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Evaluation of the Controller-Managed Spacing Tools, Flight-deck Interval Management and Terminal Area Metering Capabilities for the ATM Technology Demonstration #1

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Abstract— **NASA has developed a suite of advanced arrival management technologies combining time-based scheduling with controller- and flight deck-based precision spacing capabilities that allow fuel-efficient arrival operations during periods of high throughput. An operational demonstration of these integrated technologies, i.e., the ATM Technology Demonstration #1 (ATD-1), is slated for 2016. Human-in-the-loop simulations were conducted to evaluate the performance of the ATD-1 system and validate operational feasibility. The ATD-1 system was found to be robust to scenarios with saturated demand levels and high levels of system delay. High throughput, 10% above baseline demand levels, and schedule conformance less than 20 seconds at the 75th percentile were achievable. The flight-deck interval management capabilities also improved the median schedule conformance at the final approach fix from 5 to 3 seconds with less variance.**

Keywords-arrival scheduling; interval management; controller tools; terminal metering

I. INTRODUCTION

The future air transportation system is being designed to improve the capacity, efficiency and safety needed to handle predicted increases in traffic volume. Arrivals into high-density airports experience significant inefficiencies resulting from use of miles-in-trail procedures, step-down descents, and excess vectoring close to the airport. Use of these current procedures contributes to reducing airport throughput, increasing controller workload, increasing arrival delay, as well as increasing fuel burn, emissions and noise. Research efforts by the United States to develop the Next Generation Air Transportation System (NextGen) [1] and Europe's Single European Sky ATM Research (SESAR) Joint Undertaking [2] has led to the development of trajectory management tools enabling aircraft to simultaneously execute efficient descents while maintaining throughput using arrival scheduling capabilities. [3-6] The concept of managing precise relative spacing on the flight-deck has also shown benefits in increasing airport capacity. Research, simulation and field trials on airborne precision spacing have been conducted internationally. [7-10] Some of this research has included scheduling and air traffic control operations for simple arrival flows, but limited research has looked at fully integrated arrival operations at a busy airport for near term implementation.

NASA has developed a suite of advanced arrival management technologies combining time-based scheduling with controller- and flight deck-based precision spacing capabilities that allow fuel-efficient arrival operations during periods of high-density traffic demand. [11] An operational field demonstration of these integrated technologies, called the ATM Technology Demonstration #1 (ATD-1), is planned for 2016. [12,13] The ATD-1 system consists of three main components: 1) the Traffic Management Advisor with terminal metering capabilities (TMA-TM) for precise time-based schedules to the runway and points within the terminal area, 2) the set of Controller-Managed Spacing (CMS) decision support tools used to better manage aircraft delay with speed control, and 3) Flight-deck Interval Management (FIM) capabilities, consisting of aircraft avionics and flight crew procedures to automatically manage speeds to precisely achieve relative spacing. Aircraft will use Area Navigation (RNAV) Optimized Profile Descents (OPDs) that include transitions to a specific runway by connecting to Standard Instrument Approach Procedures (SIAP). These advanced arrival procedures allow flight crews to use their onboard Flight Management System (FMS) capabilities to fly more efficiently, reducing the use of radar vectors to the final approach course.

ATD-1 is a collaborative effort between the FAA, industry partners, and NASA Ames and Langley Research Centers. The individual technology components making up the ATD-1

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system were initially developed independently at NASA and their core functionalities have been refined and tested in a number of human-in-the-loop (HITL) simulations. NASA Langley developed the FIM concept, where studies have shown benefits in capacity through arrival delivery precision and also reduction in controller workload. [14-16] The NASA Ames Airspace Operations Laboratory (AOL) developed the set of CMS tools, where HITL simulations have indicated high ratings of the usefulness and usability of these tools as well as better route conformance. [17-19] The original TMA system was developed at NASA Ames' Air Traffic Control (ATC) laboratory and is currently used at Air Route Traffic Control Centers (or "Centers") nationwide for metering operations. [20] The TMA was enhanced to include terminal area metering, referred to as TMA-TM. TMA-TM coupled with the use of the CMS tools was tested at the ATC laboratory. Results demonstrated a reduction in the complexity of terminal area operations and an increase in airport throughput. Aircraft were able to maintain OPDs longer and with better scheduling conformance under heavy traffic demand levels. [21-24] Initial integration efforts of these technologies have been completed and tested at the AOL in HITL simulation. Initially, the ATD-1 concept was demonstrated using a typical terminal area routing network under moderate demand levels. Results indicated the concept is viable and the operations are safe and acceptable. [25,26] Building upon this work, the ATC lab recently completed its prototype of the ATD-1 system and conducted 15 HITL experimental runs in the Fall of 2012 to further validate the operational feasibility of the ATD-1 system with a different airport and to refine the operational concept for the demonstration.

This paper focuses on results from these recent HITL simulations. The major contribution from this study is an evaluation of the ATD-1 system with a more complex terminal routing infrastructure under saturated traffic demand levels. The robustness of the ATD-1 system is assessed in these conditions and findings will be used to guide the design of the scheduler and scenario settings most appropriate for a field demonstration.

The paper is organized as follows. Section II details the ATD-1 operational concept and the air traffic management tools employed as part of the integrated system. Section III describes the experimental details of the HITL simulations conducted to test the ATD-1 system. Results from the simulations are discussed in section IV, which evaluates overall system performance metrics, the FIM integration, and controller feedback of the ATD-1 system. Lastly, section V concludes with a summary of key findings and plans for further research and development.

II. ATD-1 OPERATIONAL CONCEPT

The operational concept focuses on arrivals prior to top-of-descent (TOD) in Center airspace about 100 NM from the Terminal Radar Approach Control (TRACON) boundary. Aircraft are navigating along RNAV OPDs that include runway transitions that connect to SIAPs. The TMA-TM generates an arrival schedule that conditions the flow as needed to keep arrivals on OPDs as well as meeting aircraft separation requirements. Center controllers have meter lists and delay countdown timers (DCT) shown in the resolution of tenths of minutes to assist them with metering operations. TRACON controllers are presented with CMS advisory tools to assist meeting the TMA-TM schedule. In the case that an aircraft is capable of conducting FIM (referred to as "FIM aircraft"), the Center controller will issue the clearance near TOD to commence spacing operations. The flight crew then follows the commanded speeds as generated by the FIM software to achieve and maintain relative spacing behind a given aircraft. TRACON controllers monitor the aircraft conducting spacing operations and intervene as necessary to maintain proper spacing.

The operational goal of the ATD-1 system is to enable arrivals, using onboard FMS capabilities, to fly OPDs from cruise to the runway threshold at a high density airport, at a high throughput rate, using primarily speed control to maintain separation and schedule. The three technologies in the ATD-1 system achieve this by calculating a precise arrival schedule that removes some of the excess spacing between aircraft, using controller decision support tools to provide controllers a speed for an aircraft to fly to meet a time at a particular point, and using onboard software that calculates a speed for the aircraft to achieve a particular spacing behind the preceding aircraft. [12] The following subsections describe the ATD-1 technologies in further detail.

A. *Traffic Management Advisor with Terminal Metering Capabilities*

The TMA-TM is a 4-D trajectory-based ground tool that provides the arrival sequence, scheduled times-of-arrival (STAs), runway assignments, and delay. Center controllers use this information to clear to each arrival its RNAV Standard Terminal Arrival Route (STAR) ending at its assigned runway. The STAs are computed at the meter fixes located near the TRACON boundary, metering points in the terminal area where arrival flows merge, and the runway threshold. Delays needed to meet the STAs at these meter points are distributed across the arrival route segments such that an adequate flow rate to the TRACON is maintained, but does not exceed the limitations of using speed advisories as the primary means for delay management.

B. *Flight Deck Interval Management*

Aircraft equipped with satellite-based surveillance technology, specifically ADS-B In, are candidates for FIM operations because position and altitude information of nearby ADS-B Out equipped aircraft can be received. FIM enables the controller to issue a single strategic clearance to flight crews of spacing-capable aircraft to achieve the required spacing interval behind a target (lead) aircraft at an achieve-by point. For ATD-1, the achieve-by point is the Final Approach Fix (FAF). The TMA-TM determines the target aircraft and spacing interval based on the sequence and STA at the FAF. The clearance information is displayed on the Center controller's radar display and is issued to the flight crew when appropriate. The flight crew then enters the clearance information into the on-board spacing tool and manages their speed along their lateral and vertical path to achieve precise inter-arrival spacing by the achieve-by point. Speed changes are limited to ±10% of the arrival procedure's published speeds and less than 250 knots when below 10,000 feet. The target and FIM aircraft must be within 2.5 NM laterally, 6,000 feet vertically and 90º heading deviation from their assigned RNAV path to be in active spacing mode.

C. *Controller-Managed Spacing Tools*

The CMS toolset provides the merging and spacing controller support in the TRACON and is primarily used for arrivals that are not able to conduct FIM operations. For aircraft that are conducting FIM operations, the CMS tools offer a way to monitor these aircraft and determine any off-nominal behavior. Fig. 1 shows the different types of CMS tools that can be displayed on the TRACON controller's radar display. The CMS tools provide slot marker circles, speed advisories, early/late indicators, and timelines to assist metering operations in the terminal area. The circular slot markers provide a spatial reference for each aircraft if it were to fly the nominal RNAV arrival route through the forecasted wind field, meeting all published restrictions and arriving at its STA. To follow the slot marker, a speed advisory is given to the next meter point along the arrival route. In cases where speed advisories would not be sufficient for the aircraft to absorb the delay needed to meet its STA, a late/early indicator is displayed. Timelines are also available for the controller's use to quickly monitor arrival sequence, current demand loads and delay values.

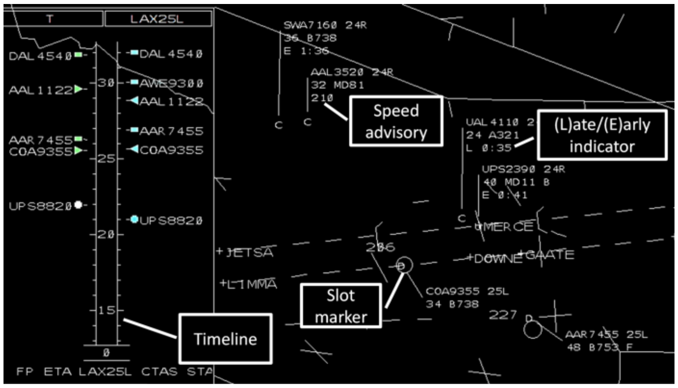


Figure 1. CMS terminal metering, merging and spacing tools.

III. EXPERIMENT DESIGN

A. *Simulation Environment*

The ATD-1 system was tested in the ATC laboratory using the Multi-Aircraft Control System (MACS) simulation platform. [27] MACS provides high-fidelity display emulations for air traffic controllers/managers as well as user interfaces and displays for confederate pilots, experiment managers, analysts, and observers. MACS also has flight deck capabilities that simulate current-day cockpit technologies that enable pilots to comply with ATC clearances. The Center and TRACON controllers worked with operational emulations of their respective radar displays.

The original software implementation of TMA-TM resided in the research prototype system developed at NASA Ames. For this HITL simulation, the terminal metering capabilities were ported to an FAA version of TMA, a necessary step in preparing the system for demonstration purposes. The TMA-TM schedule was used as input for the CMS algorithm and displays, which were embedded as part of the MACS system. NASA Langley developed the flight-deck displays, called the Aircraft Simulation for Traffic Operations Research (ASTOR) and the onboard spacing software, called Airborne Spacing for Terminal Arrival Routes (ASTAR). The flight-deck display was of medium-fidelity, based on a generalized Boeing 777 glass cockpit design. The FMS and airframe model was of high-fidelity. The ATC laboratory has three ASTOR systems, which allows up to three FIM aircraft per simulation run.

B. *Airspace*

Los Angeles International Airport (LAX) arrivals were modeled using the West Flow runway configuration with runways 24R and 25L under Instrument Meteorological Conditions (IMC). Fig. 2 illustrates the STARs modeled in the simulation. The RIIVR and SEAVU STARs are used by westbound traffic, accounting for more than 50% of the arrival traffic. These arrivals may be assigned to either 24R or 25L as determined by the TMA-TM runway balancing algorithms. Approximately one-third of the traffic arrives on the KIMMO and SADDE STARs and only use runway 24R. The rest of the arrivals on the LEENA and SHIVE STARs from the South are assigned runway 25L. Arrivals into LAX currently have an aircraft mix of approximately 85% jets and 15% turboprops.

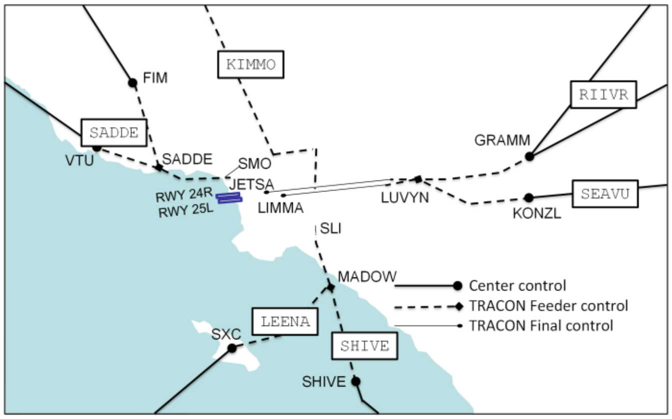


Figure 2. Arrival routes to LAX runway 24R and 25L.

The simulation airspace is segregated into two main areas of control: Los Angeles Center (ZLA) and Southern California (SoCal) TRACON. Fig. 2 shows the portions of the arrival routes for which each of these areas was responsible, along with their associated metering points. The ZLA controllers were responsible for managing each LAX arrival starting approximately 70 miles before its TOD and ending at its entry into terminal airspace located near the meter fixes. For simulation purposes, several of these sectors were combined so that three Center controllers were responsible for arrivals to the Northwestern (i.e., VTU and FIM), Eastern (i.e., GRAMM and KONZL) and Southern (i.e., SXC and SHIVE) meter fixes. Three TRACON Feeder controllers handled arrivals to the Northwestern (SADDE), Eastern (LUVYN) and Southern (MADOW) meter points. The TRACON Feeder controller managing the Southern flows also controlled arrivals on the KIMMO STAR. The SADDE STAR ends at SMO, where arrivals are given heading 070 and the expected runway. The SHIVE and LEENA STARs end at SLI, where arrivals are given heading 320 and the expected runway. The last aircraft hand-off is given to one of the two TRACON Final Controllers managing final spacing to LAX runways 24R and 25L respectively.

C. *Scenario*

The simulation scenarios were based on current LAX traffic characteristics with approximately 60 minutes of traffic starting outside the Center boundary. Anticipated demand was 75 aircraft per hour, with a peak rate of approximately 85 aircraft per hour. All jet aircraft were assumed to be equipped with ADS-B out. Three FIM aircraft were included in each scenario. Six scenarios were created, where placement of FIM aircraft was varied in the arrival flow. The scenarios differed by the number of FIM aircraft following each other, whether the target aircraft was within the same sector as the FIM aircraft, and the location in which the FIM aircraft and its target was in-trail.

D. *Participants*

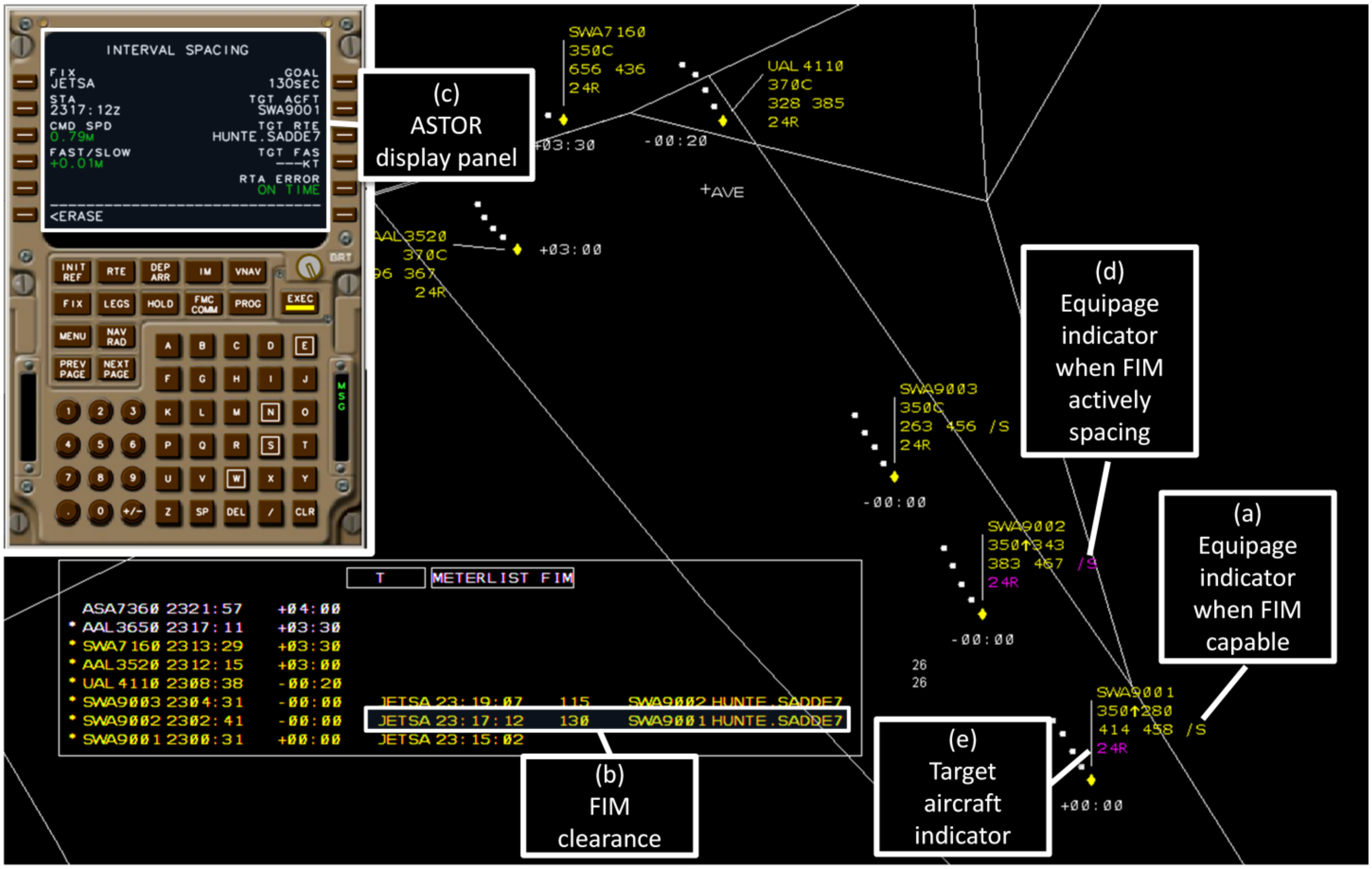
Eight controllers and thirteen pseudo-pilots participated simultaneously to cover all positions. They were experienced using the ATD-1 system from prior HITL simulations held at NASA Ames. All controller participants were recently retired (within the previous 2 years) from either SoCal TRACON or Los Angeles Center and averaged 20 years of ATC experience.

E. *Controller and Pilot Procedures*

The controller and pilot procedures remained as close to the ATD-1 operational concept as possible. [12] All controller and pilot interactions were via voice communication. The Center controller responsibilities included maintaining appropriate separation between aircraft, assigning the expected runway and STAR clearance prior to TOD for each aircraft in its sector, and ensuring that the non-FIM aircraft met the STA at the meter fix. Pseudo pilots verified the STAR in the aircraft FMS display panel along with the appropriate runway.

Fig. 3 shows the Center controller displays associated with aircraft equipped with FIM capabilities. Controllers determined FIM equipage by the /S on the data block as shown in Fig. 3a. The FIM clearance was displayed on the meter list, next to the aircraft's STA to the meter fix and delay value as displayed in Fig. 3b. Both the target and FIM aircraft must be within the tolerances of their published routes in order to begin actively spacing. To be within these constraints, Center controllers were instructed to pre-condition the FIM aircraft by reducing its delay to the meter fix to less than a minute and bring the FIM and target aircraft back on their STARs before issuing the FIM clearance. Pseudo pilots flying the FIM aircraft entered the FIM clearance into the ASTOR display panel as depicted in Fig. 3c, and reported to controllers when actively spacing behind the target aircraft. Center controllers also were able to change the color of the /S to magenta on the data block to indicate whether the FIM aircraft was actively spacing as seen in Fig. 3d.

In the terminal area, Feeder controllers received the aircraft handoffs and managed the STAs to the meter points within


INTERVAL SPACING

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STA 2317:12z
CMD SPD 0.79M
FAST/SLOW +0.01M
GOAL 130SEC
TGT ACFT SWA9001
TGT RTE HUNTE.SADDE7
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T    METERLIST FIM

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• AAL3650 2317:11   +03:30
• SWA7160 2313:29   +03:30
• AAL3520 2312:15   +03:00
• UAL4110 2308:38   -00:20
• SWA9003 2304:31   -00:00   JETSA 23:19:07   115   SWA9002 HUNTE.SADDE7
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Figure 3. Center controller and FIM pilot display.

their sector referencing the CMS advisory tools as needed. Final controllers were responsible for proper spacing to the runway. In cases where the arrivals were handed off on a heading, it was the final controller’s responsibility to turn the aircraft from its downwind leg onto final. Controllers were encouraged to use vectoring as a last resort, utilizing speed control foremost to manage the arrival traffic. FIM operations could be terminated in certain circumstances or if the target aircraft had passed the FAF. The controllers, however, were asked to give priority to those aircraft actively spacing. In cases where controller intervention was needed, they had the option to suspend FIM operations, then ask pilots to resume active spacing with its target aircraft or terminate outright.

F. Test Conditions

These scenarios were run with three different TMA-TM scheduler settings which varied the amount of delay distributed in the terminal area. Allocated TRACON delay was an average of 0, 10 and 20 seconds for each of the scheduler settings, with a maximum of 35 seconds. Center delay values averaged 2 minutes, with some aircraft having up to 6 minutes. A total of 15 simulation runs were completed, and six of these included an explicit target aircraft indication on the Center and TRACON controller displays by changing the color of the runway assignment to magenta as illustrated in Fig. 3e. The simulation did not incorporate any wind conditions.

IV. RESULTS

The integration of the TMA-TM capabilities and CMS toolset was tested in the ATC lab in prior HITL simulations conducted in the Fall of 2010 and 2011. These past simulations examined a variety of system performance and workload metrics using the same airspace and similar scenarios. The major addition to the ATC lab for the current study is the integration of the FIM component of the ATD-1 system. A second change is the use of the TMA-TM capabilities embedded in a different software baseline that progresses towards the final system to be used in the field demonstration. Results will first describe the validation of the fully integrated ATD-1 system, by comparing its system performance to past studies. The next section B focuses on factors that influenced successful FIM integration with controller tools. Controller workload metrics and feedback are then examined for the ATD-1 system in section C. This simulation only investigated the functional requirements for controller display and phraseology. Research at NASA Langley and the AOL lab will complete the development of the display elements and phraseology standards.

A. ATD-1 System Evaluation

The TMA-TM can be configured to produce a schedule with a specified amount of terminal area delay distribution. In this set of simulations, the maximum delay distributed to the terminal area was varied from 0 to 35 seconds, the range where primarily speed control can be used. Past simulations had terminal area delays with a maximum of 90 seconds. Fig. 4a shows the lateral paths of jets for a scenario from past simulations where the TMA-TM was set with 90 seconds of maximum delay distribution. Fig. 4b shows the lateral paths where the maximum delay distribution was set to 35 seconds. The terminal area is magnified in Fig. 4c and 4d. [22]

Most of the scheduled delay was absorbed in Center

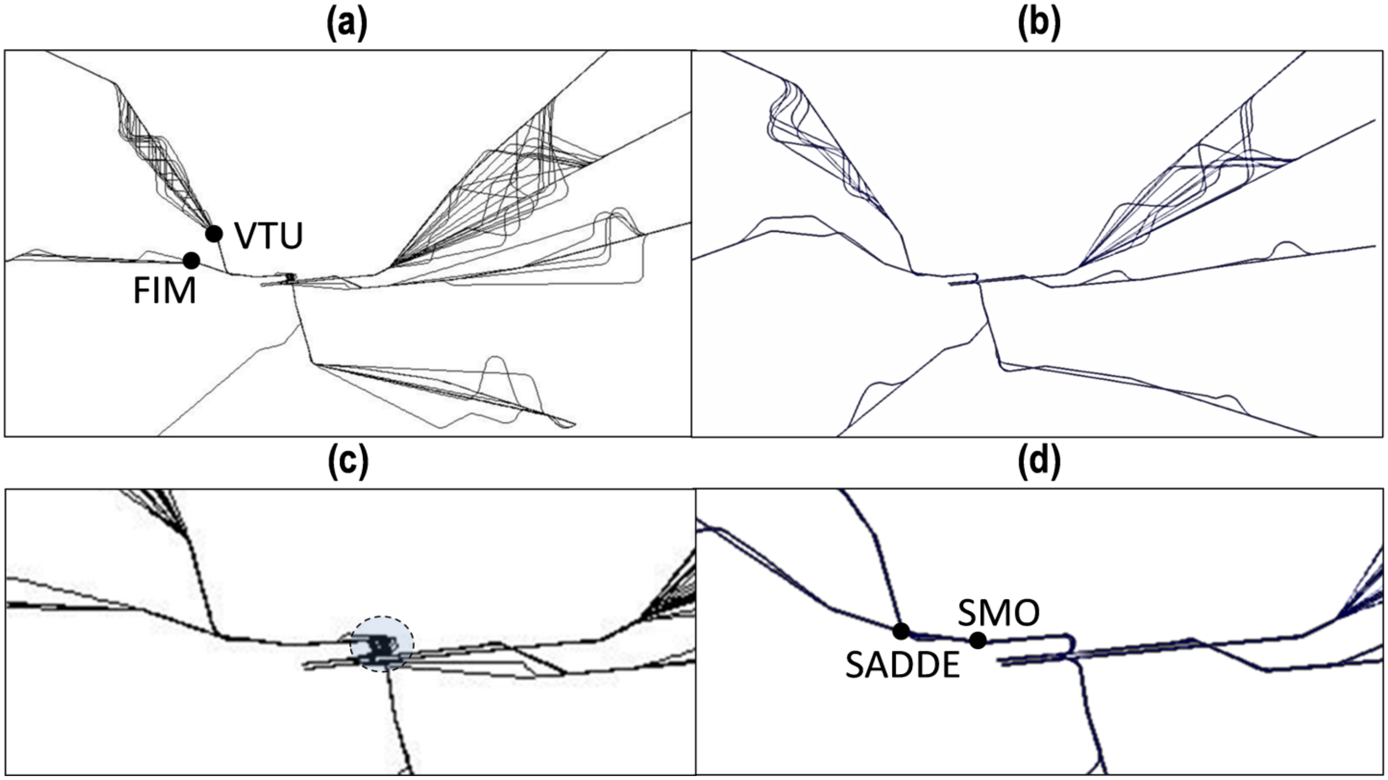

Figure 4. Lateral paths of jets when terminal delay distribution set to (a) 90 seconds, (b) 35 seconds and corresponding magnified terminal area in (c) and (d).

airspace, which often exceeded the bounds of speed authority. Fig. 4a and 4b indicate that many arrivals are path vectored prior to the meter fixes; other aircraft are also given an earlier descent for delay absorption. Fig. 5 shows the amount of time aircraft were off their published route laterally and/or vertically versus their scheduled delay. The aircraft delay was quantized in 10 second intervals and then the average off-path time, in seconds, was computed. FIM and target aircraft are differentiated by blue squares and green triangles respectively. A linear least squares fitting was used for the aircraft not participating in FIM operations with a slope of 3.4, y-intercept of 425.4 seconds, and R^2 = 0.71. Fig. 5 shows that the off-path time for FIM and target aircraft are generally less than those not participating in FIM. FIM and target aircraft, on average, have 431 and 323 seconds less off-path time than non-FIM. This illustrates the controllers being particularly sensitive to bringing these aircraft back on their published route so that FIM can occur as soon as possible.

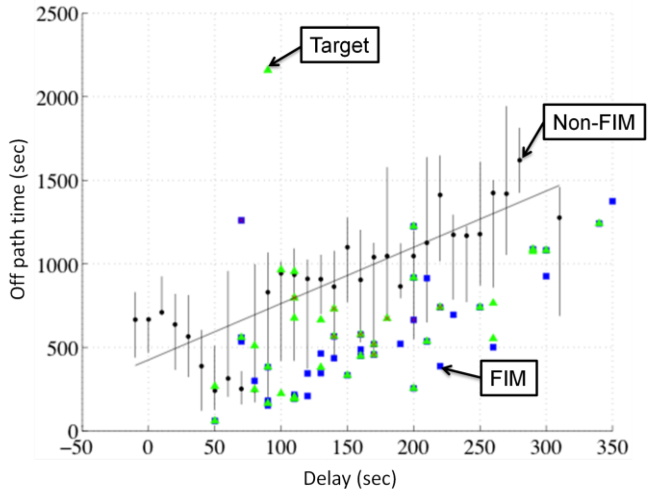

Figure 5. Off path time of all jets versus scheduled delay.

Fig. 4d also shows the lack of ‘tromboning’ of the base leg, in comparison to Fig. 4c. Reducing the maximum delay distribution to within speed authority bounds results in less variation in the lateral paths despite being given a heading after SMO until further clearance. Throughput was consistent across all simulation runs and similar to past system performance. The average and peak throughput was 71 and 83 aircraft per hour respectively with standard deviations less than 3.

Fig. 6 shows the box-and-whisker plot of the absolute value of the schedule conformance to each scheduling point across all runs, categorized by whether aircraft conducted FIM operations until the FAF. In past simulations, the Center controllers’ radar displays had DCTs displayed in resolutions of seconds, versus the tenths of minutes used in these simulations. The median schedule conformance at the meter fix, 11 seconds, was similar to results from past simulations despite the change in DCT resolution display. These data suggest that Center controllers are able to condition traffic to a certain precision level given a schedule without additional advisory tools. Compared to past results, the terminal meter point schedule conformance significantly improved in precision due to the reduced terminal delay distribution. For those FIM aircraft actively spacing until the FAF, the median and variance of the schedule conformance is worse at the meter fixes and terminal meter points in the Feeder sectors, but improves at the FAF from 5 to 3 seconds with a smaller variance. This is due to the ASTAR algorithm explicitly computing speeds to precisely meet a spacing goal by the FAF and not the upstream scheduling points.

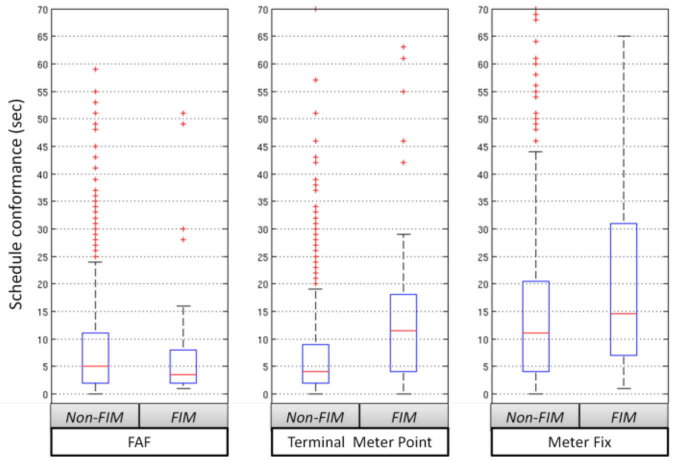

Figure 6. Box-and-whisker plot of the absolute value of the schedule conformance to each scheduling point.

Overall, the FIM component integrated with TMA-TM and the CMS tools was similar to system metrics measured in prior simulations and did not degrade overall system performance. The ATD-1 system is robust to scenarios with saturated demand and high levels of system delay. Controllers were able to adapt their delay absorption techniques for those aircraft participating in FIM by being more diligent about keeping these aircraft on their published routes. High throughput and precise schedule conformance were maintained for all scenario runs. Keeping the terminal delay within speed authority bounds resulted in less lateral path deviation and improved precision in schedule conformance at terminal meter points. Schedule conformance at the FAF also showed improvement when using FIM.

B. *FIM Integration with Controller Tools*

The ATC lab was configured to accommodate up to three FIM aircraft in each scenario. The simulation examined various ATD-1 system settings that would facilitate the integration of aircraft with FIM capabilities and controller ground tools in a mixed equipage environment. FIM aircraft, when eligible, should ideally be actively spacing behind its target aircraft beginning in Center airspace and terminating at the achieve-by-point, the FAF. There were two factors that determined whether the FIM aircraft was eligible to actively space behind its target aircraft: 1) when the pair was within ADS-B range and 2) when the target aircraft started its descent after TOD. Given the simulation airspace structure, all pairs were well within ADS-B range when the target aircraft was near TOD.

Controllers and pilots could elect to terminate FIM operations for various reasons. FIM termination was procedural in cases when the target deviated significantly from its published route. The FIM aircraft not engaging in active spacing upon entry into terminal airspace was also grounds for termination. FIM operations could also be suspended and then resumed by controller discretion to maintain proper separation or absorb scheduled delay. Any of these actions reduce the benefits of conducting FIM.

There was a total of 45 FIM aircraft across all runs. Fig. 7 plots the distance-to-runway when FIM aircraft engaged in active spacing versus termination for each FIM aircraft. The distance-to-runway was normalized to be 1, where the FIM aircraft was eligible for active spacing. References for TOD, meter fixes, terminal meter points and FAF are also marked in the plot. For those aircraft conducting FIM operations, Fig. 7 indicates that all initiate FIM prior to the meter fix, in Center airspace, with approximately 50% starting near TOD. With the exception of two aircraft, FIM operations terminated at the FAF. The two FIM aircraft that had to terminate FIM operations in the Center did so because the target aircraft was out of the lateral or vertical tolerances of its published route.

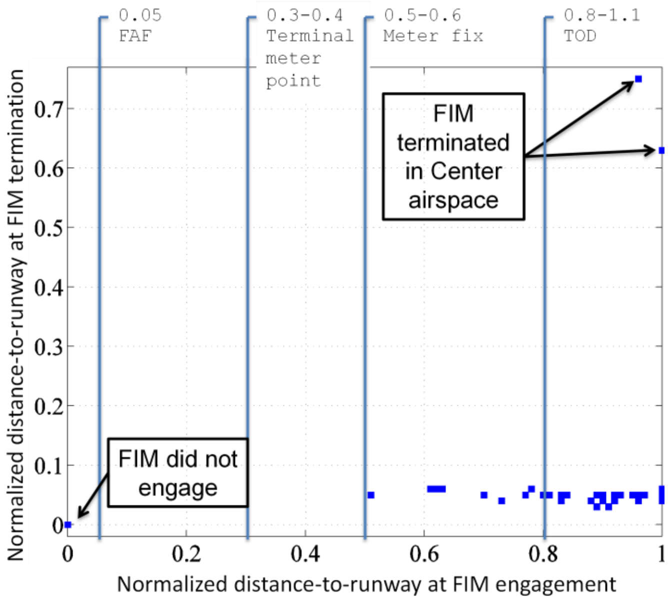

Figure 7. Normalized distance-to-runway at FIM engagement and termination.

Of all potential FIM operations, 5 failed to actively space behind their target aircraft when eligible. In one instance, the FIM pilot incorrectly entered the target aircraft's call sign in the ASTOR display panel (Fig. 3c). In the rest of the cases where FIM operations did not occur, the FIM and/or its target aircraft was vectored for delay and was not within the bounds of its published route before handoff to the Feeder sectors in the terminal area. From the 40 FIM operations conducted, seven of them suspended and then resumed operations in the terminal area.

About half of possible FIM operations had the target aircraft originating from a different route. Of the 15 simulations conducted, 6 had an indication of the target aircraft on the flight data block to aid inter-controller coordination. Fig. 8 shows the effect of these on 1) the occurrence of FIM aircraft engaging in active spacing and 2) not utilizing suspend/resume procedures. Fig. 8a indicates that when the FIM and target aircraft have the same flight plan route, there is an 11% higher chance of FIM operations occurring. Of all the FIM aircraft engaging in active spacing, Fig. 8b shows that the chance of suspending and resuming FIM reduces by 21% when the target aircraft was indicated on the controller's radar display (see Fig. 3e).

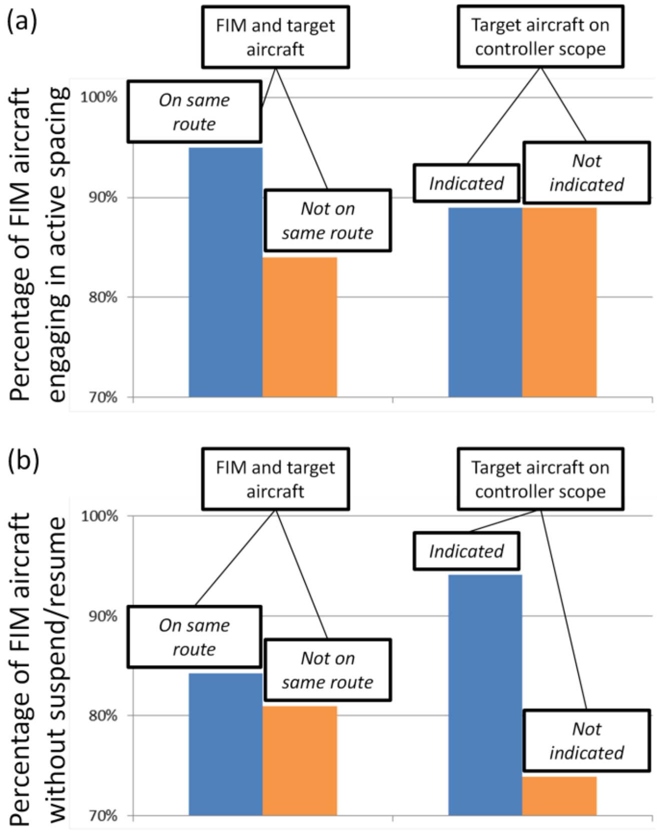

Figure 8. Percentage of (a) FIM aircraft engaging in active spacing and (b) not utilizing suspend/resume procedures

To assess the integration of FIM operations in a mixed equipage environment as designed in the current operational concept, a success metric for each FIM aircraft was defined as *the time spent by the FIM aircraft in active spacing mode to the FAF divided by the time spent by the target aircraft from its TOD point to the FAF*. FIM aircraft are considered to be 'successful' when able to engage in active spacing immediately after becoming eligible (i.e., the target has started its descent after TOD). Using this metric, in the ideal case, FIM aircraft having values of 1 indicate that FIM operations occurred when the target aircraft reached its TOD point and remained in active spacing mode until the FAF. FIM aircraft having a value of less than 1, indicates that FIM operations either 1) initiated after eligible for active spacing, 2) terminated before the FAF, or 3) there may have been a period where operations were suspended and resumed. Those that did not perform FIM operations have values of 0.

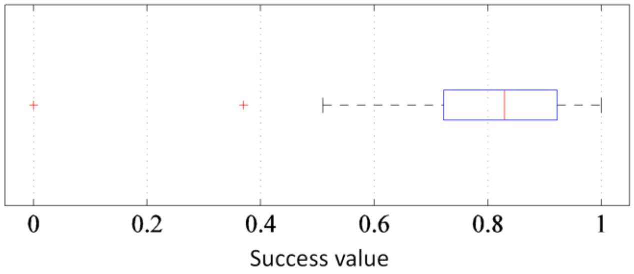

Figure 9. Box-and-whisker plot of FIM success values.

Fig. 9 displays the box-and-whisker plot of success values for all 45 FIM aircraft. The 5 aircraft that failed to actively engage in FIM are marked at 0. The median success value is 0.83 with 25th and 75th percentiles at 0.72 and 0.92 respectively. There were 4 aircraft that had success values of 1.

Fig. 10 compares the median value of overall Center delay for FIM, target, and non-FIM aircraft that failed to conduct FIM operations (i.e., with success values of 0), those that were able to engage in active spacing without interruption (i.e., with success values of 1) and the rest of the FIM aircraft (i.e., with success values greater than 0, but less than 1). The TMA-TM scheduler setting varied the amount of Center delay, but kept the terminal delay within the range of speed authority where aircraft are rarely taken off for vectoring. Fig. 10 indicates that non-FIM Center delay has less of an effect on the success values. As seen in Fig. 9, most FIM operations have fairly high success values given that a large number of aircraft have Center delays that are well outside of speed authority bounds. Success values are mostly unaffected by the FIM and target scheduled delay. In the case where FIM aircraft had success values of 1, however, the FIM and target aircraft delay was notably less.

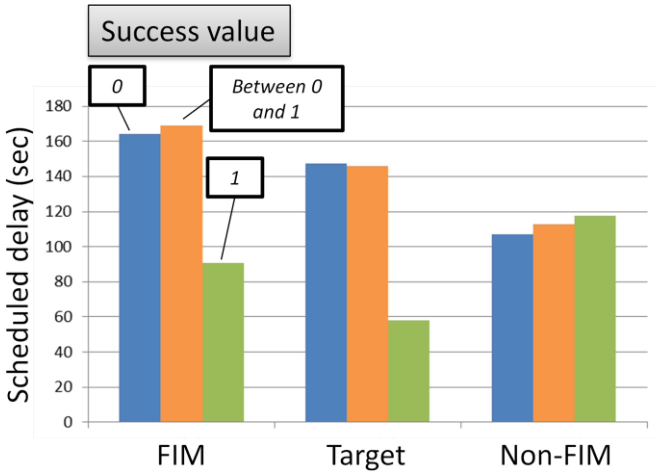

Figure 10. Median scheduled Center delay (sec) for FIM , target, and non-FIM aircraft.

Fig. 11 shows the box-and-whisker plot of the FIM aircraft initial deviation from the assigned spacing goal as issued in the FIM clearance by the Center controller. The 99th percentile is less than 60 seconds, which shows the effect of pre conditioning in Center airspace before the FIM clearance is issued.

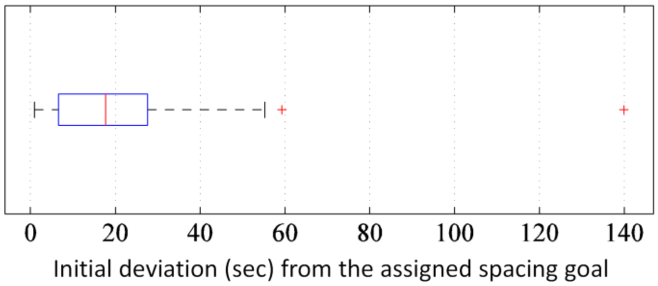

Figure 11. FIM aircraft deviation (sec) from its assigned spacing goal when beginning active spacing behind its target aircraft.

Overall the FIM integration with controller advisory tools is reasonably robust given the range of scenarios tested in the simulation. FIM operations are generally insensitive to the amount of overall Center, FIM and target delay. Operationally, there are some factors that would facilitate FIM operations:

- FIM and target delay within speed authority
- FIM and target aircraft on the same flight plan route
- Controllers made aware of a potential target aircraft

C. Controller feedback

There were 58 questions in the post-run questionnaire for the controllers. Each controller completed the questionnaire at the end of every run, for a total of 136 sets of responses. Questions focused on the FIM operations, their impact on controller strategies and tasks, and the impact of procedural changes to accommodate FIM.

Workload data were collected using the rating portion of the NASA Task Load Index (TLX). [28] Controllers rated their level of workload on a scale from 1 "very low" to 7 "very high." Fig. 12 shows the mean workload rating for Center and TRACON controllers. The workload ratings given by the Center controllers were higher in all cases than the ratings for the same subscales given by the TRACON controllers. Center controllers had the additional responsibilities of issuing the FIM clearance as well as assuring that the FIM pair was within the tolerances of its published route required for FIM engagement. Overall, mean workload ratings were below 4, indicating that all Controllers had manageable levels of workload. Participants did use all 7 points in the TLX scales,

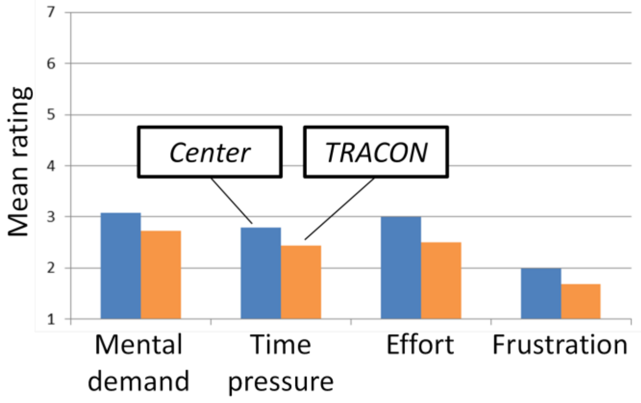

Figure 12. Mean workload rating for NASA TLX sub scales for Center and TRACON controllers.

although they used the lower side of the scale far more often. The mean workload ratings by TRACON controllers were slightly lower compared to past simulations, possibly due to less terminal delay distribution and less advisories given to FIM aircraft.

Controllers reported minimal change in air traffic management strategy when managing the non-FIM aircraft to incorporate FIM aircraft. Most of the time, controllers did not have to maneuver the non-FIM aircraft to accommodate FIM aircraft. The few cases where this was needed were due to maintaining separation or trying to get the target aircraft back onto its route. For 80% of controller responses, they did not encounter spacing issues when the FIM aircraft was actively spacing behind its target aircraft. No issues were reported in 80% of the cases when the target aircraft were arriving on different routes. In cases where there was an issue, it was due to the target aircraft having to be slowed for delay absorption, which then caused a spacing issue that sometimes resulted in FIM operations being suspended. The scheduled delay for the non-FIM aircraft was rated as being "manageable/small." This was rated slightly greater for FIM aircraft, but still "quite manageable." Participants rated their task complexity as having "low to moderate" complexity overall.

Controllers were asked to compare the amount of time spent communicating with FIM aircraft versus non-FIM aircraft. The total time taken for the transmission of the FIM clearance by the Center controller, the pilot read-back and entry into the FIM panel averaged 127 seconds with a standard deviation of 40 seconds. There is a notable distinction between Center and TRACON controller responses that illustrates how the workload of the FIM task falls to the Center controllers. Center controllers reported that they talked to FIM aircraft "more" or "much more" than those not participating in FIM operations. Center controllers had an increase in communication due to issuing the FIM clearance and additional advisories to ensure that the FIM pair was within the tolerances of its published route needed for FIM engagement. TRACON controllers reported that they talked to FIM aircraft the "same" or "less than" the rest of the aircraft. In cases where FIM aircraft were actively spacing behind their target aircraft, TRACON controllers preserved FIM operations as long as possible and intervened only when necessary to maintain minimum separation.

The usefulness and usability of Center and TRACON advisory tools were also assessed. Center controllers mostly used the delay countdown timer and runway designator and rated them as "very useful." The FIM clearance listed in the meter list and the FIM data block indicator (as shown in Fig. 3) were also "very useful" although they were used less often. TRACON controllers found the slot markers, timeline and speed advisories to be the most useful for managing non-FIM aircraft. These tools received lower usefulness ratings for FIM aircraft, since they were not used explicitly to manage these aircraft. For example, TRACON controllers reported using the speed advisory about 75% of the time but only rated them as "somewhat useful" for FIM. The FIM data block indicators and spacing cones were rated as more useful for FIM management than the slot markers, despite being used 40% of the time overall. TRACON participants were also asked whether they saw any mismatch between a FIM aircraft and its slot marker when actively spacing behind its target aircraft. They reported mismatches about 46% of the time, but long-term mismatches only about 13% of the time. Feeder and Final controllers reported these mismatches with equal frequency. These mismatches were due to the differences in trajectory prediction algorithms in ASTAR and the CMS system.

Out of all the FIM clearances issued, only two discrepancies were noted between the actual status of FIM operations and the data block indicator. Controllers were still conscientious about marking the right state of the FIM aircraft in their data tags despite the short training time provided. Controllers did not indicate that they wanted to be able to have other status conditions for the FIM aircraft (e.g., suspended or terminated). When invited to list additional icons they would like, there were no responses except an affirmation that they liked to know the target aircraft.

V. CONCLUSION

NASA has developed a suite of advanced arrival management technologies combining time-based scheduling with controller- and flight deck-based precision spacing capabilities, with a planned field demonstration (i.e., ATD-1) in 2016. Fifteen high-fidelity HITL simulation runs were conducted at NASA Ames Research Center's ATC lab to evaluate the performance of the ATD-1 system using a complex terminal routing infrastructure under saturated traffic demand levels. The ATD-1 system was assessed in a variety of conditions and findings were used to guide the design of the scheduler, procedures, and scenario settings most appropriate for a field demonstration.

The ATD-1 system represented in these simulations was found to be robust to scenarios with saturated demand levels and high levels of system delay. The incorporation of the FIM component with TMA-TM and the CMS tools achieved similar performance compared to prior simulations and did not degrade overall system performance. The system sustained high throughput (10% above baseline demand levels) and the schedule conformance was within 20 seconds at the 75th percentile. The FIM aircraft also had improvements in the median and variance of their schedule conformance at the FAF. Controllers rated their workload low overall. The usefulness, usability, and functionality of the advisory tools and displays were also validated using controller feedback. To better facilitate FIM operations, it is advisable to pre-condition the FIM and target aircraft before issuing the FIM clearance and also configure the TMA-TM so that delay allocated to the terminal area is within the limits where primarily speed adjustments are used for schedule conformance. Best system performance was achieved when the FIM and target aircraft was on the same flight plan route and had initial scheduled delay within the speed control authority.

Future HITL simulations will test the ATD-1 system using the proposed field demonstration site. These simulations will continue to add refinements to the ASTAR algorithm, such as being able to account for FIM aircraft being issued a direct-to fix advisory and widening the tolerance widths of allowable deviation from its published route. Further research to improve the FIM flight deck displays will minimize incorrectly keyed entries and more concise phraseology will also reduce transmission time. Incorporation of wind conditions, truth and forecasted, in future simulations is planned.

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