CHAPTER XX

Controller-Managed Spacing within Mixed-Equipage Arrival Operations involving Flight-Deck Interval Management

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ABSTRACT

New NASA research focuses on integrated arrival operations along efficient descent profiles using advanced scheduling automation, tools to aid air traffic controllers, and airborne precision-spacing automation to enable fuel-efficient arrivals at busy airports during peak traffic periods. This paper describes an initial human-in-the-loop study and presents results that address human factors of controller tools and operational procedures for managing a mix of scheduled arrivals in which some aircraft use Flight-Deck Interval Management (FIM) automation to achieve precise spacing behind their lead aircraft. The results are consistent with prior research and suggest potential enhancements from the ground-side perspective to support mixed-FIM-equipage arrival operations.

Keywords: aircraft arrival management, air traffic controller tools, flight-deck interval management, scheduling

1 INTRODUCTION

A major Next Generation Air Transportation System (NextGen) goal is to enable low-noise, fuel-efficient arrivals with high throughput in congested metroplex areas (JPDO, 2010). Today, aircraft equipped with Flight Management Systems (FMSs) can fly Optimized Profile Descents (OPDs) along Area Navigation (RNAV) routes to provide the required environmental benefits. However, because current air traffic control techniques rely largely on heading adjustments and step-down descents, RNAV OPD operations are only feasible during light traffic conditions. Maintaining OPDs requires controllers to use speed adjustments as the primary means of control, which, without suitable tools, can be difficult (Davison-Reynolds, Reynolds, and Hansman, 2005). Tools for 'Controller-Managed Spacing' (CMS) of scheduled arrivals have been developed in the Airspace Operations Laboratory (AOL) at NASA Ames Research Center, and were found to be useful in enabling OPD operations in simulations with moderately high traffic levels (Kupfer, Callantine, Martin, Mercer, and Palmer, 2011).

A recently inaugurated NASA project called Air Traffic Management Demonstration-1 (ATD-1) seeks to operationally demonstrate the feasibility of fuel-efficient, high-throughput arrival operations using air- and ground-based NASA technologies and Automatic Dependent Surveillance-Broadcast (ADS-B) (Prevot et al., 2012). Under ATD-1, the CMS tools, an advanced arrival scheduler called the Traffic Management Advisor for Terminal Metering (TMA-TM), and advanced avionics for Flight-Deck Interval Management (FIM) will be integrated to form the Interval Management Terminal-Area Precision Scheduling System (IM-TAPSS) (Figure 1). The TMA-TM is an extension to the currently fielded TMA, which is a trajectory-based automation system developed at NASA Ames, that constructs an arrival schedule tailored specifically for high-capacity OPD operations (Swenson et al., 2011). FIM capabilities, as implemented in the Airborne Spacing for Terminal Arrival Routes (ASTAR) algorithm developed at NASA Langley Research Center, enable flight crews to assist air traffic controllers by managing their own speeds to

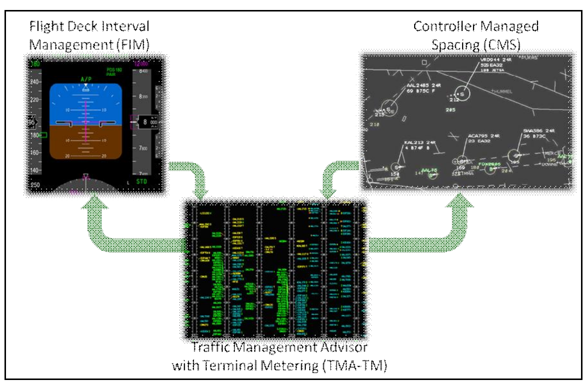


Figure 1. NASA-developed FIM capabilities, CMS tools, and TMA-TM, integrated as IM-TAPSS for ATD-1.

precisely achieve capacity-maximizing arrival spacing (Barmore, Abbott, and Capron, 2005). Following laboratory fine-tuning, verification, and validation, ATD-1 will implement IM-TAPSS in a field prototype for an operational demonstration at a U.S. airport, targeted for 2015.

This paper presents an initial human-in-the-loop simulation conducted, first, to integrate the IM-TAPSS components in the AOL to support follow-on ATD-1 simulations; and, second, to investigate how the CMS tools and operational procedures perform in a mixed-equipage environment where controllers manage the spacing of non-FIM-equipped ('CMS') aircraft, while flight crews manage the spacing of FIM-equipped ('FIM') aircraft. The integration goal was achieved to a sufficient degree to warrant preliminary research on enhancing the CMS tools and operational procedures. The paper first provides background on the IM-TAPSS component technologies and the operational concept IM-TAPSS supports. It then describes the first CMS ATD-1 simulation ('CA-1') in detail. After presenting results derived from the subjective data sets, including participant observation and feedback, post-trial and experiment-summary questionnaires, and a post-simulation debriefing discussion, the paper concludes with recommendations for further research.

2 BACKGROUND

While it principally serves to improve the efficiency of terminal-area air traffic management, IM-TAPSS starts functioning in en-route airspace up to 200 nmi from the terminal-area boundary. Before aircraft begin descending toward the destination airport, TMA-TM performs runway assignments and generates schedules at terminal-area entry fixes, merge points, and runways. The schedules help controllers maximize arrival capacity and strategically coordinate arrival flows from different en-route sectors. TMA-TM freezes the arrival schedule at a preset 'freeze horizon' to provide stable control targets. Schedules are presented as timelines (see Fig. 2) with estimated and scheduled times-of-arrival (ETAs and STAs) with aircraft symbols advancing down the timeline toward the current time at the bottom as they near the scheduling point.

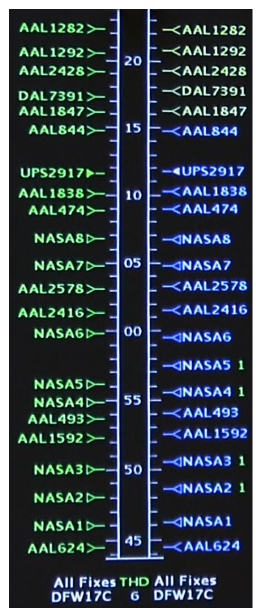
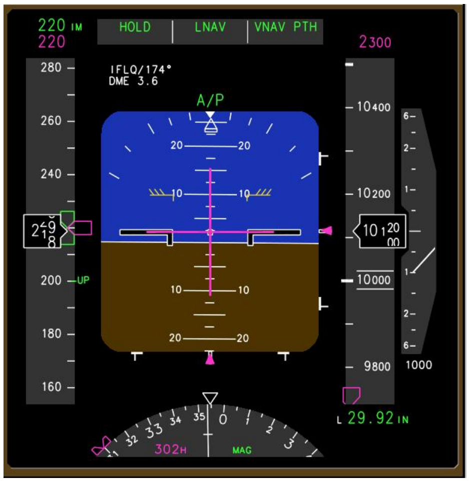


Figure 2. TMA-TM schedule timeline with ETAs on the left (in green), and STAs on the right (frozen STAs in blue; not-yet-frozen STAs in yellow).

Once aircraft are scheduled, en-route controllers can correct schedule errors with lateral maneuvers to absorb delay as they are typically more fuel-efficient at these higher altitudes. Controller tools to support en-route flow conditioning are also



under development at NASA and elsewhere, but are beyond the scope of this paper. For FIM aircraft, controllers issue parameters required by ASTAR (e.g., the planned lead aircraft, the runway spacing interval), so that flight crews can enter them well in advance. Once engaged, ASTAR calculates speed targets for the aircraft to achieve and displays them to the crew. Figure 3 shows a Primary Flight Display (PFD) enhanced with the target speed and FIM speed 'bug' on the speed tape;

Figure 3. PFD with green FIM target speed (upper left), magenta crew-entered target speed below it, and matching green and pink speed bugs on the speed 'tape' (left side).

such information may instead be displayed elsewhere. The ASTAR algorithm also provides speed targets to meet a required time-of-arrival (RTA), while an aircraft is not yet within ADS-B range of its assigned lead aircraft.

Upon entry to the terminal-area FIM aircraft are typically following ASTAR speed commands, while controllers are responsible for issuing speeds to the CMS aircraft. 'Feeder' controllers use the CMS tools, which include schedule timelines, early/late indicators, slot markers, and speed advisories, to monitor and adjust the schedule conformance of arriving aircraft. 'Final' controllers primarily use spacing cones (a pre-existing tool available on some terminal-area controller displays) to space aircraft on final approach. FIM status designators in a FIM aircraft's data block (an '®' for RTA mode or 'S' for paired-spacing mode) have also been introduced as reminders controllers can enter to keep track of FIM operations. Figure 4 illustrates how these tools appear on a controller's Multi-Aircraft Control System (MACS) display in the AOL. Kupfer et al. (2011) describe the core CMS tools in detail; generally they range from simple representations of arrival-schedule information (timeline, early/late indicators), to nominal-trajectory-based translations of schedule information as spatial targets (slot markers), to speed advisories computed using trajectory predictions to place aircraft back on schedule.

3 CA-1 SIMULATION

CA-1 constituted the initial integration step for ATD-1 in which IM-TAPSS components were integrated in the AOL. It served the critical purpose of enabling researchers to begin to assess how the components function together operationally. To provide a preliminary perspective on the CMS tools and key aspects of air traffic

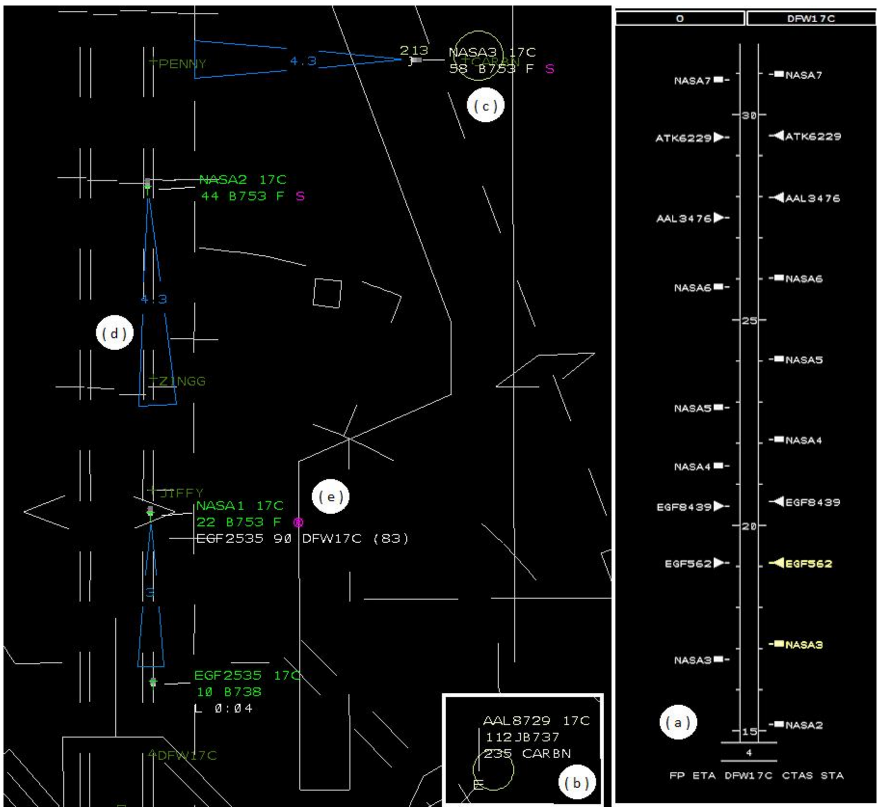


Figure 4. Terminal-area controller tools: (a) timeline, (b) data block with slot marker and speed advisory, (c) data block with slot marker, early/late indicator, and paired-spacing mode designator, (d) spacing cone, (e) RTA-mode designator.

controller procedures and clearance phraseology for managing mixed-FIM-equipage arrival flows, CA-1 was conducted as a fully staffed weeklong simulation in Dallas/Fort Worth (DFW) airspace (Figure 5). Aircraft flew charted OPDs on merging RNAV routes to DFW Runway 17C that were based closely on routes used in prior ASTAR research at NASA Langley.

Nine retired air traffic controllers took part in the simulation. Terminal-area controllers, all of whom had previously participated in CMS research, staffed three Feeder sectors (numbered 258, 259, and 264 in Figure 5) and one Final position (269). Three controllers staffed en-route sectors (24, 25 and 75) and the remaining two served as en-route 'Ghost' and Tower confederates. A mix of general aviation students and pilots flew eight Langley-developed, FIM-equipped Aircraft Simulator for Traffic Operations Research (ASTOR) single-piloted simulators and staffed eight MACS pseudo-aircraft stations used to control CMS aircraft.

The first day of CA-1 included an initial briefing, followed by four one-hour training sessions. Over the next four days, eighteen one-hour experimental trials

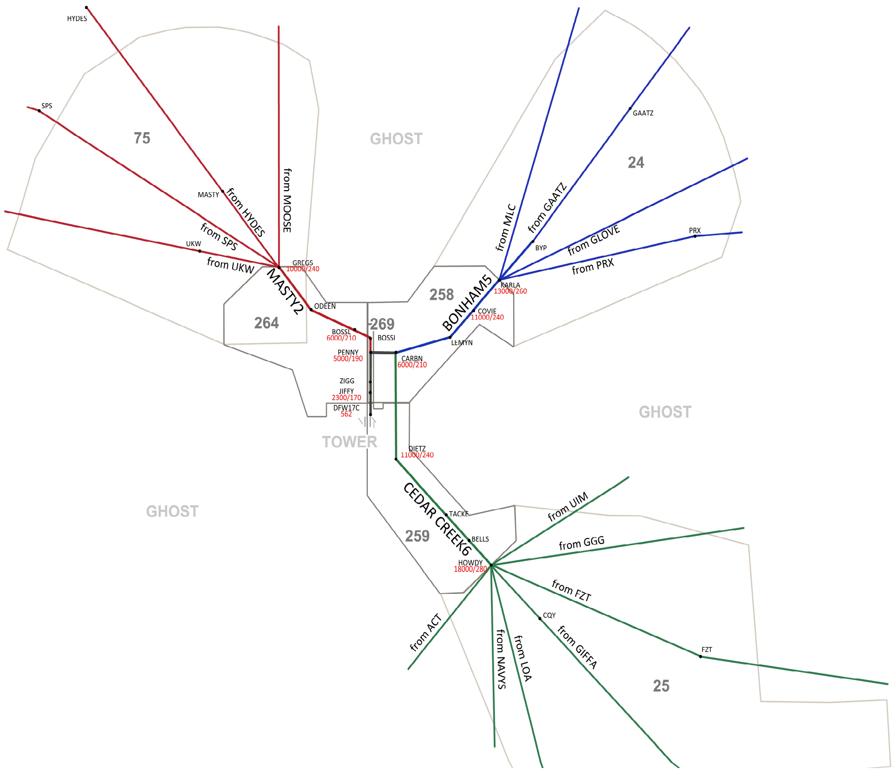


Figure 5. Simulated DFW airspace, with charted RNAV OPDs merging to runway 17C.

were conducted in which three traffic scenarios were presented twice (with different aircraft call signs) under each of three conditions: a ‘Full ATD’ condition with all the controller tools available, an ‘ATD Lite’ condition in which terminal controllers did not have timelines or speed advisories, and a baseline condition with no terminal-area controller tools and ASTORs participating but not conducting FIM operations. Digital data, including flight state information, pilot and controller entries, and schedule information, were logged from all MACS and ASTOR stations, as well as from TMA-TM. Controllers completed questionnaires after each experimental trial, as well as a comprehensive post-simulation questionnaire prior to the final debriefing session.

Controllers were asked to maintain charted OPD operations to the extent possible by primarily issuing speeds to separate and space aircraft. In the ‘ATD’ conditions, operations began with en-route controllers issuing FIM clearances to FIM aircraft while controlling CMS aircraft toward their terminal-area-entry-fix STAs. Outstanding integration issues limited the FIM aircraft to spacing only behind other FIM aircraft; in the traffic scenarios, FIM aircraft were interspersed in various sized clusters with the CMS aircraft. To enable close examination of the behavior of the FIM algorithm in an operational setting, controllers were also requested to allow FIM operations to proceed unimpeded, even when it appeared they should intervene to ensure proper spacing. While these instructions run counter to the IM-TAPSS concept of operations in which controllers are responsible for issuing clearances to FIM aircraft as necessary to ensure separation, they were deemed necessary for supporting the integration objectives of CA-1. The following section presents results from the CA-1 study.

4 RESULTS

A key hypothesis is that CA-1 would affirm performance trends and controller human factors results observed in previous CMS research for IM-TAPSS operations with mixed-FIM-equipage arrival flows. Subjective data from controller questionnaires, researcher observations, and the closing debriefing session show similarities in workload levels and tool preferences, as well as a general acceptance of operational procedures and clearance phraseology.

Post-trial workload ratings fell in a nominal mid-scale range; controllers most often rated workload as 'Manageable' and never rated it as 'Too high.' Real-time Workload Assessment Keypad (WAK) ratings logged every three minutes were generally low throughout CA-1 (M=1.56, SD=0.74; 1:'Very low', 7:'Very high'). FIM operations on average did not increase task complexity (M=4.05, SD=1.01; 1:'Substantially increased complexity', 7:'Made other tasks less complex'), according to combined post-trial responses for both 'ATD' conditions. Issuing and following up on FIM clearances also minimally impacted other controller tasks (M=1.75, SD=1.25; 1:'No interference at all', 7:'Interfered with all other tasks'), and had limited impact on the controllers' confidence in being able to achieve the required inter-arrival spacing at the runway threshold (baseline: M=6.29, SD=0.69; ATD conditions: M=5.96, SD=0.75; 1:'No confidence', 7:'Highest confidence'), according to post-trial questionnaire responses.

CA-1 afforded an opportunity to examine the clearance phraseology required to conduct FIM operations in a voice communications environment. En-route controllers, in particular, issued lengthy initial FIM clearances that included the lead aircraft, required spacing interval, achieve-by point, and RTA (e.g., "NASA5, for interval spacing, scheduled time at runway one seven center is one four, three two, plus fifteen Zulu; cross runway one seven center, four point three nautical miles behind NASA4 on the CEDAR CREEK arrival."). When asked to comment, post-simulation, on 'which clearances were smooth and which clearances were not smooth,' all controllers indicated they had few, if any, issues with the FIM clearances. In the post-simulation debriefing, controllers agreed that splitting the initial clearance into an RTA clearance and an interval-spacing clearance could be beneficial, and that issuing the RTA in two-digit 'chunks' helped read-back accuracy. Controllers also noted that an initial request to "advise when ready to copy" reduced the risk of read-back errors. Post-trial questionnaire reports show that controllers had to repeat FIM clearances 15% of the time; however, on average they found this rate to be 'Very acceptable' (M=5.96, SD=1.65; 1:'Completely unacceptable', 7:'Completely acceptable').

Communications involved with querying FIM pilots about the status of the FIM operations were also investigated. Controllers were observed to make such queries to resolve uncertainty about whether a FIM aircraft was conducting RTA or paired-spacing operations, or whether a pilot was successfully following FIM speed commands. In CA-1 controllers were generally amenable to delayed pilot responses to status requests, reporting that “stand by” responses were either ‘always acceptable’ or ‘usually acceptable.’ Confusion sometimes arose concerning the meaning of the term “following” when it was used in status requests, indicating structured phraseology for such requests would be beneficial.

Controllers commented positively about FIM aircraft transitioning from RTA to paired-spacing mode as the assigned lead aircraft entered ADS-B range. The data-block status designators (‘®’ and ‘S’) introduced to support FIM operations in CA-1 were generally well received. Controllers rated ‘adding/removing/updating’ the FIM status indicators favorably in the post-simulation questionnaire (M=5.86, SD=1.68; 1:‘Very unreasonable, not at all workable’, 7: ‘Very reasonable, completely workable’). However, controllers agreed that a toggling scheme, in which the designator would change from ‘®’ to ‘S’ to blank using a single repeatable command, would improve ease of use.

Other tools received ratings in line with prior research. Feeder controllers preferred the slot markers and used them most often to condition CMS aircraft for merging; the Final controller found the spacing cones most effective for managing spacing on final approach. Figure 6 depicts average Feeder controller ratings for various tools in the ATD conditions in which they were available. On the whole, helpfulness and usability ratings are similar for each tool. They were ambivalent about the spacing cones (used primarily by the Final controller) and the speed advisories (which require further research to be properly integrated with the TMA-TM scheduling scheme). While the helpfulness ratings of slot markers and early/late indicators for managing CMS or FIM aircraft are similar, usability ratings for both

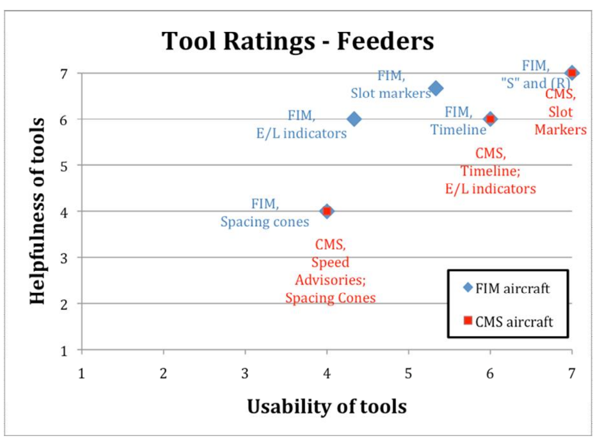


Figure 6. Tool helpfulness vs. usability ratings by the Feeder Controllers

tools are notably higher for CMS aircraft. This is likely due in part to allowing the

FIM aircraft to descend unimpeded to support CA-1 integration objectives, so that both the early/late indicators and slot markers often reflected large schedule errors for FIM aircraft. The similar helpfulness ratings suggest controllers would welcome the ability to use these tools to manage FIM aircraft; responses to strategy-related questions in which controllers expressed a desire to have both CMS and FIM aircraft in their slot markers confirm this sentiment.

In the post-trial questionnaires, terminal-area controllers responded that they 'would not have done anything differently with regard to the FIM aircraft' 93% of the time. They also responded that they did not have to change how they worked to accommodate the FIM aircraft 80% of the time. Responses that indicated a need to work differently were generally accompanied by comments about discomfort with FIM aircraft well ahead of or behind their slot markers. Researcher observations suggest that controllers were not entirely sure about the performance of the FIM ASTAR algorithm relative to the TMA-TM arrival schedule reflected in the slot-marker locations. Controllers reported the presence of 'problematic' aircraft in 24% of post-trial questionnaires; the majority of these were FIM aircraft arriving early.

5 DISCUSSION

The CA-1 simulation was the first in a series of integration studies, and allowed an initial investigation of the performance of the IM-TAPSS components working in concert. Removing the limitations imposed to support integration objectives will improve operations and enable further analysis of the IM-TAPSS concept. First, while enabling FIM operations to proceed unimpeded provided useful insights about the operational behavior of the ASTAR algorithm—as well as increased opportunity for pilots to gain experience using it—it was inconsistent with controller separation responsibilities and control strategies. In succeeding simulations controllers will actively manage FIM traffic as necessary, which should improve spacing performance and controller acceptability. Second, en-route controllers did not actively condition the FIM aircraft in CA-1. Applying en-route control to mitigate schedule errors before clearing FIM aircraft to activate ASTAR is expected to allow the FIM aircraft to fly near-nominal speed profiles, and arrive in the terminal-area with small schedule errors. This would have several desirable effects, including enabling ASTAR to command near-nominal speeds, increasing the usability of the slot markers, and reducing the controllers' perceived need to intervene. Third, because the slot markers currently reflect the schedule and nominal speed profile, they do not provide feedback to the controllers on how well FIM aircraft are progressing toward the advised spacing. Further research will address the enhancement of slot markers for FIM aircraft in order to provide such feedback; this is likely to increase slot-marker usefulness and usability, and therefore controller acceptability. Lastly, the simulation software used for CA-1 limited FIM operations to consecutive FIM aircraft, so that FIM aircraft behind CMS aircraft in the arrival sequence had only the RTA mode available. This resulted in controllers having to continuously monitor their spacing. Work is underway to remove this limitation, which should further reduce controller workload and merge-point conflicts, and improve the traffic flow to the Final controllers.

The CA-1 study showed controllers are receptive to the IM-TAPSS mixed-FIM-equipage arrival operations planned for ATD-1. Controllers found the workload acceptable, rated support tools positively, and generally agreed with the proposed FIM clearance phraseology. Research to address the above issues is in progress, and is expected to enable detailed analyses of key performance metrics (e.g., inter-arrival spacing accuracy, throughput), as well as refinements to IM-TAPSS that are necessary to support validation and prototype-development work for the ATD-1 demonstration.

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