challenging in arrival and approach operations when flight crews normally only decelerate and have to configure the aircraft for landing (i.e., deployment of flaps). The observer noted that pilots had issues with IM speeds that required an acceleration after the aircraft started the configuration for landing. This issue has been noted in other IM activities (e.g., Penhallegon, Bone, and Stassen, 2016b). Only 3% of the IM speeds were reversals but 17% of the IM speeds were speed increases. Fewer of both occurred for the achieve stage as compared to the maintain stage, and most speed reversals occurred later in the operation and when in the final controller's airspace.

The majority of the pilots reported that it was clear the IM speeds were driving toward achieving and maintaining the ASG, though responses were variable and the observer noted that participants had issues with this. Regardless, the majority of pilots reported the spacing achieved / maintained was acceptable and that they were able to detect whether they would remain within tolerances for the ASG.

About half the pilots reported trying to out-guess the IM algorithm, though only a few reported choosing to fly a speed other than the IM speed.

As with the controllers, IM operations went well for the flight crews with most clearances being flown and few reports of "unable." However, some level of distrust in the IM algorithm operations was observed. Based on reports from pilots, the issue seemed to be related to the question of feasibility of the IM operation.

5.3 Aircraft Spacing and Separation

In general, aircraft entered the feeder controller's airspace slightly ahead of schedule on average (as described in Section 3.1.6). On average, aircraft were also ahead of, but within 3 seconds of, schedule at the constraint points of DERVL and RHYAN. Aircraft stayed ahead of schedule at the FAF / YOKXO by approximately 7 seconds (for IM aircraft) and 5 seconds (for non-IM aircraft).

Aircraft were in their slot markers about half time in the feeder controller's airspace but IM aircraft were inside for less time (46%) than non-IM aircraft (54%). When aircraft were outside of their slot markers, they were generally ahead of the slot markers (ahead of schedule). At the handoff from the feeder to final controller, aircraft were on average within 2 seconds of their slot marker centers. Both IM and non-IM aircraft were in the slot markers approximately 18% of the time in the feeder controller's airspace. Again, when aircraft were out of the slot markers, they were generally ahead of the slot markers (ahead of schedule). Wynnyk and Kopald (2013) 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.

Although aircraft were often outside of their slot markers and ahead of schedule, the relative position of the trail aircraft to the lead is important. 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. While minor differences between IM and non-IM pairs existed when the lead aircraft was behind its slot marker, they appeared minor and were resolved as the aircraft merged at DERVL and arrived at the FAF / YOKXO. Overall, IM and non-IM aircraft met the performance baseline / goals expected for the operations.

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 became more concerned with relative spacing of aircraft, as seen in past simulations. For example, Wynnyk and Kopald (2013) 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 looks much like the controller's behavior 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 (e.g., Cabrall et al., 2012). This was seen in this simulation in the feeder controller's airspace and most likely due to achieve-by aircraft working toward the ASG though not as quickly as the controller was getting aircraft into the slot markers for handoff to the final controller. 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.

There were no controller comments suggesting that candidate IM aircraft should be in their slot markers in feeder controller's airspace prior to starting IM (as there were in the concept evaluation activities mentioned in Section 2.4.2.3).

There were only five events where the spacing within an aircraft pair was below the separation standard in the feeder or final controller's airspace. None of the events were for an aircraft actively conducting IM. The specific reasons for the events were unclear.

5.4 Displays

5.4.1 Controllers

Controllers were asked about the terminal metering tools, but only in relation to IM operations. They were also asked about the usefulness of the new IM display elements. Three controller tool sets were examined in this simulation:

- **Basic:** TSAS features, the IM clearance window, as well as the IM trail and lead aircraft status fields in the data blocks
- **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 (shown in parentheses after the lead aircraft identification in the IM clearance window)

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 of these 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 or 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.

The ratings for the terminal metering tools were also generally similar for both IM and non-IM aircraft except for the slot markers (without the additional IM cue). Controllers found the slot markers (without the additional IM cue) less useful for IM but the responses had a lot of variability. However, observations indicate the slot markers (without the additional IM cue) were still important and utilized for IM aircraft. IM aircraft behavior relative to the slot markers was reported in the previous section. When considering the results for the terminal metering tools, they did not appear to conflict with IM operations and several seemed to provide as much useful information for IM aircraft as for non-IM aircraft.

Overall, past work such as Cabrall et al. (2012) 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. Thipphavong et al. (2013) also had similar results and reported controllers found the slot markers, timeline, and speed advisories were useful but less so for IM aircraft.

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 (e.g., Peterson et al., 2012; Callantine et al., 2013; Thipphavong et al. 2013). Benson et al. (2011) and Peterson et al. (2012) 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 (e.g., Benson et al., 2011; Cabrall et al., 2012; Callantine et al., 2012; Callantine et al., 2013). Presenting the status of the lead aircraft is not only helpful in understanding aircraft roles, it was found by Thipphavong et al. (2013) to reduce the chance of suspending an IM operation by 20%.

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. The cue was introduced for the simulation based on feedback received during the concept evaluation activities leading up to the simulation. Those individuals reported the cue as useful and helpful as compared to situations without it. However, controllers in this simulation did not clearly report it to be as useful and helpful.

For the different controller tool sets, statistical tests found no statistically significant difference between tool sets (or controller roles) for the question of being confident the IM aircraft spacing would remain outside the separation requirement. There was also no difference for the question of whether they had the necessary 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.

The currently-fielded ATPA feature was available and utilized in the simulation. Some controllers reported issues with the ATPA distance covering the trail aircraft IM status (e.g, T(A)) when aircraft were on final and ATPA was active. They liked the IM information in the data block and if they did not have the slot marker cue, the only way they knew the aircraft was doing IM was in the IM clearance window.

5.4.2 Pilots

Two flight deck tool sets were examined in the simulation. The first was termed "min" and was built to the standards specified in DO-361 (RTCA, 2015a). The second was the "min+" tool set that included two features not required in DO-361 (RTCA, 2015a): the graphical progress indicator and speed tape. IM information was presented on two different displays: the CDTI traffic display and the AGD.

The AGD was the primary display to be used during IM and contained the key information elements. It was expected to be where the pilots primarily focused with an occasional reference to the CDTI traffic display. Pilots reported being able to primarily focus on the AGD while occasionally referencing the CDTI traffic display. Pilots reported the AGD was easier than the CDTI traffic display to integrate into the normal instrument scan. The pilot replies were variable as to how well the CDTI traffic display could be integrated into their normal instrument scan. However, the majority agreed that their overall scan time was acceptable and generally agreed that the required head down time was acceptable. Related to this, pilots reported wanting the

IM information integrated into the PFD and navigation display, versus into new displays such as an auxiliary traffic display.

The min IM speed change advisory was reported as useful and a minimum requirement for IM by the pilots. The majority of pilots also reported that placing a box around new IM speeds was sufficient for detecting the presence of a new speed. Pilots did not report a need for an aural alert for each new IM speed. Data did show that when pilots had not complied with IM speeds they had been presented for a shorter period of time (around 8 seconds) than those that were complied with. That could be due to pilots missing the IM speed (which was noted by the observer in some cases) or pilots not having time to implement the IM speed before another one was displayed. Either way, it seems that it was reasonable operationally to miss the speed as another one was about to be presented. All pilots agreed that the IM speed conformance monitoring alert was useful and the majority agreed that it is a minimum requirement. This alert has an aural associated with it and seemed to be sufficient for an aural alert related to IM speeds.

Since the IM speed conformance alerting was, unintentionally, implemented differently than specified in DO-361 (RTCA, 2015a), it is interesting to determine whether the behavior seen in the simulation helps validate the requirements. Approximately 58% of the advisories provided in the simulation were per the standard. The other 42% were not and were inside the tolerance threshold specified in the standard. The number of advisories seen in the simulation were not reported to be problematic and may have actually helped more with conformance than if the alerting was implemented per the standard. The use of this result is a bit unclear due to the potential interaction between the additional alerts and the speed conformance.

The display implementation purposefully did not make a distinction for the pilots about whether they were in the achieve or maintain stage of the achieve-by then maintain clearance type. The distinction was not believed to something that the flight crew needed to act on, so the information was not provided. This approach did not reveal any issues with pilot awareness of IM operations, which suggests this should not be a minimum requirement.

A majority of pilots reported a willingness to perform IM with both the min and min+ tool sets and that both included the necessary information. The majority also agreed that they were able to detect spacing issues with both tool sets. Additionally, two statistical tests run on the use of the two tool sets did not reveal any statistically significant findings. This indicates that the min tool set may be sufficient as a minimum implementation. However, caution should be exercised with these results as past work and some data from this simulation indicate that at least the graphical progress indicator should be considered for a useful minimum requirement. This result and caution is similar to that reported in Swieringa et al. (2014) where a simulation similar to that reported here was conducted. The following paragraphs will review the two min+ features (i.e., the graphical progress indicator and speed tape).

The graphical progress indicator was reported as useful by the majority of pilots, but opinions were mixed as to whether it is a minimum requirement. However, much of the past work on IM has either required this feature or has worked to perfect it. EUROCONTROL requires a graphical spacing cue (Hoffman et al., 2006), NASA Ames used one (NASA, 2004), and NASA Langley has been working to perfect one (e.g., Swieringa et al., 2014). MITRE recommended one but did not have one developed based on supporting a specific implementation (Bone et al., 2003). Pilots have also indicated a strong preference for such a feature (e.g., Baxley et al., 2013). Additionally, the feasibility check as implemented in this simulation was based on DO-361 (RTCA, 2015a) defined bounds that were found to be in error (based on the use in this simulation). As a result, the bounds used in this simulation flagged infeasible operations more than was intended by the authors of DO-361 (RTCA, 2015a). Additionally, operations that were shown as infeasible would become feasible again before the flight crew acted. Pilots appeared to have difficulty determining whether an operation was going to remain infeasible and what action to take. These issues could have led to questioning whether the graphical progress indicator should be a minimum. Pilot comments in various questions indicate that it is important to clarify tolerances and the associated actions.

Pilot opinions were variable on whether the speed tape on the CDTI traffic display was useful and a minimum requirement. Pilot opinion of the speed tape was likely driven by the placement of the feature on the CDTI traffic display, which was not where the pilots were expected to, or did, focus. Moving this feature to the AGD or PFD could impact this result and make the feature more desirable, as it contains key details such as the IM speed, whether the IM speed is set in the MCP, and whether the aircraft is flying the IM speed. Such information has been displayed or required in past research (e.g., Hoffman et al., 2006; Bone and Long, 2014; Latorella, 2015).

Overall, the min+ tool set received more “yes” replies (compared to the min) when pilots reported whether the display included all the necessary information. Additionally, higher / more positive ratings were provided (compared to the min) when pilots reported the ability to detect developing spacing issues. The ratings were also higher for the min+ tool set (compared to the min) when pilots were asked whether the displays were acceptable during IM execution.

The objective data also shows more positive trends for the min+ tool set. While the rate of IM speeds per minute and magnitude of IM speed for both tool sets were similar, pilots complied with approximately 6% more IM speeds and had less spacing error at the ABP for the min+ tool set (though the trends should only be considered in light of other trends as neither were statistically significant). Pilots also received approximately 6% less IM speed conformance advisories for the min+ tool set.

Few to no comments were received about the need for additional display features beyond the min or min+ tool sets. However, there were pilots replies from different questions asking for trend information on the graphical progress indicator, especially when near or at the tolerance boundaries.

5.5 Communications

The participant pilots did not receive capture then maintain clearances, but those clearances are shorter and so the amount of information contained in them should also be acceptable. The capture then maintain clearance was reported as acceptable by controllers. The amount of information in the achieve-by clearance type was reported as acceptable by participant pilots. However, the achieve-by clearance type acceptability had variable controller responses. Just less than half of the controllers reported wanting to keep the clearance concise, though efforts had already been made in this simulation to keep the clearance concise (e.g., not stating the PTP in the clearance).

The pilots also reported that the necessary information was available from the clearance to detect and select the lead aircraft. The information provided was the lead aircraft identification (e.g., American one twenty-three). Once the flight crew had the lead aircraft identification, they could either select the traffic by touching it on the display or they could enter the aircraft identification and it would be selected for them. The majority of the time they did the latter.

Pilots and controllers reported the use of the lead aircraft identification in the IM clearance was acceptable, though there was some variability in the pilot replies. The majority of both pilots and controllers reported no issues when the lead aircraft identification was used.

5.6 IM Benefits

The spacing error (the difference between the planned interval and the achieved interval) was measured for all aircraft at the FAF / YOKXO. For IM aircraft, the planned interval became the ASG at the ABP and the spacing error is a direct measure of how close the IM aircraft were to the ASG. For non-IM aircraft, it is a measure of how well the aircraft met the planned interval. Both IM and non-IM aircraft had a small spacing error (under 1 second) but the IM aircraft had half the variance (4.1 seconds less) of non-IM aircraft. These results are similar to past work that found IM reduces the inter-arrival spacing variation (e.g., Rognin et al., 2005; Prevot et al., 2007). IM aircraft met the ASG with a 4.1 second SD. Therefore, IM aircraft met the performance goal of 5.0 seconds IAT SD mentioned in Section 2.2.2.1. Overall, IM and non-IM aircraft met the performance baseline / goals expected for the operations.

Aircraft conducting IM spent approximately 1.5 minutes more on the RNAV path (less time vectored) as compared to non-IM aircraft. This result is similar to that found by Thipphavong et al. (2013) who also found IM aircraft (and their lead aircraft) remained on the RNAV routes longer than those not conducting IM. Keeping IM aircraft on their routes is an indication that controllers were allowing those aircraft to conduct IM and that IM was not causing enough of a spacing / separation concern to vector the IM aircraft off the optimized RNAV routes.

6 Recommendations

6.1 IM During Terminal Metering General Acceptability

While IM during terminal metering was found acceptable by controllers and flight crews in general, some topics may require additional study.

- Initiation geometries different than those examined here may be more challenging. One example may be when the trail aircraft performing IM is in one feeder controller's airspace and the lead aircraft is in another feeder controller's airspace (such as opposite corner posts). The display tool sets and topics examined in this simulation could also be examined in these more challenging geometries. For example, the topic of IM aircraft potentially being out of their slot markers more often than non-IM aircraft may be more of an issue for feeder controllers who are working the aircraft into the slot markers for the next constraint and the handoff to the final controller. If the lead aircraft is not in the feeder controller's sector, this could be more of an issue. Dependent runway operations such as those currently being defined in RTCA may introduce new issues, and therefore, should also be examined.

Overall, the vast majority of IM operations were initiated and only a few were suspended or terminated by the controller. This indicated at least some level of trust on the part of the controller. Trust may also come with additional experience. However, controllers did report increased monitoring and showed some signs of mistrust.

- The topic of controller trust in the behavior of IM aircraft should continue to be examined until the appropriate operations and tools are identified to support sufficient trust in IM.

Controllers did not have significant issues with receiving aircraft from en route controllers that were already conducting IM. This was noted as a potential issue in the concept evaluation activities leading up to the simulation.

- Situations should be identified where receiving aircraft conducting IM from en route controllers is an issue. Once they are identified, they should continue to be examined to determine whether the issue can be addressed or those operations should be excluded.

The simulation only proposed an achieve-by clearance to controllers when the ASG was between 70 and 240 seconds (as noted in Appendix A). There were times when the controller noted ASGs closer to 240 seconds and did not find IM necessary for such large intervals.

- Consideration should be given to the maximum reasonable ASG in the terminal environment so controllers are not bothered with IM clearances they may want to reject.

Flight crews were generally in agreement about the acceptability of IM speeds and algorithm behavior, but there was some variability in replies related to the clarity of IM speeds driving toward the appropriate spacing. Also, approximately half the pilots reported trying to outguess the algorithm.

- The topic of flight crew trust in the behavior of IM should continue to be examined until the appropriate tools are identified to support sufficient trust (discussed further in display Section 6.3.2).

While IM may contribute to controllers monitoring traffic more than actively engaging with them, the overall environment in which IM was placed (i.e., structured arrivals that join the final approach course with speed and altitude restrictions) already had reduced controller active engagement (e.g., limited vectoring).

- The topic of controllers as monitors may require additional study or, at least, continued consideration.

While not an IM issue, RNP RF turns from downwind to the FAF were found to be challenging for controllers.

- It may be desirable to ensure controllers have the appropriate tools (e.g., slot markers on final) to ensure these turns are not too demanding.

6.2 Aircraft Spacing and Separation

IM aircraft appeared to behave in a manner similar to non-IM aircraft. However, an issue that has been noted in past research (e.g., Cabrall et al., 2012) is that IM aircraft may be outside their slot markers for longer periods of time than non-IM aircraft. In this simulation, it was seen in the feeder controller’s airspace and was most likely due to achieve-by aircraft working toward the ASG, though not as quickly as the controller was getting non-IM aircraft into their slot markers for handoff to the final controller. If aircraft conducing IM are not expeditiously trending toward their slot markers, this could still be an issue.

- 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. In this simulation environment, it did not appear to be a major issue.

Related to this topic, there were no discussions in this simulation of wanting to get IM aircraft into their slot markers in the feeder controller’s airspace prior to starting IM.

- This simulation indicated no need for this to be a standard operating procedure.

6.3 Displays

Controller and pilot roles and responsibilities play a key role in the information that should be displayed to them. The flight crew needs sufficient information to tell the controller when they are unable to comply with the IM clearance (since controllers expected to hear that). The graphical progress indicator, or something similar, could be a key element.

The controller mainly needs to know when separation will be an issue. A predicted spacing / ETA differential, or something similar, could be a key element.

- Controller and pilot roles and responsibilities and the necessary display information to support those roles and responsibilities should continue to be defined and explored. It is not expected that many new elements are needed, but that the appropriate ones to support the roles and responsibilities need to be identified and tested. The following sections provide suggestions related to this topic area.

6.3.1 Controllers

Terminal metering tools did not appear to conflict with IM operations and several seemed to provide as much useful information for IM aircraft as for non-IM aircraft (similar to results in past simulation such as Cabrall et al., 2012 and Thipphavong et al., 2013).

- Based on the results of this simulation, the terminal metering tools tested did not conflict with IM and there were no results indicating any should be removed, including the slot markers. The only terminal metering information that was removed, and was suggested to stay removed, was the speed advisory and early / late indicator.

While it is relatively early in the development of the controller information requirements for IM, the tool sets implemented were based on past work, including those with en route controllers. The basic tool set (i.e., the information in the IM clearance window and the trail and lead aircraft IM status information in the data block) was found to be useful and helpful. The validity checks and feasibility checks also appeared useful. The data did not reveal clear trends for the benefits of the additional tools of the slot marker IM cue or spacing prediction / ETA differential.

- 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.
- Additional work should be performed to see if a display feature (e.g., alert to a speed change of a certain magnitude) would be helpful in overcoming the concern of controllers about not knowing when aircraft conducting IM will change speeds and by how much.
- When implementing the IM features, it should be ensured that features like ATPA distance information when near / on final approach do not override IM information in the data block.

6.3.2 Pilots

The information displayed to the flight crew was based on an established community standard (i.e., DO-361 / RTCA, 2015a). The standard went through a long period of development and was informed by past IM simulations and studies. This simulation found the minimum requirements in that standard to be acceptable on several measures, indicating the minimum requirements are reasonable and encompassing. Therefore, the MOPS should be considered mature for the display features for the IM operations covered in that version (DO-361 / RTCA 2015a). However, the following flight deck items are still recommended for consideration.

- This simulation chose not to distinguish between achieve stage and maintain stage operations (e.g., for the graphical progress indicator or the label for the spacing interval [SI] field on the AGD). While DO-361 (RTCA, 2015a) does not require this, the results of this simulation suggest that such a distinction is not necessary and that it should not become a requirement.
- The need for an indication of speed limiting may also be a topic of interest for additional study. It was not examined in this simulation; however, some pilot confusion was noted that appeared to be related to speed limiting. While this feature has been utilized in past simulations (e.g., Lohr et al., 2005; Baxley et al., 2013), the results do not appear to be conclusive. This information may support trust and may support the flight crew in knowing the best time to configure the aircraft for landing. However, the feature may provide information that has limited usefulness (as reported in Baxley et al., 2016) or encourage pilots to fly a non-IM speed. The usefulness of this information could be studied.
- When developing the next version of DO-361 (RTCA, 2015a), the impact of those new operations on any current requirements and findings in this report should be considered. Additional validation of the requirements on new operations, such as arrivals to dependent runways, should be conducted.

The aural alerts for conformance monitoring appeared sufficient for informing the flight crew of the need to check the IAS against the IM speed. However, consideration should be given to the implementation utilized in this simulation that (unintentionally) alerted more often than specified in DO-361 (RTCA, 2015a). Several past simulations have reported a pilot desire for, or better performance with, more salient notifications (i.e., better visual indications or aural alerts) for each new IM speed (e.g., Bone et al., 2003; Penhallegon et al., 2011; Baxley et al., 2013; Swieringa et al., 2014). More salient notifications are desirable and would reduce the time necessary to monitor IM displays. Features such as an aural alert for each new IM speed may be too intrusive, especially when the speeds are frequent. Therefore, the following recommendation is made:

- Continue the examination of the most appropriate scheme for alerting to the conformance to IM speeds. If an aural alert is considered too intrusive, testing should include sufficiently salient notifications that do not require excessive monitoring of the IM displays.

While pilot opinions were mixed as to whether the graphical progress indicator should be a minimum requirement, the feedback on this one question should be considered in light of simulation issues, other feedback on the tool, and past work. All major IM HITL simulation efforts ended up requiring or trying to perfect this type of feature (e.g., Bone et al., 2003; Hoffman et al., 2006; NASA, 2004; Swieringa et al., 2014). The results of this simulation had more speed compliance and more positive replies for the min+ tool set, and the graphical progress indicator was reported as useful.

The implementation in this simulation was directly driven by requirements available in DO-361 (RTCA, 2015a). While it proved useful to have these requirements, they were found to be in error (based on the use in this simulation)[22]. The result was that the bounds defined and used in this simulation flagged infeasible operations more than was intended by DO-361 (RTCA, 2015a). This caused the flight crew to see operations flagged as infeasible and then return to feasible. This likely led to confusion about whether the operation was infeasible or not and what action to take. Not knowing what action to take was present in past simulations too (e.g., Bone et al., 2008a; Baxley et al., 2016). These issues likely led to questioning of what operations were feasible and whether the graphical progress indicator should be a minimum. Therefore, the following are recommendations related to the graphical progress indicator.

- The graphical progress indicator is believed to be a useful feature and likely a minimum requirement. It should be designed to support pilot trust and an accurate mental model. It should avoid providing information that causes the flight crew to try to out-guess or override the IM algorithm and the associated IM speeds. It should provide clear indications of infeasible operations. It should not require excessive monitoring and should include features that reduce monitoring (e.g., spacing error trend information and out-of-tolerance alerting [as seen in implementations like Hoffman et al., 2006]). To determine the best design, it should be studied further in future simulations in nominal and off-nominal situations after setting the feasibility threshold to the corrected values.
  - For a non-graphical progress indicator as required per the minimum in DO-361 (RTCA, 2015a), similar topics should be examined. For example, clear indications of infeasible operations may be more important with only numerical values.

The information provided in the speed tape is also considered to be a key set of information (i.e., the relationship between the IAS, MCP speed, and IM speed). Such information has been displayed or required in much past research (e.g., Hoffman et al., 2006; Bone and Long, 2014; Latorella, 2015).

- Consideration should be given and further research should be conducted to determine whether this information is a minimum requirement and whether it should be in the primary field-of-view.

[22] The requirements in DO-361 (RTCA, 2015a) are being updated to fix the error.

6.4 Communications

While the IM clearances were generally found to be acceptable, controllers did report some concerns with the achieve-by clearance types and the amount of information in them.

- Efforts should continue to examine ways to keep the clearance concise. Attention should also be paid to the amount of lead aircraft IFPI shared in the clearance. This simulation only had one element (the name of the arrival procedure). If the clearances are as concise as possible, past work has found the use of an advanced organizer such as "Interval spacing clearance available, advise when ready to copy" has been well received by pilots (Bone and Long, 2014) and controllers (Callantine et al., 2012). A few pilot requests for such a communication were noted in this simulation.

While the use of lead aircraft identification was included in the simulation, it was not fully exercised with potentially confusing call signs and the use of the participant aircraft identification in IM clearances. However, no issues were identified and pilots reported they had the necessary information to detect and select the lead aircraft.

6.5 Benefits

Pairs of aircraft conducting IM, as expected, had half the spacing variance of non-IM pairs at the FAF. However, IM and non-IM pairs had the same spacing error at the FAF.

- To take advantage of the reduced variance seen and expected with IM operations, the appropriate reduction in the spacing buffer used by TBFM for IM aircraft should be determined.

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Appendix A IM Validity and Feasibility Checks

The following were the IM validity and feasibility checks that are expected to be conducted by TBFM for IM operations. **Validity** checks determine whether the criteria for initiating an IM operation, or allowing an IM operation to continue, are met. **Feasibility** checks determine whether IM can achieve the ASG (with speed alone).

A.1 Validity Checks

- In order to propose an IM operation, the following **validity** criteria were required to be met:
    - The trail aircraft was in the sector of the controller
    - Trail aircraft was IM capable (as indicated in the flight plan)
    - The trail and lead aircrafts' routes were the same from the ABP to PTP
    - Aircraft were in surveillance range, i.e., 90 NM (per IM Performance Analysis Team [IMPAT] 4/6/16)
    - Trail aircraft and lead aircraft passed their respective freeze horizons
    - The following validity checks were expected for a real-world implementation but were not implemented for the simulation
        - Lead aircraft is target (lead) capable (broadcasting ADS-B of sufficient quality for ATC surveillance)
            - Note: Should be checked during the Active, Suspended, and Terminated stages.
        - The trail and lead aircraft are conforming to their cleared routes.
            - Note: Should be checked during the Active, Suspended, and Terminated states
        - The trail and lead aircraft are landing at the same runway in sequential order.
            - Note: Should be checked during the Active, Suspended, and Terminated states
- In order to propose an Achieve-by then Maintain operation, the following **validity** criteria were required to be met:
    - Both the trail and lead aircraft were on different routes until the ABP, then were on a common route
    - Trail aircraft had not reached the ABP or PTP

- Trail aircraft calculated ASG was between 70 and 240 seconds
  - Note: The value of 70 seconds was expected to support the minimum separation standard of 2.5 NM. 240 seconds was determined to be a maximum reasonable value.
- If Trail aircraft had passed the ABP (but not the PTP) after an Achieve-by then Maintain clearance was eligible, the trail aircraft shall remain eligible but the clearance shall switch to a Capture then Maintain

- In order to propose a Capture then Maintain operation, the following **validity** criteria were required to be met:
  - Both the trail and lead aircraft were on the same route
  - The trail aircraft and lead aircraft current spacing are within 30 seconds of the ASG

A.2 Feasibility Checks

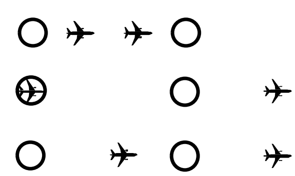
A.2.1 Dependent Feasibility Checks

The following pair-dependent **feasibility** criteria were met prior to displaying an IM clearance to the controller or during a proposed or suspended IM operation. If they were not met during a proposed or suspended operation, the controller was notified.

- If the absolute value of [trail aircraft STA – ETA] – [lead aircraft STA – ETA] was greater than 50 seconds, the infeasible / no speed solution situation was displayed to the controller. Example as shown in Figure A-1.

Example

Trail aircraft STA – ETA	Lead aircraft STA – ETA	Difference Absolute value	Feasible
20 (early)	-35 (late)	= 55	No
0 (on time)	55 (early)	= 55	No
29 (early)	30 (early)	= 1	Yes



The aircraft pair shall meet the following criteria:

|[trail aircraft STA – ETA] – [lead aircraft STA – ETA]| ≤ 50 seconds
(i.e., <51 second differential)

Figure A-1. Trail and Lead Aircraft Independent Feasibility Criteria Example

For time-based achieve-by then maintain operations, the following pair-dependent feasibility criteria were met prior to displaying the IM clearance to the controller when the trail aircraft was greater than 30 NM (approximately 7 minutes) from the ABP during an active, proposed, or suspended IM operation. If they were not met during these states, the controller was notified.

- ASG > (trail aircraft ETA – lead aircraft ETA) by more than 15% of the trail aircraft's TTG to the ABP (i.e., trail aircraft ETA – trail aircraft current time)
  - ($ETAT - ETA_L + 0.15 \times TTG_T$) < ASG
  - ASG too large / Not able to slow down enough to achieve the ASG
- ASG < (trail aircraft ETA – lead aircraft ETA) by more than 11% of the trail aircraft's TTG to the ABP (i.e., trail aircraft ETA – trail aircraft current time)
  - (ETAT - ETAL – 0.11 x TTGT) > ASG
  - ASG too small / Not able to speed up enough to achieve the ASG
- Notes
  - This is the same feasibility check that was done on the flight deck but was using TSAS information.
  - It may be desirable to change the 15% to 12% and the 11% to 8% so the controller is able to detect and resolve potentially infeasible conditions prior to the flight crew reporting "unable."

The check is shown in a graphical representation in Figure A-2.

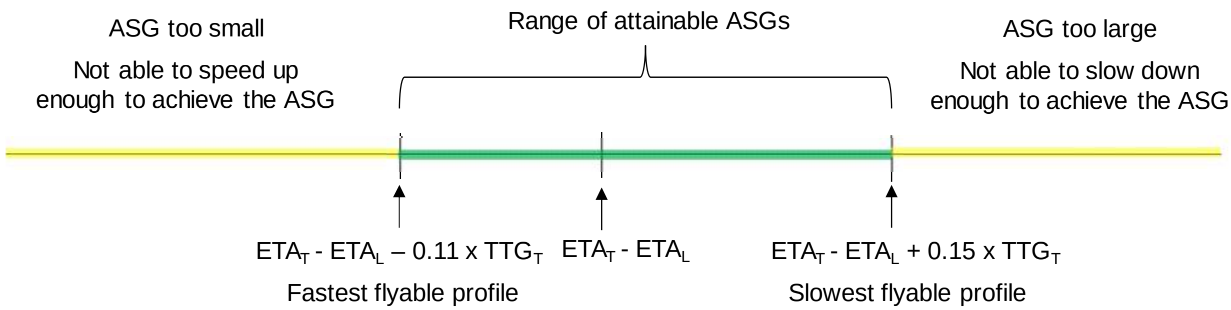


Figure A-2. Feasibility Criteria When Greater than 30 NM / 7 Minutes from the ABP

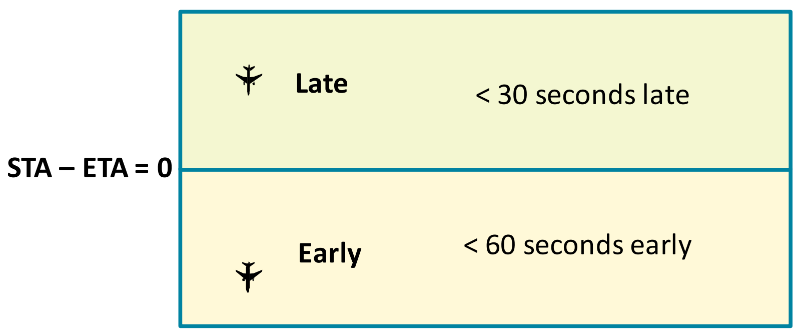
A.2.2 Independent Feasibility Checks

While not implemented in the simulation, the following pair-independent **feasibility** criteria should be considered prior to displaying an IM clearance to the controller or during a proposed or suspended IM operation. If they are not met during a proposed or suspended operation, the controller shall be notified. See Figure A-3 for examples.

- There is a speed solution for TSAS (i.e., an "E" or "L" is not shown)
- The trail aircraft STA – ETA or the lead aircraft STA – ETA, is greater than 60 seconds or less than -30 seconds.

Example
(Trail or Lead Aircraft)

Status	**STA – ETA**	**Difference**
Early	30 – 15	= 15
On time	30 – 30	= 0
Late	30 – 59	= -29



Both aircraft independently shall meet the following criteria:

STA – ETA > - 30 seconds (i.e., <30 seconds late)
STA – ETA < 60 seconds (i.e., <60 seconds early)
(-30 < STA – ETA <60)

Figure A-3. Trail and Lead Aircraft Independent Feasibility Criteria Example

Appendix B Post-Scenario Questionnaires

B.1 Controller Baseline Post-Scenario Questionnaire

IM DURING TERMINAL METERING HITL POST BASELINE SCENARIO ATC QUESTIONNAIRE

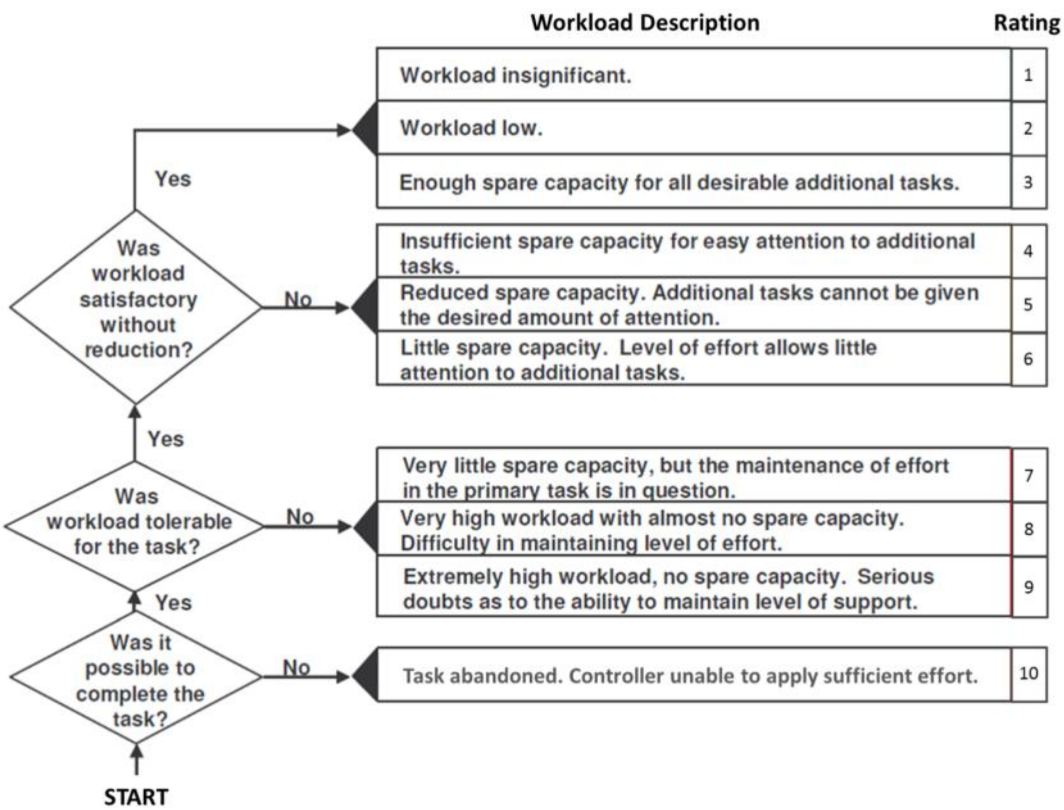
Instructions: Please answer the questions by drawing a line through the option on each of the scales at the point which matched your experience or circling an option (e.g., yes / no). When choosing an option, keep in mind that the **integration of IM into terminal metering is the area of interest** (not terminal metering alone). **Consider only the current scenario when answering**. If you have any questions, please ask the experimenter.

Workload

1. Using the chart below, how would you rate your *average* level of workload?

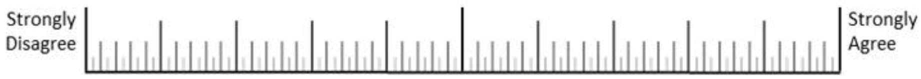
(a) Working up from the bottom left corner, answer each yes/no question and follow the path.

(b) Circle the numerical rating that best reflects your experience.



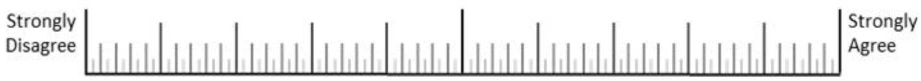
Operations

2. I was able to detect when spacing / separation issues were developing for aircraft. (draw a line on each scale)



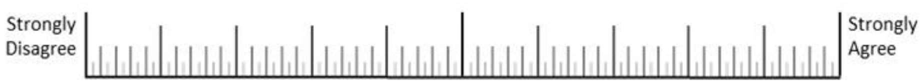
Comments:

3. I was confident that the spacing of the aircraft would remain outside my separation requirement. (draw a line on each scale)



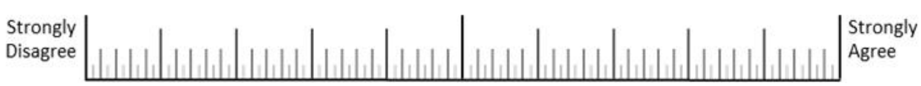
Comments:

4. The spacing of the aircraft was acceptable. (draw a line on the scale)



Comments:

5. Given the appropriate training, this operation is acceptable. (draw a line on each scale)



Comments:

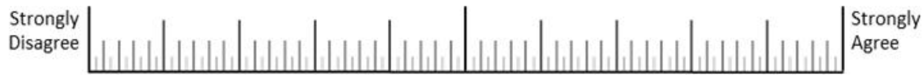
6. Were there any times when you had an issue with an aircraft? (circle one)

Yes	No

If yes, what was the issue?

Displays

7. I had the necessary display elements. (draw a line on the scale)



Comments:

8. Did you experience any display difficulties? (circle one)

Yes	No

If yes, explain:

Communications

9. Did you experience any communication difficulties? (circle one)

Yes	No

If yes, explain:

Overall

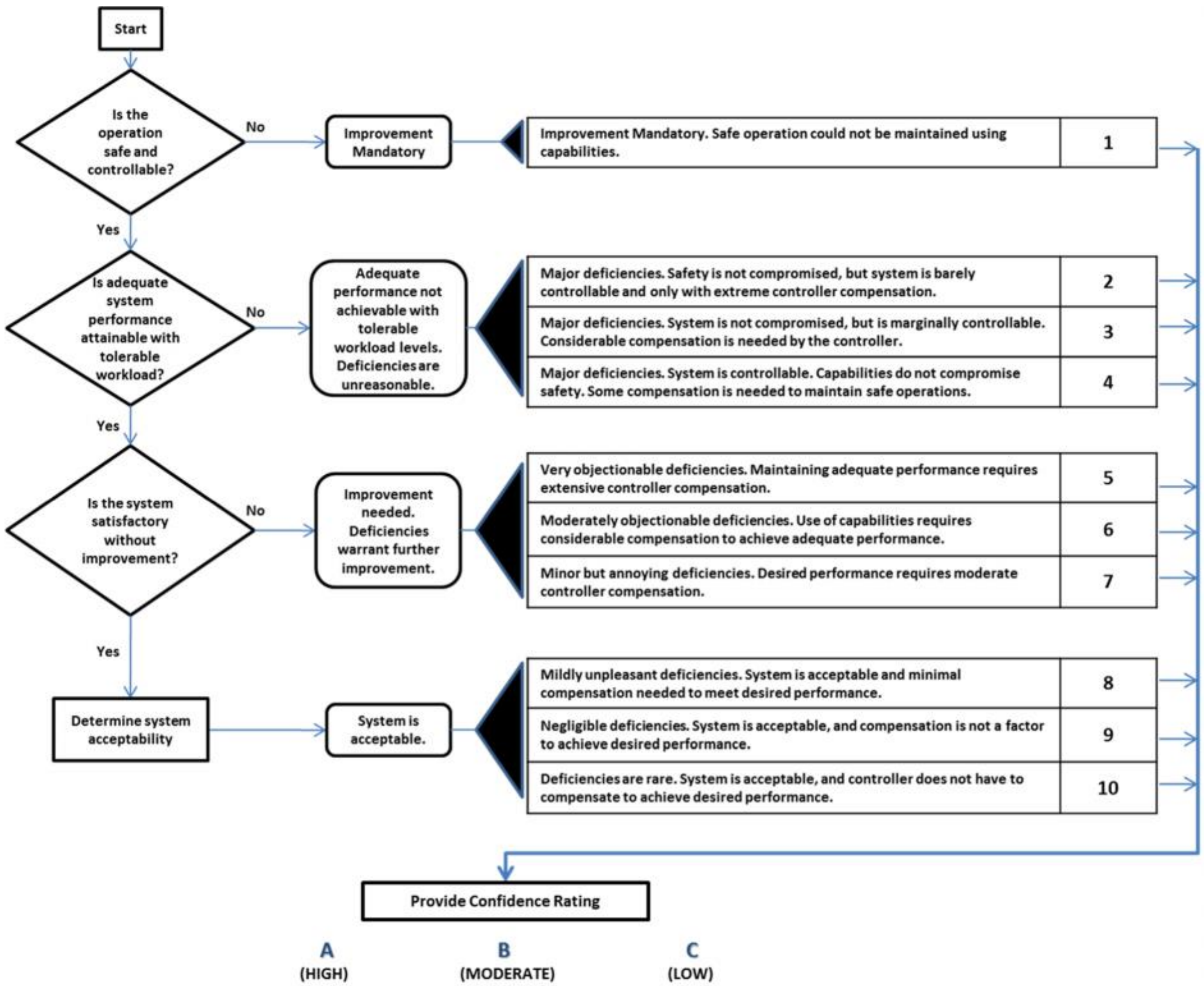
10. Did you have any other difficulties with this particular run? (circle one)

Yes	No

If yes, explain:

11. Using the chart below, how would you rate your acceptability of the operation.

(a) Working from the top left-hand corner, answer each yes / no question and follow the path.
(b) Circle the numerical rating that best reflects your experience.



12. If you have any other comments about this run, please provide them.

B.3 Controller IM Post-Scenario Questionnaire

IM DURING TERMINAL METERING HITL POST IM SCENARIO <u>ATC</u> QUESTIONNAIRE

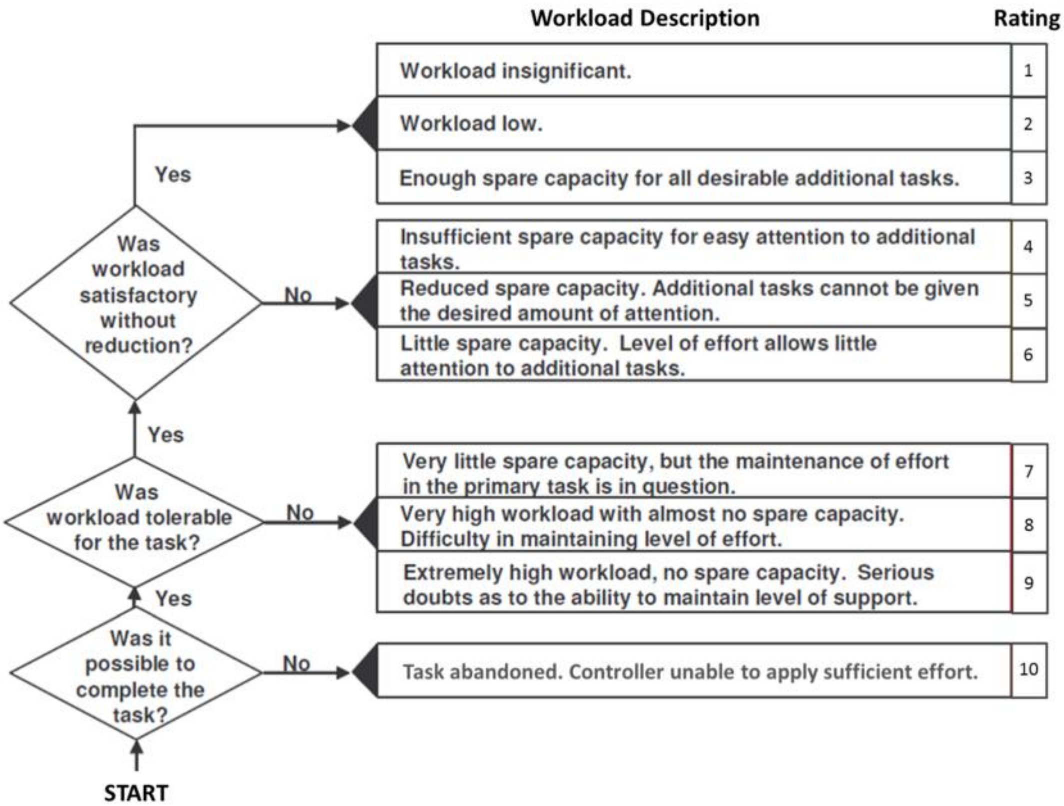
<u>Instructions</u>: Please answer the questions by drawing a line through the option on each of the scales at the point which matched your experience or circling an option (e.g., yes / no). When choosing an option, keep in mind that the **integration of IM into terminal metering is the area of interest** (not terminal metering alone). **Consider only the current scenario when answering**. If you have any questions, please ask the experimenter.

Workload

1. Using the chart below, how would you rate your *average* level of workload?

(a) Working up from the bottom left corner, answer each yes/no question and follow the path.

(b) Circle the numerical rating that best reflects your experience.



2. I was able to detect when spacing / separation issues were developing for aircraft. (draw a line on each scale)

   IM Aircraft:

   Strongly Disagree | Strongly Agree

   Non-IM Aircraft:

   Strongly Disagree | Strongly Agree

Comments:

3. I was confident that the spacing of the aircraft would remain outside my separation requirement. (draw a line on each scale)

   IM Aircraft:

   Strongly Disagree | Strongly Agree

   Non-IM Aircraft:

   Strongly Disagree | Strongly Agree

Comments:

4. The spacing of the IM aircraft was acceptable. (draw a line on the scale)

   Strongly Disagree | Strongly Agree

Comments:

5. Did you ever need to terminate or suspend an IM operation? (circle one)

Yes	No

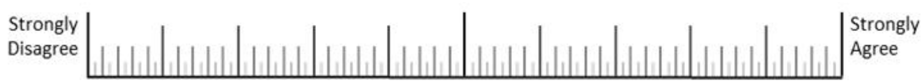
If yes, why?

a) Did you restart / resume the operation? (circle one)

Yes	No

Comments:

6. Given the appropriate training, IM during terminal metering is operationally acceptable. (draw a line on each scale)



Comments:

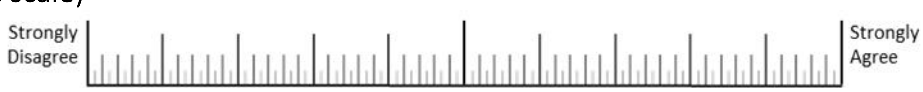
7. Were there any times when you had an issue with an IM aircraft? (circle one)

Yes	No

If yes, what was the issue?

Displays

8. I had the necessary display elements for conducting IM operations. (draw a line on the scale)



Comments:

9. Did you experience any IM-related display difficulties? (circle one)

Yes	No

If yes, explain:

Communications

10. Did you experience any IM-related communication difficulties? (circle one)

Yes	No

If yes, explain:

Overall

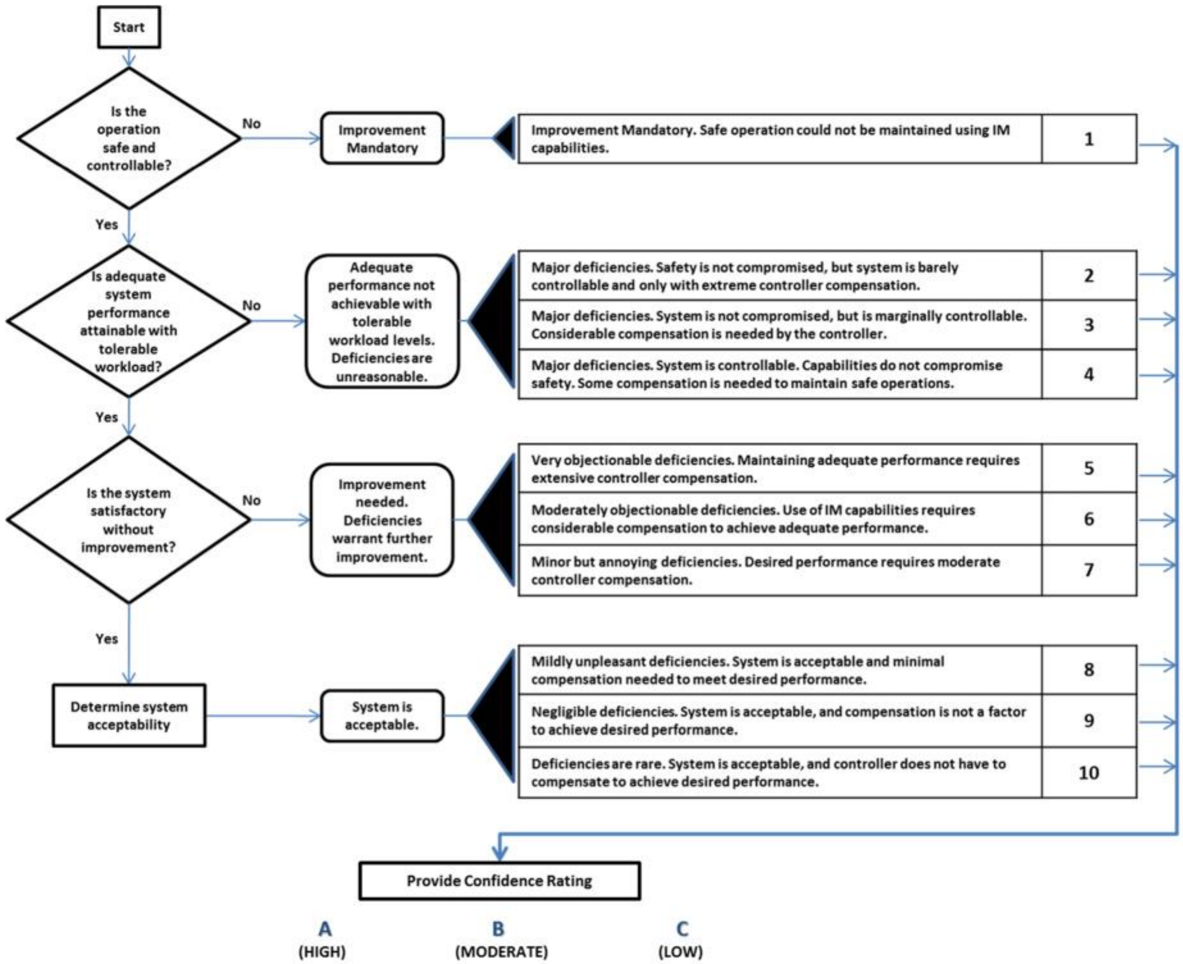
11. Did you have any other IM-related difficulties with this particular run? (circle one)

Yes	No

If yes, explain:

12. Using the chart below, how would you rate your acceptability of the operation.

(a) Working from the top left-hand corner, answer each yes / no question and follow the path.
(b) Circle the numerical rating that best reflects your experience.



13. If you have any other comments about this run, please provide them.

B.5 Pilot Baseline Post-Scenario Questionnaire

IM (During Terminal Metering) HITL Post Baseline Scenario Pilot Questionnaire

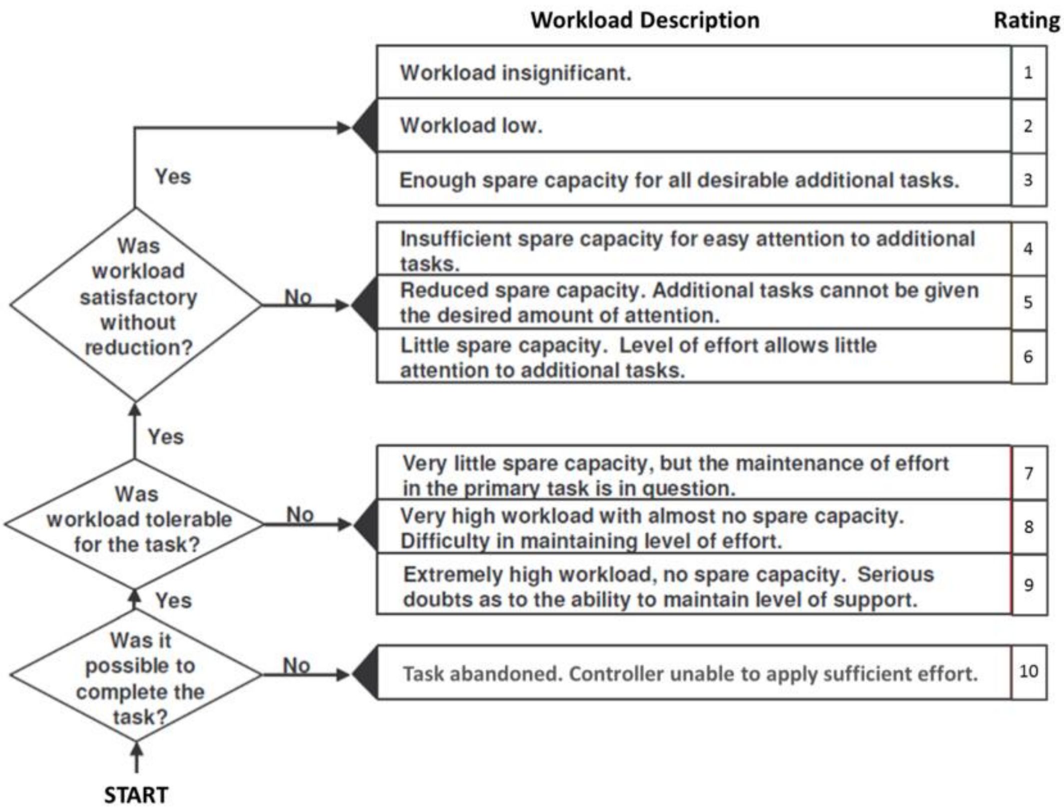
Instructions: Please answer the questions by drawing a line through the option on each of the scales at the point which matched your experience or circling an option (e.g., yes / no). **Consider only the current scenario when answering**. If you have any questions, please ask the experimenter.

Workload

1. Using the chart below, how would you rate your *average* level of workload?

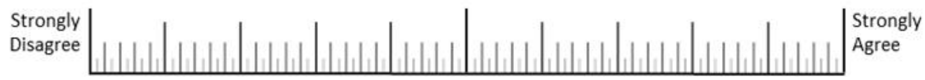
(a) Working up from the bottom left corner, answer each yes/no question and follow the path.

(b) Circle the numerical rating that best reflects your experience.



Operations

2. Overall, I found this run acceptable.



3. Were there any times when you had an issue flying the approach and arrival? (circle one)

Yes	No

If yes, what was the issue?

Displays

4. Did you experience any display difficulties? (circle one)

Yes	No

If yes, explain:

Communications

5. Did you experience any communication difficulties? (circle one)

Yes	No

If yes, explain:

Overall

6. Did you have any other difficulties with this run? (circle one)

Yes	No

If yes, explain:

7. If you have any other comments about this run, please provide them.

B.7 Pilot IM Post-Scenario Questionnaire

IM (DURING TERMINAL METERING HITL) POST IM SCENARIO <u>PILOT</u> QUESTIONNAIRE

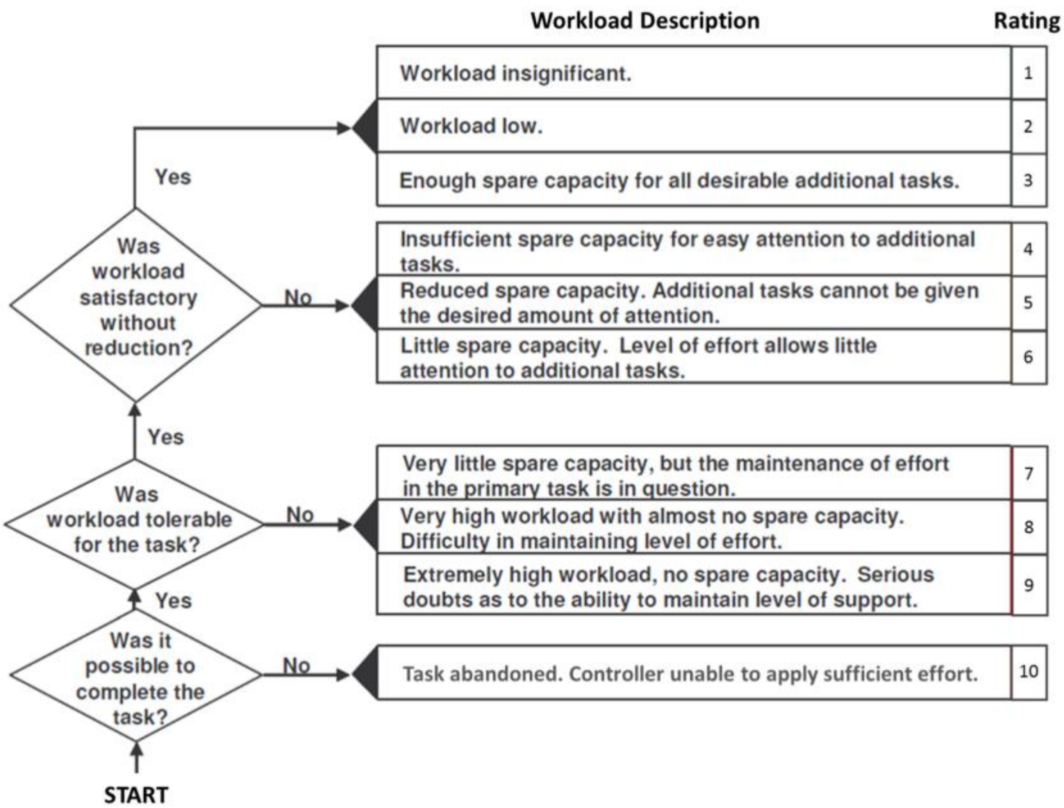
<u>Instructions</u>: Please answer the questions by drawing a line through the option on each of the scales at the point which matched your experience or circling an option (e.g., yes / no). When choosing an option, keep in mind that **IM is the area of interest** (e.g., not a traffic display alone). **Consider only the current scenario when answering**. If you have any questions, please ask the experimenter.

Workload

1. Using the chart below, how would you rate your *average* level of workload?

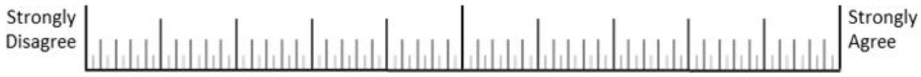
(a) Working up from the bottom left corner, answer each yes/no question and follow the path.

(b) Circle the numerical rating that best reflects your experience.



Operations

2. I could detect whether I would remain within tolerances to achieve and maintain the assigned spacing goal. (draw a line on the scale)



Comments:

3. Did you ever consider reporting "unable interval spacing" and not do so? (circle one)

Yes	No

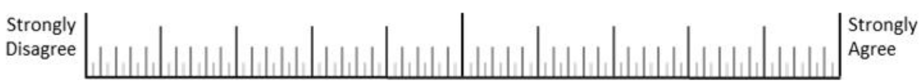
If yes, why? Describe.

4. Did you ever report "unable interval spacing"? (circle one)

Yes	No

If yes, why?

5. Given the appropriate training, IM is operationally acceptable. (draw a line on the scale)



Comments:

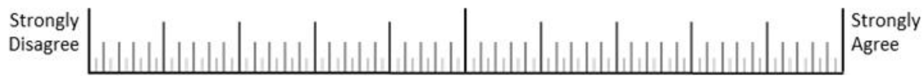
6. Were there any times when you had an issue conducting IM? (circle one)

Yes	No

If yes, what was the issue?

Displays

7. I had the necessary display elements for conducting IM. (draw a line on the scale)



Comments:

8. Did you experience any IM-related display difficulties? (circle one)

Yes	No

If yes, explain:

Communications

9. Did you experience any IM-related communication difficulties? (circle one)

Yes	No

If yes, explain:

Overall

10. Did you have any other IM-related difficulties with this particular run? (circle one)

Yes	No

If yes, explain:

11. If you have any other comments about this run, please provide them.

Appendix C Post-Simulation Questionnaires

C.1 Controller Post-Simulation Questionnaire

IM DURING TERMINAL METERING HITL POST EVALUATION ATC QUESTIONNAIRE

Instructions: Please answer the questions by drawing a line through the option on each of the scales at the point which matched your experience or circling an option (e.g., yes / no). When choosing an option, keep in mind that the **integration of IM into terminal metering is the area of interest** (not terminal metering alone). Unless otherwise indicated, consider all scenarios when answering. If you have any questions, please ask the experimenter.

Operational Integration

1. Rank the operations from most challenging to least challenging aspect of the simulation environment.

   Enter “terminal metering,” “RNP RF turn operations,” and “Interval Management” in the cells below. Each operation should appear only once.

Most challenging	
Least challenging	

   Comments:

   a. Did one operation make another more challenging? (circle one)

Yes	No

   If yes, describe:

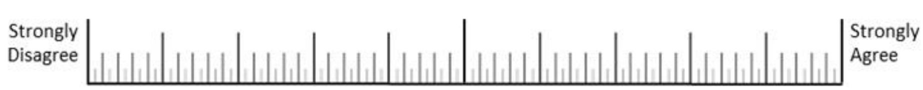
2. Provide any comments on or concerns about terminal metering or RNP RF turns (independent of IM) below. (*The remainder of the questionnaire is related to IM integration into that terminal metering environment with RNP RF turns*).

   Terminal metering:

   RNP RF turns:

IM Operations

3. IM is operationally desirable. (draw a line on the scale)



   Comments:

4. IM is compatible with terminal metering operations. (draw a line on the scale)

Strongly Disagree | Strongly Agree

Comments:

5. Given the appropriate training, IM during terminal metering is operationally acceptable. (draw a line on each scale)

Strongly Disagree | Strongly Agree

Comments:

6. I was confident that the spacing of the aircraft would remain outside my separation requirement. (draw a line on each scale)

IM Aircraft:

Strongly Disagree | Strongly Agree

Non-IM Aircraft:

Strongly Disagree | Strongly Agree

Comments:

7. It was acceptable to receive aircraft already performing IM from the feeder controller. (draw a line on the scale)

Strongly Disagree | Strongly Agree

Comments:

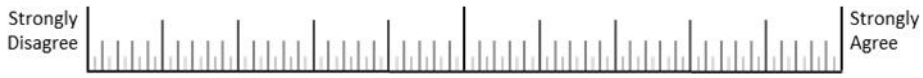
8. It was acceptable to receive aircraft already performing IM from the center. (draw a line on the scale)

Strongly Disagree | Strongly Agree

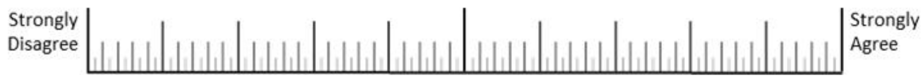
Comments:

9. It was clear that the speed changes made by the aircraft were driving towards the goal of appropriate spacing. (draw a line on the scale)

IM Aircraft:



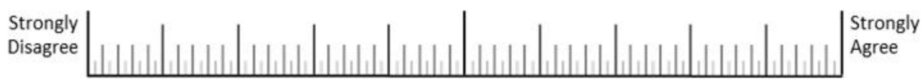
Non-IM Aircraft:



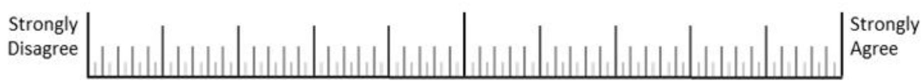
Comments:

10. The spacing achieved by the aircraft was acceptable. (draw a line on each scale)

IM Aircraft:



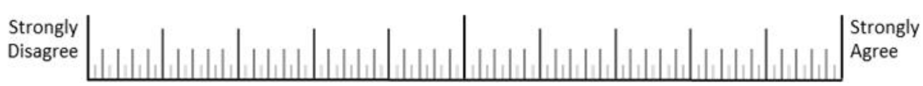
Non-IM Aircraft:



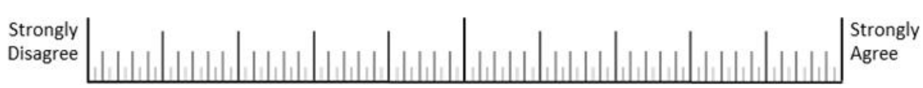
Comments:

11. I was able to detect when spacing / separation issues were developing for aircraft. (draw a line on each scale)

IM Aircraft:



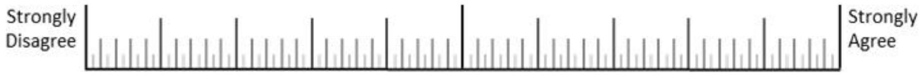
Non-IM Aircraft:



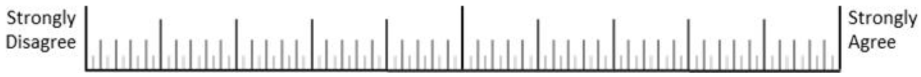
Comments:

13. I was confident that the aircraft I was handing off would be accepted with minimal problems. (draw a line on each scale)

IM Aircraft:



Non-IM Aircraft:



Comments:

14. Did you notice a difference between IM aircraft conducting “Achieve” operations versus “Capture” operations? (circle one)

Yes	No

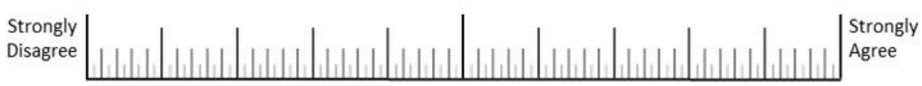
If yes, describe:

Which operation was acceptable? (circle one)

Achieve	Capture	Both

If one is not acceptable, explain:

15. There were an acceptable number of aircraft performing IM. (draw a line on the scale)



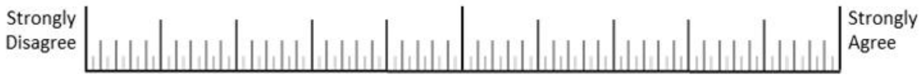
What percentage and above is reasonable? (This simulation had ~ 60% IM equipped)

___________%

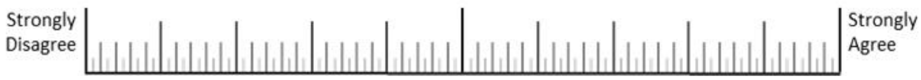
Explain:

16. My roles and responsibilities were clear. (draw a line on the scale)

IM Aircraft:

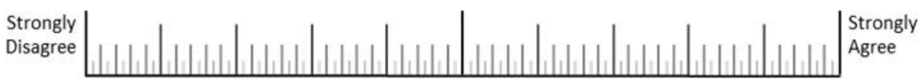


Non-IM Aircraft:



Comments:

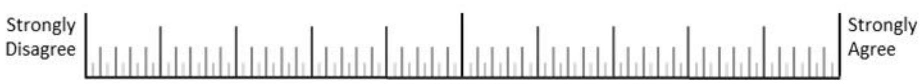
17. My overall workload was acceptable. (draw a line on the scale)



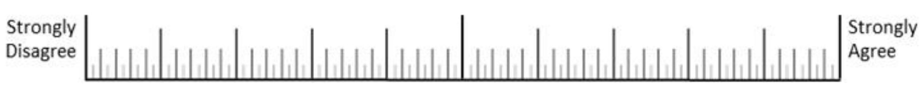
Comments:

18. My level of traffic awareness was acceptable. (draw a line on each scale)

IM Aircraft:



Non-IM Aircraft:



Comments:

19. How did aircraft conducting IM during terminal metering effect your need to monitor traffic? (circle one per row)

IM aircraft	Greatly *Increases*	*Increases*	Somewhat *Increases*	No Effect	Somewhat *Reduces*	*Reduces*	Greatly *Reduces*

Non-IM aircraft	Greatly *Increases*	*Increases*	Somewhat *Increases*	No Effect	Somewhat *Reduces*	*Reduces*	Greatly *Reduces*

Comments:

20. The necessary aircraft monitoring was acceptable. (draw a line on each scale)

IM Aircraft:

Strongly Disagree | Strongly Agree

Non-IM Aircraft:

Strongly Disagree | Strongly Agree

Comments:

Communications

21. The IM clearance instruction was acceptable. (draw a line on each scale)

Achieve:

Strongly Disagree | Strongly Agree

Capture:

Strongly Disagree | Strongly Agree

Comments:

22. Did any of the IM clearance elements cause you any difficulties? (circle one)

Yes	No

If yes, which elements? (circle all that apply):

1. Trail aircraft identification
2. Clearance type
3. Assigned spacing goal
4. Achieve-by point
5. Lead aircraft identification
6. Lead aircraft route

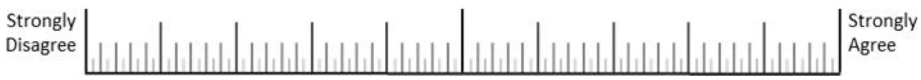
Describe any difficulties:

23. Did you have any issues during communications when the lead aircraft call sign was used? (circle one)

Yes	No

If yes, describe:

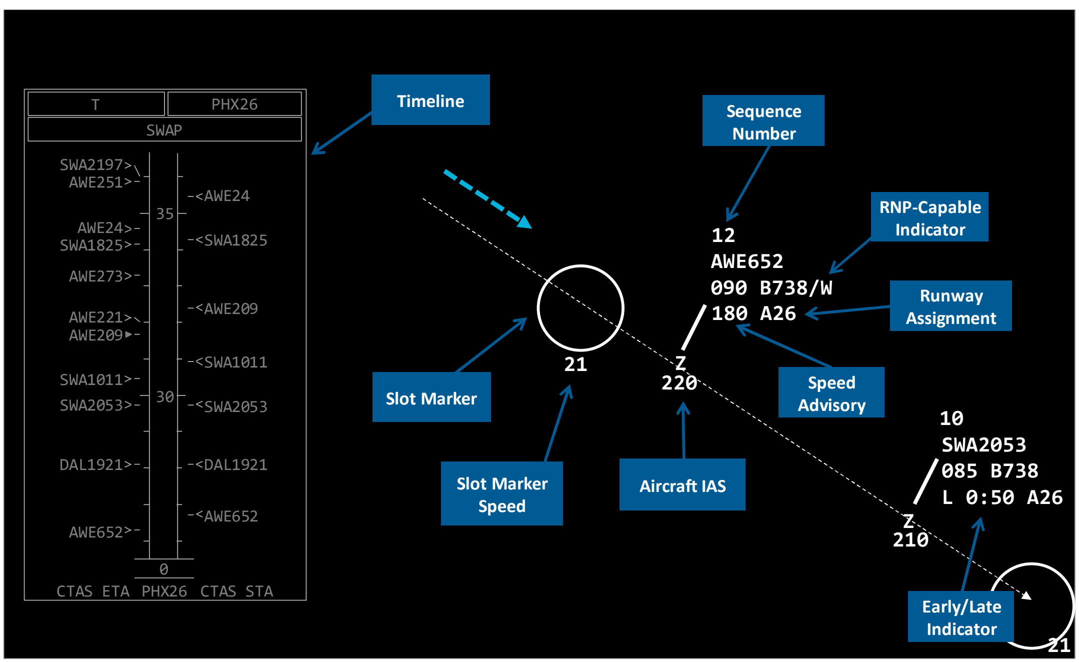
24. Use of the lead aircraft call sign in the IM clearance is operationally acceptable. (draw a line on the scale)



Comments:

Display

25. The terminal metering elements were helpful for the IM and non-IM aircraft. (draw a line on each scale)



(Non-Blue) Slot Markers **– IM Aircraft**

Strongly Disagree | Strongly Agree

(Non-Blue) Slot Markers **– Non-IM Aircraft**

Strongly Disagree | Strongly Agree

Speed Advisories **- IM Aircraft**

Strongly Disagree | Strongly Agree

Speed Advisories **- Non-IM Aircraft**

Strongly Disagree | Strongly Agree

Early / Late indicator **- IM Aircraft**

Strongly Disagree | Strongly Agree

Early / Late indicator **- Non-IM Aircraft**

Strongly Disagree | Strongly Agree

Slot Marker Speeds **- IM Aircraft**

Strongly Disagree | Strongly Agree

Slot Marker Speeds **- Non-IM Aircraft**

Strongly Disagree | Strongly Agree

Aircraft Indicated Airspeed **- IM Aircraft**

Strongly Disagree — Strongly Agree

Aircraft Indicated Airspeed **- Non-IM Aircraft**

Strongly Disagree — Strongly Agree

Runway Sequence Number **- IM Aircraft**

Strongly Disagree — Strongly Agree

Runway Sequence Number **- Non-IM Aircraft**

Strongly Disagree — Strongly Agree

Runway assignment **- IM Aircraft**

Strongly Disagree — Strongly Agree

Runway assignment **- Non-IM Aircraft**

Strongly Disagree — Strongly Agree

Timeline **- IM Aircraft**

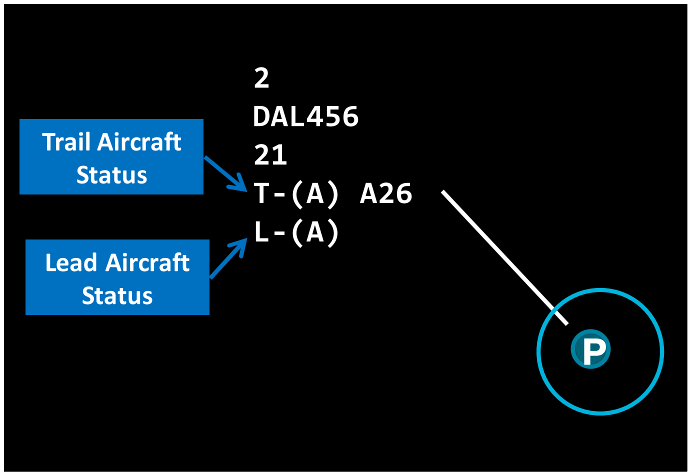
Strongly Disagree — Strongly Agree

Timeline **- Non-IM Aircraft**

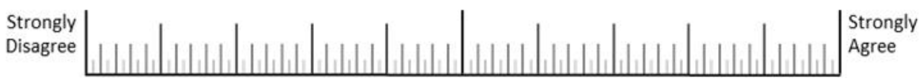
Strongly Disagree — Strongly Agree

Comments:

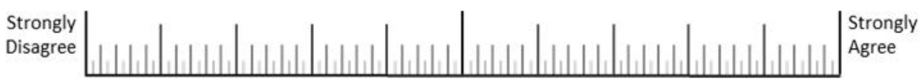
26. The IM elements were helpful for IM operations / aircraft. (draw a line on each scale)



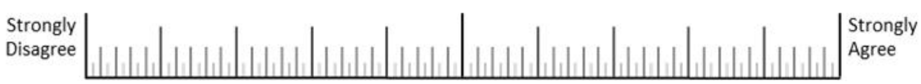
Trail aircraft status (i.e., T(E) – Eligible, T(A) – Active, T(S) – Suspended)



Lead aircraft status (i.e., L(A) – Active, L(S) – Suspended)



Blue slot marker (to differentiate between IM aircraft from non-IM aircraft)



Comments:

27. The information in the IM window was helpful for IM operations / aircraft. (draw a line on each scale)

Trail Aircraft	Clearance Type	Spacing Goal	Lead Aircraft (sector)	ABP	Lead Aircraft Route	Status
SWA1825	Achieve	85	AWE209	DERVL	EAGUL6	Eligible
SWA1011	Capture	93 (99)	SWA2053			Active

IM status information (i.e., Eligible, Active, Suspended, Terminated)

Strongly Disagree — Strongly Agree

Projected spacing / ETA differential [i.e., (87)] alongside the spacing goal

Strongly Disagree — Strongly Agree

Comments:

28. The position of IM aircraft relative to the slot markers was logical. (draw a line on the scale)

Strongly Disagree — Strongly Agree

Comments:

29. The behavior of IM aircraft relative to the slot markers was acceptable. (draw a line on the scale)

Strongly Disagree — Strongly Agree

Comments:

30. It was helpful to be informed and alerted to when IM was predicted to have no speed solution. (draw a line on the scale)

Strongly Disagree — Strongly Agree

Comments:

Overall

31. What was the most difficult situation to deal with when aircraft were conducting IM during terminal metering operations?

32. What was the easiest situation to deal with when aircraft were conducting IM during terminal metering operations?

33. How could the conduct of IM during terminal metering operations be improved?

Evaluation

34. The training I received was adequate. (draw a line on each scale)

    IM operations:

    Strongly Disagree | Strongly Agree

    Terminal metering operations:

    Strongly Disagree | Strongly Agree

    Comments:

35. The overall activity was effective as a context for evaluating IM during terminal metering operations. (draw a line on the scale)

    Strongly Disagree | Strongly Agree

    Comments:

36. Was there anything about the event that artificially affected using it as a context for evaluating IM during terminal metering operations? (circle one)

    Yes | No | Don't Know

If yes, explain:

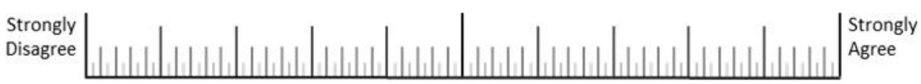
C.3 Pilot Post-Simulation Questionnaire

IM (DURING TERMINAL METERING) HITL POST EVALUATION PILOT QUESTIONNAIRE

Instructions: Please answer the questions by drawing a line through the option on each of the scales at the point which matched your experience or circling an option (e.g., yes / no). When choosing an option, keep in mind that **IM is the area of interest** (e.g., not a traffic display alone). Unless otherwise indicated, consider all scenarios when answering. If you have any questions, please ask the experimenter.

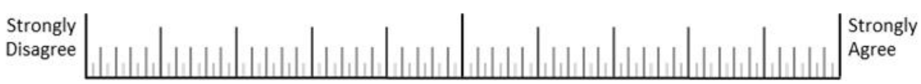
Operations

1. I received an acceptable number of IM speeds. (draw a line on the scale)



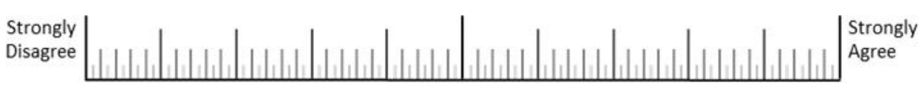
Comments:

2. I trusted that the algorithm was providing me the appropriate IM speeds to achieve and maintain my assigned spacing goal. (draw a line on the scale)



Comments:

3. It was clear that the IM speeds were driving towards the goal of appropriate spacing. (draw a line on the scale)



Comments:

4. The spacing I achieved / maintained when conducting IM was acceptable. (draw a line on the scale)

Strongly Disagree — Strongly Agree

Comments:

5. I was able to detect whether I would remain within tolerances to achieve and maintain the assigned spacing goal. (draw a line on the scale)

Strongly Disagree — Strongly Agree

Comments:

6. Did you ever try to "out-guess" the IM algorithm and the IM speeds? (circle one)

Yes	No

Describe:

7. Did you choose not to fly an IM speed? (circle one)

Yes	No

If yes, describe the situation(s) and why:

8. Normal termination (e.g., termination at the FAF upon completion of IM) procedures were clear. (draw a line on the scale)

Strongly Disagree — Strongly Agree

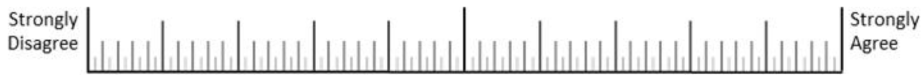
Comments:

9. Abnormal termination (e.g., termination prior to the FAF due to a spacing issue) procedures were clear. (**if applicable**) (draw a line on the scale)

Strongly Disagree — Strongly Agree

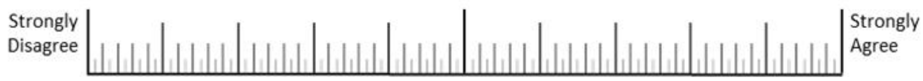
Comments:

10. Suspend procedures were clear. (**if applicable**) (draw a line on the scale)



Comments:

11. Resume procedures were clear. (**if applicable**) (draw a line on the scale)



Comments:

12. Did you notice a difference between “Achieve” operations versus “Maintain” operations? (circle one)

Yes	No

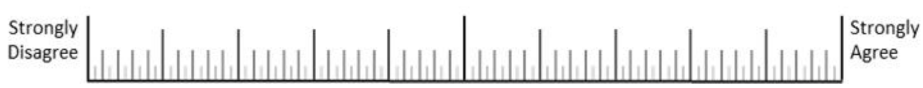
Comments:

Which operation was acceptable? (circle one)

Achieve	Maintain	Both

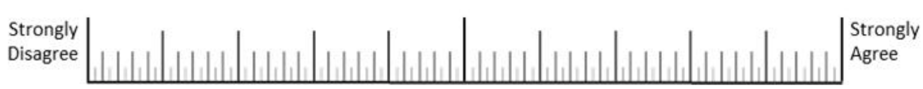
If one is not acceptable, explain:

13. My roles and responsibilities related to *IM operations* were clear. (draw a line on the scale)



Comments:

14. My overall workload was acceptable. (draw a line on the scale)



Comments:

15. My level of traffic awareness was acceptable. (draw a line on each scale)

Lead aircraft for IM:

Strongly Disagree | Strongly Agree

Aircraft other than the lead aircraft:

Strongly Disagree | Strongly Agree

Comments:

16. IM is operationally desirable. (draw a line on the scale)

Strongly Disagree | Strongly Agree

Comments:

17. Given the appropriate training, IM is operationally acceptable. (draw a line on the scale)

Strongly Disagree | Strongly Agree

Comments:

Communications

18. The amount of information communicated by ATC in the IM clearance was acceptable. (draw a line on the scale)

Strongly Disagree | Strongly Agree

Comments:

19. Did any of the IM clearance elements cause you any difficulties? (circle one)

Yes	No

If yes, which elements? (circle all that apply):

1. Clearance type (i.e., “Achieve”)
2. Assigned spacing goal
3. Achieve-by point
4. Lead aircraft identification
5. Lead aircraft route

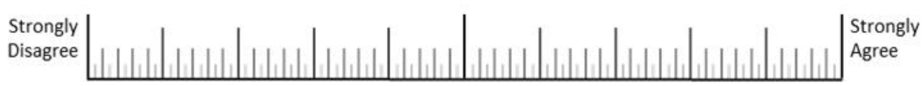
Describe any difficulties

20. Did you have any issues during communications when the lead aircraft identification was used? (circle one)

Yes	No

If yes, describe:

21. With additional experience and practice, use of the lead aircraft identification would be operationally acceptable. (draw a line on the scale)



Comments:

Display

22. The CDTI and AGD displays are acceptable for the following stages (draw a line on each scale)

Clearance Entry:

Strongly Disagree — Strongly Agree

Entry evaluation / cross-flight deck coordination:

Strongly Disagree — Strongly Agree

Execution / IM conduct (***without*** the graphical progress indicator on the AGD and airspeed tape on CDTI):

Strongly Disagree — Strongly Agree

Execution / IM conduct (***with*** the graphical progress indicator on the AGDand airspeed tape on CDTI):

Strongly Disagree — Strongly Agree

Suspension (if applicable):

Strongly Disagree — Strongly Agree

Resumption (if applicable):

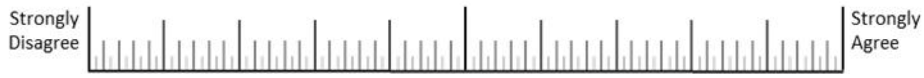
Strongly Disagree — Strongly Agree

Termination (if applicable):

Strongly Disagree — Strongly Agree

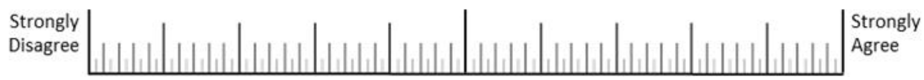
Comments:

23. The necessary information was available from the ATC clearance to detect and select the lead aircraft (draw a line on the scale)



Comments:

24. I was able to perform IM by primarily focusing on the AGD information while occasionally referencing the CDTI. (draw a line on the scale)



Comments:

25. Considering total time on the IM displays, estimate the total percentage of time using each display (total should equal 100). (enter a value for each display)

Display	Percentage Use
AGD	

CDTI	

Total	100%

Comments:

26. I was able to detect when spacing issues were developing during IM operations. (draw a line on each scale)

With **only** the ASG and SI numeric information on the AGD

Strongly Disagree — Strongly Agree

With the ASG and SI numeric information **&** graphical progress indicator on the AGD

Strongly Disagree — Strongly Agree

Comments:

27. The graphical progress indicator on the AGD is useful for IM. (draw a line on the scale)

Strongly Disagree — Strongly Agree

Comments:

28. The graphical progress indicator on the AGD is a minimum requirement for IM. (draw a line on the scale)

Strongly Disagree — Strongly Agree

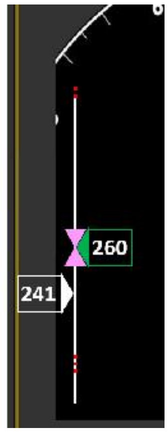
Comments:

29. The graphical progress indicator is unnecessary. The numeric ASG (Assigned Spacing Goal) and numeric SI (Spacing Interval) are sufficient information to determine whether the assigned spacing goal will be achieved and maintained. (draw a line on the scale)

Strongly Disagree — Strongly Agree

Comments:

30. The speed tape on the CDTI is useful for IM. (draw a line on the scale)



Strongly Disagree — Strongly Agree

Comments:

31. The speed tape on the CDTI is a minimum requirement for IM. (draw a line on the scale)

Strongly Disagree — Strongly Agree

Comments:

32. The IM speed change advisory (e.g., box around IM Speed on AGD) was sufficient to detect the presence of a new IM speed. (draw a line on the scale)

Strongly Disagree — Strongly Agree

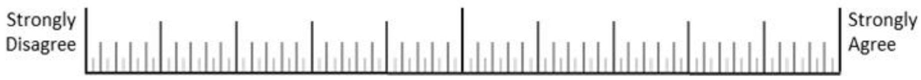
Comments:

33. The IM speed conformance monitoring alert (e.g., visual and aural alert when the IM speed was not being flown) is useful for IM. (draw a line on the scale)

Strongly Disagree — Strongly Agree

Comments:

34. The IM speed conformance monitoring alert (e.g., visual and aural alert when the IM speed was not being flown) is a minimum requirement for IM. (draw a line on the scale)



Comments:

35. Did the combination of both the AGD and CDTI implementations include all the information necessary for you to conduct IM? (circle one for each)

Without the graphical progress indicator on the AGD and airspeed tape on CDTI

Yes	No

With the graphical progress indicator on the AGD and airspeed tape on CDTI

Yes	No

If no, describe any instances where you would have liked more information, and the form in which the additional information would have been most useful.

36. Did you find any elements on the displays to be confusing or misleading? (circle one per row)

AGD	Yes	No

CDTI	Yes	No

If yes, describe:

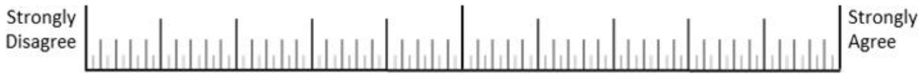
37. Did you have any issues with the two separate displays? (circle one)

Yes	No

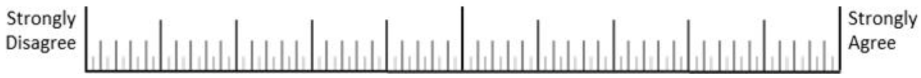
If yes, describe:

38. I could integrate the displays into my normal instrument scan. (draw a line on each scale)

AGD:

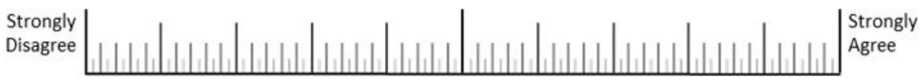


CDTI:



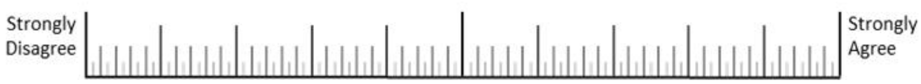
Comments:

39. The necessary scan time was acceptable. (draw a line on the scale)



Comments:

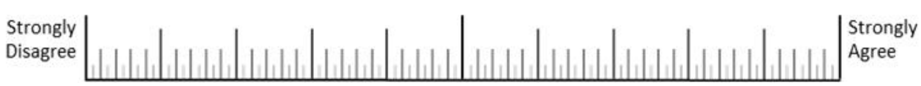
40. My level of head down time was acceptable. (draw a line on the scale)



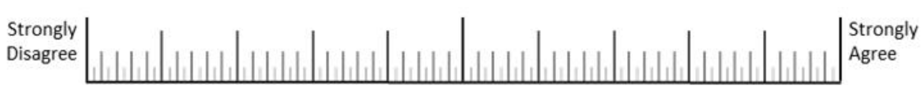
Comments:

41. I would be willing to perform IM with the CDTI and AGD I used today (ignore simulation issues if any existed, e.g., readability of text on the displays). (draw a line on each scale)

Without the graphical progress indicator on the AGD and airspeed tape on CDTI



With graphical progress indicator on the AGD and airspeed tape on CDTI



Comments:

Overall

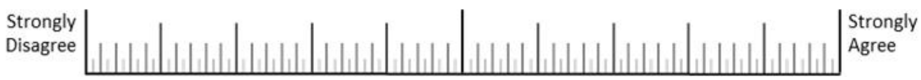
42. What was the most difficult situation to deal with when conducting IM?

43. What was the easiest situation to deal with when conducting IM?

44. How could IM be improved?

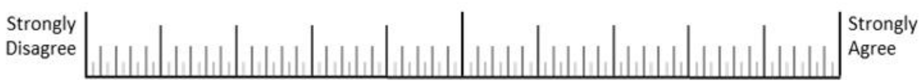
Evaluation

45. The training I received was adequate. (draw a line on the scale)



Comments:

46. The overall activity was effective as a context for evaluating IM. (draw a line on the scale)



Comments:

47. Was there anything about the event that artificially affected using it as a context for evaluating IM? (circle one)

Yes	No	Don't Know

If yes, explain:

Appendix D Descriptions of Objective Measures

This section provides descriptions and, where appropriate, details on each of the objective measures.

D.1 IM Operations Conduct

- IM initiation delay by the controller
  - Definition: Difference in time between when the IM clearance was presented to the controller and it was accepted by controller action
- IM initiation point
  - Definition: Position where IM started as defined by controller acceptance action
- Frequency of IM initiations by the controller
  - Definition: Number of times the controller initiated IM after an IM operation was presented
- Frequency of IM rejections by the controller
  - Definition: Number of times the controller refused an IM clearance after it was presented
- Frequency and location of IM suspensions by the controller
  - Definition: Location and number of times the controller took action to make IM temporarily inactive
- Frequency and location of IM terminations by the controller, as well as flight crew reports of "unable IM"
  - Definition: Location and number of times IM is made inactive
- Frequency of flight crew reports of unable IM
  - Definition: Number of times participants reported being unable to conduct IM

D.2 IM Speeds and Flight Crew Actions

- Frequency of IM speed changes
  - Definition: Number of times a new IM speed is presented
- Magnitude of IM speed change relative to previous IM speed
  - Definition: Degree of change between IM speeds

- Frequency of IM speed reversals
  - Definition: This occurs when a previous IM speed change was an increase that is then followed by an IM speed decrease (or vice versa). Table D-1 provides examples of situations that are and are not considered reversals.

Table D-1. Speed Reversal Determination Methodology

IM speed (current -2)		IM speed (current -1)		IM speed (current)	Reversal?
180	Increase to	190	Increase to	200	No
180	Increase to	190	Decrease to	180	Yes
200	Decrease to	190	Increase to	200	Yes
200	Decrease to	190	Decrease to	180	No

- Frequency of IM speed increases
  - Definition: This occurs when the previous IM speed was lower than a new IM speed
- Time between IM speed changes and distance to go
  - Definition: How often IM speeds changed relative to how close the aircraft was from the runway
- Frequency of flight crew compliance with IM speeds
  - Definition: Measure of whether the flight crew dialed the IM speed into the MCP window
  - Note: While ideally compliance would be zero difference between the MCP speed and the IM speed, the simulation MCP implementation sometimes made it difficult to match the number exactly. Therefore, setting the MCP speed to +/- 2 knots of the IM speed was considered compliance in this simulation
- Frequency of IM Speed Conformance Monitoring Advisories
  - Definition: The number of times the equipment determined that the IM speed was not being conformed with and displayed an advisory to the flight crew

D.3 Aircraft Spacing and Separation

- Schedule conformance at various points (e.g., TRACON entry, constraint points)
  - Definition: Difference between the aircraft's STA and ATA
  - Note: This measure is an indication of whether aircraft were on schedule (but does not directly indicate whether aircraft were in their slot markers or how their schedule conformance relates to the aircraft ahead or behind)
- Absolute slot marker deviation
  - Definition: Difference between aircraft position and the center of the slot marker
  - Note: This measure is more operational than the schedule conformance measure and provides information about whether an aircraft was in the slot marker, and if not, how far outside. It does not indicate how its slot marker position relates to the aircraft ahead or behind.
  - Note: The on-going measures in the controller airspace were determined by voice frequency changes (e.g., feeder airspace was bounded by checking in on the feeder's frequency and then checking in on the final's frequency)
  - Note: See Figure D-1 for slot marker deviation examples
- Aircraft time in slot markers
  - Definition: The amount of time aircraft were inside the slot markers
  - Note: Slot markers had a radius of 15 seconds in the feeder controller's airspace and 5 seconds in the final controller's airspace
- Relative slot marker deviation
  - Definition: Difference between trail aircraft position and the center of the slot marker and the lead aircraft position and the center of the slot marker
  - Note: This measure is more operational than the schedule conformance measure and provides relative spacing information. For example, if a lead is outside its slot marker, this measure will show if the trail aircraft is outside its slot marker in the same or opposite direction. When aircraft are performing IM, the expected behavior at the ABP would be that the trail IM aircraft is outside its slot marker in the same direction and magnitude as the lead aircraft.
  - Note: This was measured when the lead (instead of the trail) crossed the points to avoid any issues (e.g., lead landed) inside the FAF.
  - Note: See Figure D-1 for relative slot marker deviation examples

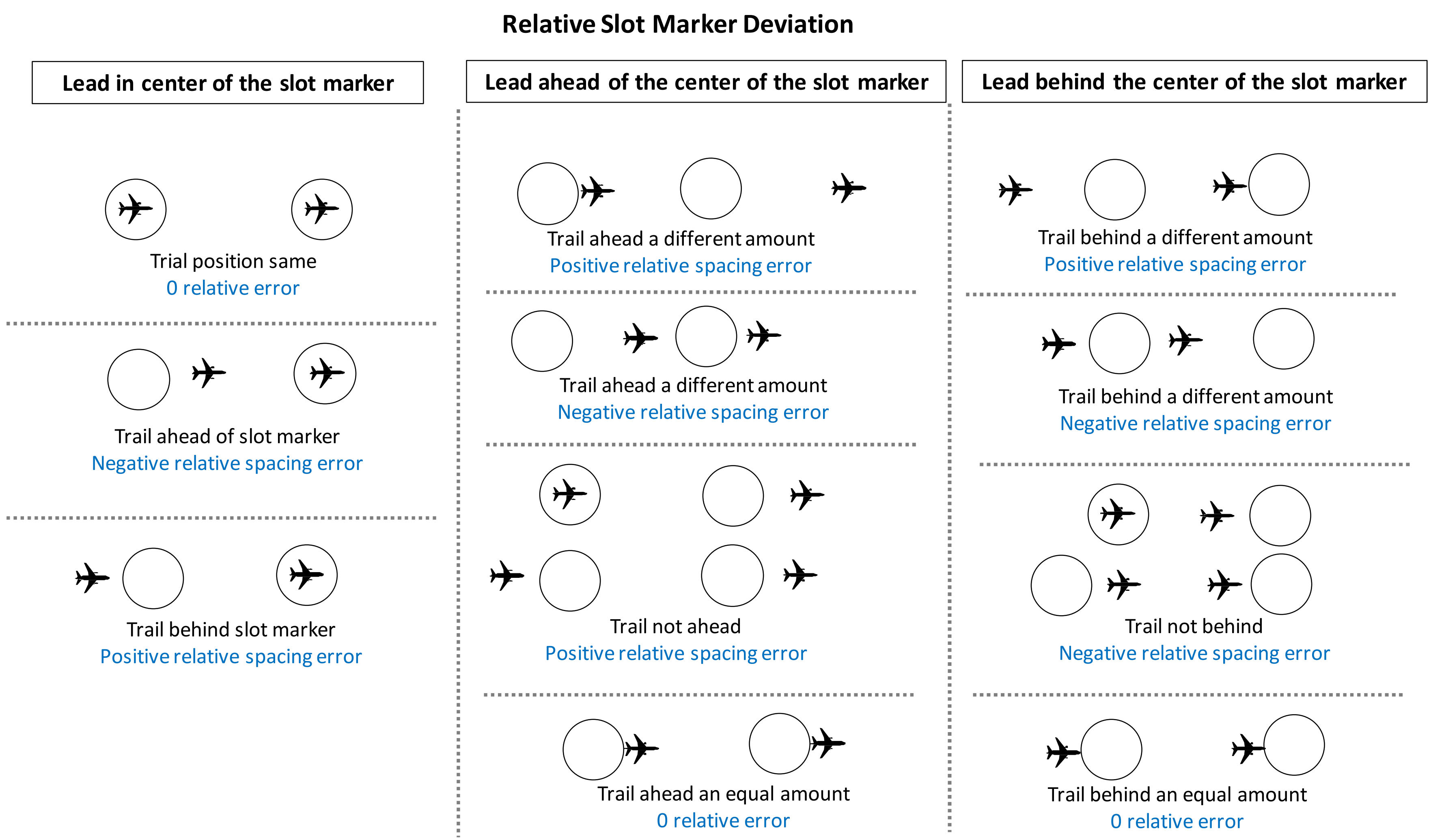


Figure D-1. Slot Marker Deviation

- Spacing error
  - Definition: Error in meeting the ASG (for trail IM aircraft) or the TBFM interval (for non-IM aircraft)
  - Note: This measure indicates how well a pair did relative to the planned interval between aircraft, even if off the original schedule (slots irrelevant). This is a relative measure. For trail IM aircraft, it is a measure of how well the ASG was met. For non-IM aircraft, it is a measure of how well aircraft met the TBFM-planned interval.
  - Note:
    - For the IM aircraft: (ATA_{trail} at the ABP- ATA_{lead} at the ABP) – ASG
    - For non-IM aircraft: (ATA_{trail} at the ABP- ATA_{lead} at the fix) - (STA_{trail} at the ABP - STA_{lead} at the fix)
- How well the ASG was maintained
  - Definition: Difference between ASG and current spacing of the trail IM aircraft from the lead aircraft
    - Note: For capture operations, started measure once trail IM aircraft got within 10 seconds
- Frequency and location where aircraft pair's spacing was below the separation standard
  - Definition: Location and number of times spacing between an aircraft pair was below the applicable separation standard for the aircraft pairing and location
- Arrival rates / throughput (AAR – number of aircraft per hour)
  - Definition: Number of aircraft landing (AAR – number of aircraft per hour)
- Time aircraft remained on the RNAV arrival procedure
  - Definition: Amount of time aircraft remained on their route
  - Note: Indication of whether a spacing operation was working well enough to avoid aircraft being vectored off their optimized route

Appendix E Relative Slot Marker Analysis Detail

This section provides the data used to derive the figures in Section 4.5.2.3. Slot marker deviations are shown in Table E-1 (seconds) and Table E-2 (NM) when the lead aircraft was ahead of its slot marker center. Figure E-1 shows a graphical representation. Slot marker deviations are shown in Table E-3 (seconds) and Table E-4 (NM) when the lead aircraft was behind its slot marker center. Figure E-2 shows a graphical representation.

Table E-1. Lead and Trail Deviation in Mean Seconds (SD) Relative to Slot Markers When the Lead Aircraft was Ahead of its Slot Marker Center

Aircraft role - IM clearance type	Airspace location									
	Feeder airspace		Handoff to final		Final airspace		DERVL (merge)		YOKXO (FAF)	
	Lead	Trail	Lead	Trail	Lead	Trail	Lead	Trail	Lead	Trail
IM trail - Achieve-by	-23.0 (11.7)	-15.9 (15.7)	-8.1 (6.8)	-4.6 (11.5)	-12.7 (8.9)	-15.3 (12.9)	-6.8 (3.7)	-6.0 (3.3)	-9.1 (7.0)	-8.8 (6.9)
IM trail - Achieve-by then maintain	-16.5 (9.4)	-17.5 (17.2)	-6.8 (4.8)	-1.5 (12.6)	-11.0 (9.2)	-10.0 (14.5)	-6.4 (4.7)	-5.7 (4.2)	-12.3 (12.6)	-11.4 (11.3)
IM trail - Capture then maintain	-17.9 (8.6)	-12.1 (14.9)	-8.4 (5.6)	-4.2 (10.4)	-13.4 (7.5)	-9.7 (12.4)	-7.2 (5.4)	-6.3 (4.8)	-10.1 (8.1)	-9.7 (7.8)
IM trail - Total	-19.0 (10.4)	-15.2 (16.2)	-7.7 (5.8)	-3.3 (11.7)	-12.2 (8.7)	-11.4 (13.7)	-6.8 (4.8)	-5.9 (4.3)	-10.5 (9.7)	-10.0 (9.0)
Non-IM trail	-11.5 (10.0)	-9.9 (12.3)	-6.3 (5.5)	-3.4 (8.8)	-9.3 (8.5)	-5.4 (10.2)	-5.6 (3.8)	-4.9 (3.3)	-8.9 (9.2)	-8.3 (8.5)

Table E-2. Lead and Trail Deviation in Mean NM (SD) Relative to Slot Markers When the Lead Aircraft was Ahead of its Slot Marker Center

Aircraft role - IM clearance type	Airspace location									
	Feeder airspace		Handoff to final		Final airspace		DERVL (merge)		YOKXO (FAF)	
	Lead	Trail	Lead	Trail	Lead	Trail	Lead	Trail	Lead	Trail
IM trail - Achieve-by	-1.8 (0.9)	-1.4 (1.4)	-0.6 (0.5)	-0.3 (1.0)	-0.8 (0.5)	-1.0 (0.9)	-0.3 (0.2)	-0.2 (0.4)	-0.4 (0.3)	0.3 (0.4)
IM trail - Achieve-by then maintain	-1.3 (0.7)	-1.6 (1.5)	-0.5 (0.3)	-0.1 (1.1)	-0.7 (0.6)	-0.7 (1.0)	-0.3 (0.2)	-0.3 (0.4)	-0.6 (0.6)	0.6 (0.7)
IM trail - Capture then maintain	-1.4 (0.7)	-1.0 (1.3)	-0.6 (0.4)	-0.3 (0.9)	-0.8 (0.4)	-0.6 (0.9)	-0.3 (0.2)	-0.2 (0.5)	-0.6 (0.4)	0.4 (0.6)
IM trail - Total	-1.5 (0.8)	-1.3 (1.4)	-0.6 (0.4)	-0.2 (1.0)	-0.8 (0.5)	-0.8 (0.9)	-0.3 (0.2)	-0.3 (0.4)	-0.5 (0.5)	0.5 (0.6)
Non-IM trail	-0.9 (0.8)	-0.8 (1.1)	-0.5 (0.4)	-0.2 (0.7)	-0.6 (0.5)	-0.3 (0.7)	-0.3 (0.2)	-0.2 (0.4)	-0.5 (0.5)	0.5 (0.6)

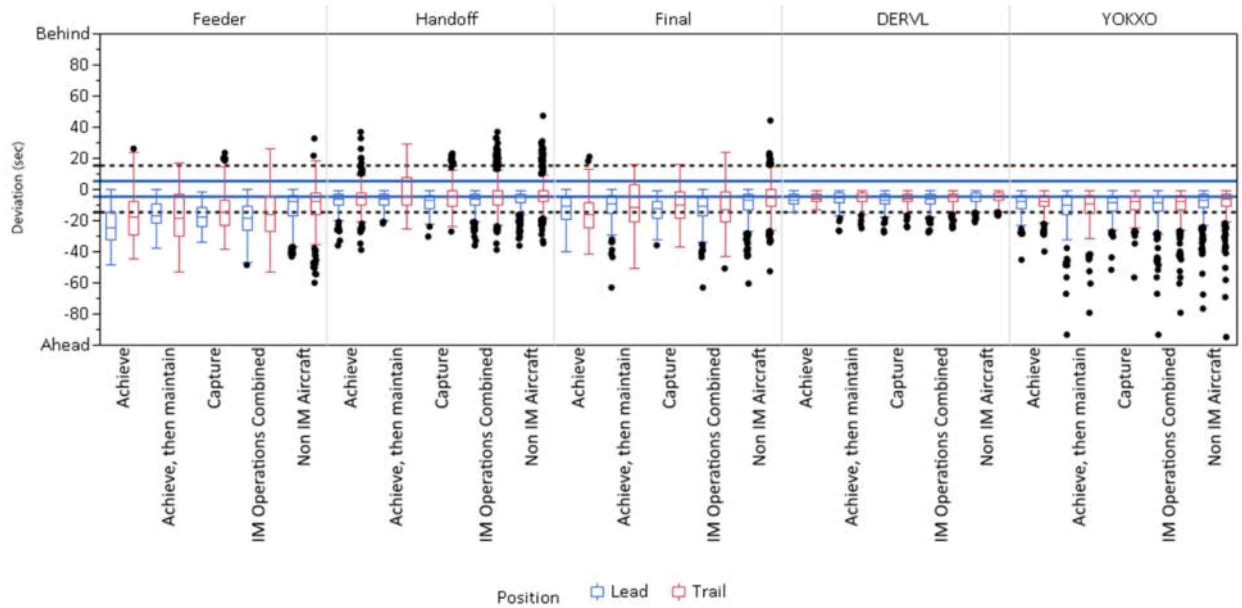


Figure E-1. Relative Slot Marker Deviation at Various Airspace Locations When Lead Aircraft was Ahead of its Slot Marker Center

Table E-3. Lead and Trail Deviation in Mean Seconds (SD) Relative to Slot Markers When the Lead Aircraft was Behind its Slot Marker Center

Aircraft role - IM clearance type	Airspace location									
	Feeder airspace		Handoff to final		Final airspace		DERVL (merge)		YOKXO (FAF)	
	Lead	Trail	Lead	Trail	Lead	Trail	Lead	Trail	Lead	Trail
IM trail - Achieve-by	6.1 (5.9)	-4.8 (21.4)	7.9 (5.5)	5.3 (12.1)	5.7 (4.4)	3.3 (11.2)	10.0 (4.9)	8.6 (4.1)	7.8 (6.8)	7.0 (5.4)
IM trail - Achieve-by then maintain	13.0 (7.6)	-1.7 (14.9)	13.0 (6.6)	4.7 (11.4)	7.0 (5.1)	3.0 (11.6)	8.0 (5.5)	7.0 (5.0)	7.5 (5.1)	7.3 (5.0)
IM trail - Capture then maintain	7.2 (4.3)	5.6 (8.5)	9.7 (3.8)	8.0 (4.6)	7.0 (4.5)	7.5 (4.8)	14.1 (9.5)	10.9 (6.0)	8.9 (8.2)	7.8 (6.5)
IM trail - Total	9.2 (7.2)	-1.4 (17.1)	10.4 (6.1)	5.6 (10.7)	6.4 (4.7)	4.0 (10.6)	9.8 (6.5)	8.3 (5.1)	8.1 (6.8)	7.5 (5.7)
Non-IM trail	12.7 (8.0)	-9.9 (15.9)	11.8 (8.4)	-2.1 (9.7)	5.0 (5.7)	-5.2 (9.9)	8.4 (7.1)	7.2 (6.1)	7.5 (6.2)	7.0 (5.6)

Table E-4. Lead and Trail Deviation in Mean NM (SD) Relative to Slot Markers When the Lead Aircraft was Behind its Slot Marker Center

Aircraft role - IM clearance type	Airspace location									
	Feeder airspace		Handoff to final		Final airspace		DERVL (merge)		YOKXO (FAF)	
	Lead	Trail	Lead	Trail	Lead	Trail	Lead	Trail	Lead	Trail
IM trail - Achieve-by	0.5 (0.5)	-0.3 (1.8)	0.6 (0.4)	0.5 (1.0)	0.4 (0.3)	0.3 (0.8)	0.4 (0.2)	0.6 (0.4)	0.4 (0.2)	0.2 (0.5)
IM trail - Achieve-by then maintain	1.1 (0.6)	-0.2 (1.3)	1.0 (0.5)	0.3 (0.9)	0.5 (0.3)	0.2 (0.8)	0.4 (0.3)	0.2 (0.5)	0.4 (0.2)	0.4 (0.4)
IM trail - Capture then maintain	0.6 (0.3)	0.5 (0.7)	0.7 (0.3)	0.6 (0.4)	0.5 (0.3)	0.5 (0.3)	0.5 (0.4)	0.3 (0.5)	0.3 (0.2)	0.3 (0.4)
IM trail - Total	0.8 (0.6)	-0.1 (1.5)	0.8 (0.5)	0.5 (0.9)	0.4 (0.3)	0.3 (0.7)	0.4 (0.3)	0.3 (0.5)	0.3 (0.2)	0.3 (0.4)
Non-IM trail	1.1 (0.6)	-0.8 (1.3)	0.9 (0.7)	-0.1 (0.8)	0.4 (0.4)	-0.3 (0.7)	0.4 (0.3)	0.0 (0.4)	0.3 (0.2)	0.0 (0.4)

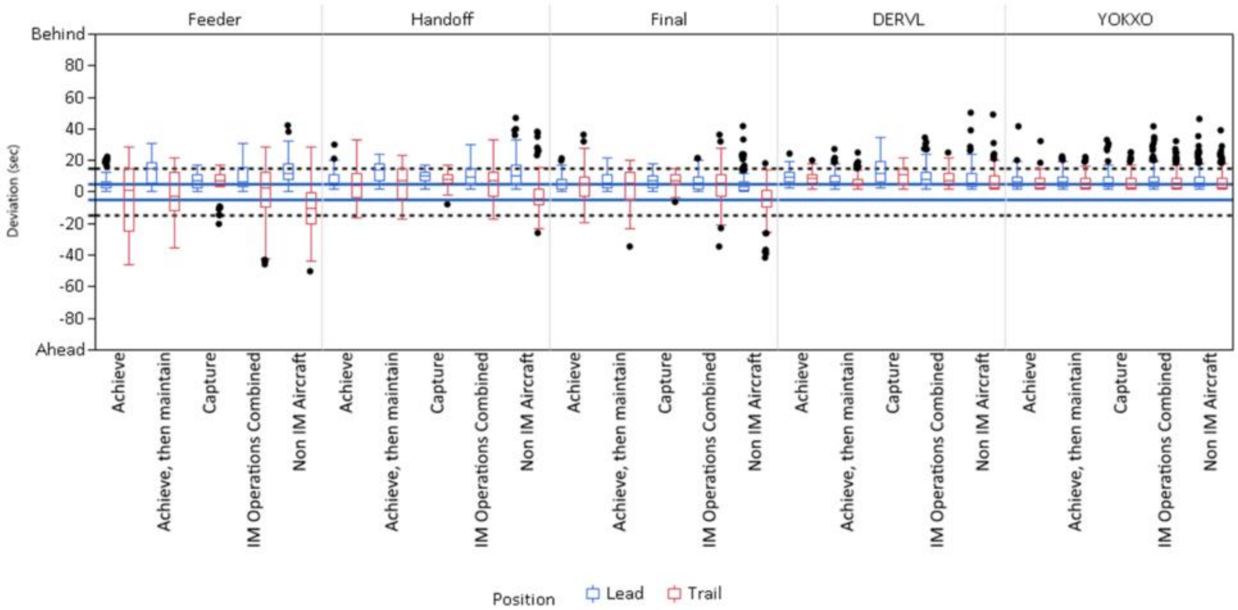


Figure E-2. Relative Slot Marker Deviation at Various Airspace Locations When Lead Aircraft was Behind its Slot Marker Center

Appendix F Acronyms and Abbreviations

Acronym	Definition
A80	Atlanta TRACON
ABP	Achieve-By Point
ACSS	Aviation Communication & Surveillance Systems
ADS-B	Automatic Dependent Surveillance-Broadcast
ADV	Advisory
AGD	ADS-B Guidance Display
ANOVA	Analysis of Variance
ASG	Assigned Spacing Goal
ATC	Air Traffic Control
ATD	Air Traffic management Demonstration
ATP	Air Transport Pilot
ATPA	Automated Terminal Proximity Alert
CA	CMS ATD
CARS	Controller Acceptance Rating Scale
CDTI	Cockpit Display of Traffic Information
CDU	Control and Display Unit
CLT	Charlotte TRACON
CMS	Controller Managed Spacing
CPC	Certified Professional Controller
CPDLC	Controller Pilot Data Link Communications
EFB	Electronic Flight Bag
EICAS	Engine-Indicating and Crew-Alerting System
ETA	Estimated Time of Arrival
F11	Orlando TRACON
FAA	Federal Aviation Administration
FAF	Final Approach Fix
FIAT	Fully Integrated ATD-1 Test

Acronym	Definition
FIM	Flight deck-based Interval Management
FMS	Flight Management System
FO	First Officer
HITL	Human-in-the-loop
IDEA	Integration, Demonstration, and Experimentation for Aeronautics
IFPI	Intended Flight Path Information
GIM-S	Ground-based Interval Management-Spacing
IAS	Indicated Air Speed
IAT	Inter-Arrival Time
IM	Interval Management
IMAC	Interval Management Alternative Clearances
IMPAT	IM Performance Analysis Team
KATL	Hartsfield–Jackson Atlanta International Airport
KORD	O'Hare International Airport
KPHX	Phoenix International Airport
KSFO	San Francisco International Airport
kt	knot
LED	Light-Emitting Diode
M	Mean
MANOVA	Multivariate Analysis of Variance
MCDU	Multifunction Control and Display Unit
MCP	Mode Control Panel
MIA	Miami TRACON
MOPS	Minimum Operational Performance Standards
MSI	Measured Spacing Interval
MTE	Meet Time Error
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
ND	Navigation Display

Acronym	Definition
NM	Nautical Miles
OIA	Operational Integration Assessment
PBN	Performance Based Navigation
PCT	Potomac TRACON
PF	Pilot Flying
PFD	Primary Flight Display
PHL	Philadelphia TRACON
PM	Pilot Monitoring
PSI	Predicted Spacing Interval
PTP	Planned Termination Point
RF	Radius-to-Fix
RNAV	Area Navigation
RNP	Required Navigation Performance
RTA	Required Time of Arrival
SCX	Sun Country
SD	Standard Deviation
SI	Spacing Interval
STA	Scheduled Time of Arrival
STAR	Standard Terminal Arrival Route
STARS	Standard Terminal Automation Replacement System
TBFM	Time Based Flow Management
TBO	Trajectory Based Operations
TOAC	Time of Arrival Control
TPA	Tampa TRACON
TRACON	Terminal Radar Approach Control
TSAS	Terminal Sequencing and Spacing
TSS	Terminal Sequencing and Spacing
TTG	Time-To-Go

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