HUMAN CENTERED DECISION SUPPORT TOOLS FOR ARRIVAL MERGING AND SPACING

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A simulation of terminal area merging and spacing with air traffic controllers and commercial flight crews was conducted. The goal of the study was to assess the feasibility and benefits of ground and flight-deck based tools to support arrival merging and spacing operations. During the simulation, flight crews arrived over the northwest and southwest arrival meter fixes and were cleared for the flight management system arrivals to runways 18 and 13 right. The controller could then clear the aircraft to merge behind and space with an aircraft on a converging stream or to space behind an aircraft on the same stream of traffic. The controller remained responsible for aircraft separation. Empirical research was performed to assess air and ground tools and the effects of mixed equipage. During the all tools conditions, 75% of the arrivals were equipped for merging and spacing. All aircraft were ADS-B equipped and flew charted FMS routes which were coordinated based on wake turbulence separation at the arrival runway. The aircraft spacing data indicate that spacing and merging were improved with either air or ground based merging and spacing tools, but performance was best with airborne tools. Both controllers and pilots exhibited low to moderate workload and both reported benefits from the concept.

Introduction

At the core of the concept of Distributed Air-Ground Traffic Management is the idea that National Airspace System (NAS) participants can be information suppliers and team members who collaborate at all levels of traffic management decision making (Raytheon ATMSDI, 2003). One such concept and the focus of this paper is Concept Element 11 (Terminal Arrival Self-Spacing for Merging and in-Trail Separation).

Sorensen (2000) characterizes the CE 11 approach process as involving one of three operational modes. Each mode possesses potential benefits but also presents significant operational and technical challenges. These modes are: Free Maneuvering, Merging, and Spacing. During *Free Flight Maneuvering*, equipped aircraft can design their own direct path within a defined approach corridor (not under investigation in this study). *Merging* occurs when an equipped aircraft is delegated the responsibility for adjusting in-trail position behind the designated lead aircraft approaching from another stream; finally, the *Spacing* concept is one in which an *equipped aircraft is cleared to maintain a specified temporal position from a designated lead aircraft*.

The objective of CE 11 is to minimize the in-trail spacing buffers between terminal area arriving aircraft flying under instrument meteorological conditions (IMC). CE 11 utilizes time-based, in-trail spacing to take advantage of the natural spacing compression of arriving aircraft as they decelerate in preparation for landing (Abbott, 2002). To support the transition of responsibility for maintaining the desired spacing interval, from the controller to the flight crew, advanced ATM technologies (decision support tools – DST) were developed for both controller and flight crews (Granada, Dao, Wong, Johnson, Battiste, 2005).

In a previous study of merging and spacing, NASA ARC researchers employed a human-in-the-loop simulation with pilots and controllers, and tested time-based merging and spacing. Results of this study highlighted the need for clear delegation of responsibilities and unambiguous procedures under a variety of operational scenarios. Specifically, controllers were unclear about pilots' separation responsibilities. This ambiguity was particularly apparent when aircraft were spacing less than the assigned interval but still further than the legal separation requirement. Results of a follow-up study at NASA ARC reflected the progress made through the development of tools and procedures. When given the choice of issuing a spacing clearance to equipped aircraft, the TRACON controllers opted to provide the clearance about 85 percent of the time. This finding suggests that controllers were comfortable with the tools and procedures, and confident with the ability of pilots to accurately self-space (Lee, et al., 2003).

During an operational evaluation of in-flight spacing and merging, display integration was identified by flight crews as an issue when spacing information was presented on the NAV Display (ND). The FAA

Safe Flight 21 operational evaluation data collected from flight crews identified display integration, clutter, and heads-down time as important display integration issues (Cieplak, Hahn, and Olmos, 1999).

The Flight Deck Display Research Group at NASA Ames has designed a suite of tools which should enable operators to safely and efficiently perform the necessary merging and spacing tasks essential to the success of the concept. In this report, we focus mainly on the evaluation of the flight deck DST. However, some discussion of the controller tools and tasks are necessary to set the context in which the flight deck tools were evaluated. The cockpit situation display (CSD), which is presented on the ND, includes a 3-D cockpit display of traffic information (CDTI), and the merging and spacing tools (FDDRL, 2004). The CSD integrates information derived from the spacing algorithms with traffic position, aircraft identification and intent to present a display of the current and predicted traffic situation (see Figure 1). Armed with this information and tools, flight crews were allowed to perform airborne merging and spacing operations when cleared to do so by the controller. This paper also examines the feasibility of the merging and self-spacing concepts from the flight deck perspective under mixed traffic conditions, where only some of the aircraft were equipped for self-spacing and merging. See Callantine, Lee, Mercer, Prevot and Palmer (ATM-2005) for CE-11 ground side results.

Figure 1: 3-D Cockpit Situation Display

Methods

Pilot Participants

Nine air transport and/or commercial rated pilots and four certified professional controllers participated in the study. Pilots had an average of 10,405 flight hours and 3,912 hours in glass cockpits. All flight crew members were familiar with the advanced 3-D CDTI display system and received 2 days of training on the merging and spacing task and procedures. Four full performance level controllers with TRACON experience manned the feeder and final control positions in dual TRACON operations.

Experimental Conditions

Four experimental conditions were created to examine pilot and controller performance: No Tools, Ground Tools only, Air Tools only, and Air & Ground Tools. Data was collected from thirty two trials, with eight trials per condition. To assess the operational feasibility of the concept from the flight deck perspective, the following items were assessed: assigned vs. achieved inter-arrival spacing, usability/usefulness, flight crew workload, and safety. Additionally, pilots were asked to provide comments on the issue of call sign confusion when multiple aircraft IDs (call signs) are used in a single transmission. Post run and simulation questionnaires were used to assess concept feasibility and display usability.

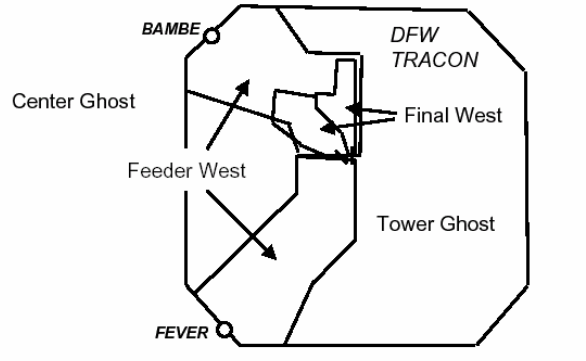


Figure 2: DFW TRACON Airspace.

Airspace and Controller Tasks

Controllers pairs (feeder and final) managed the western portion of the Dallas Fort Worth TRACON airspace. The feeder controller initially cleared the aircraft for either the Fever or Bambe FMS arrival, and if applicable, to follow a lead aircraft to 18R (see Figure 2). The Final controller managed the merge between the two arrival streams, which were procedurally separated by 1,000 feet at the GIBBI intersection.

Controller Display and Tasks

Controllers utilized a wake-vortex aware arrival schedule, which computed estimated times of arrival for runway 18R. In the conditions with ground tools, merging and spacing information was incorporated into each aircraft's data tag. For example, as illustrated in Figure 4,COA 538, a B733, landing 18R, assigned to follow BAW 601 80 seconds in trail and is currently 69 seconds in trail. Additionally, the spacing circle provides relative information about the spacing goal (see Figure 3).

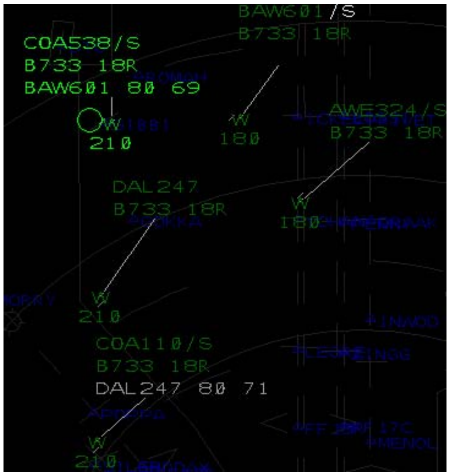
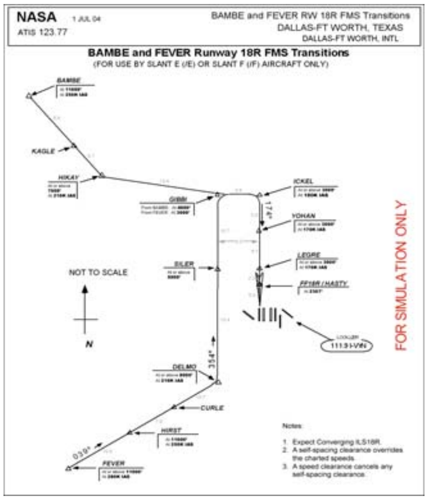


Figure 3: Controller Display with merging and spacing tools.

Roles and Responsibilities

Controllers were responsible for separation at all times. Flight crews could be cleared to merge behind then follow a lead aircraft on a conjoining route or to follow an aircraft on the same route. Controllers could cancel a spacing clearance at any time.



Notes:
1. Expect Converging ILS18R.
2. A self-spacing clearance overrides the charted speeds.
3. A speed clearance cancels any self-spacing clearance.

Figure 4: FMS transitions to runway 18R - Streams merged at GIBBI.

Procedures

Each aircraft started the scenarios 15 to 40 nm from the BAMBE or FEVER meter fixes. Upon entry, pilots were cleared to fly an FMS arrival route (see Figure 4) and were instructed to allow their aircraft to fly and descend along the FMS arrival path, even if Ownship seemed to follow another aircraft too closely – i.e., they did not adjust speed or altitude unless commanded by the air traffic controller (ATC). Pilots checked in with controllers when they received a data link clearance or at 5 nm from the meter fix. Pilots were instructed to expect spacing clearances any time after reaching the meter fix. Controllers issued clearances to merge and follow or follow behind a designated lead aircraft. Controllers utilized normal controller procedures – radar vectors, “direct to”, speed and altitude – to manage the unequipped aircraft. The pilots utilized the airborne spacing tools and procedures to implement the assigned spacing command.

Pilot Clearance and Tasks

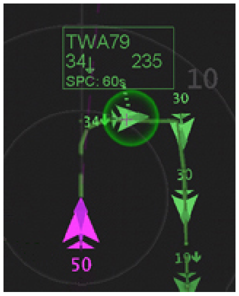
ATC provided clearances such as “Continental 538, merge behind then follow Speedbird 601– 80 seconds in trail,” or “Continental 538, follow Speedbird 601 – 80 seconds in trail.” Pilots read back the clearance and engaged self-spacing; see flight deck procedures below. If the algorithms did not command appropriate speeds based on the spacing setting, pilots were asked to disengage spacing and inform ATC that they were unable to space.

Tools for Merging & Spacing Operations

If a merging and spacing clearance was assigned, the flight crew followed the steps listed below using a mouse to position the curser:

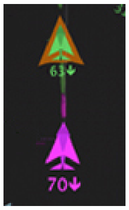
1) Pilots first clicked on the Spacing button on the CSD tool strip.

2) Pilots then selected the assigned lead aircraft by clicking on its symbol within the CSD. In this case, TWA79 was selected.



3) The spacing interval specified by ATC was then entered. To increase the spacing interval, pilots right-clicked on the seconds (**Sec:XX**) button; to decrease the interval pilots left-clicked the seconds button.

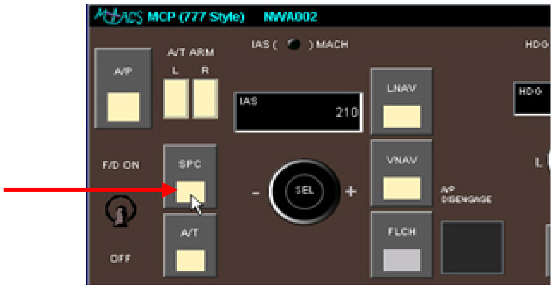
4) Pilots then clicked the start button on the CSD tool strip, which is located next to the “seconds” button in the figure



above. Pilots were informed they would need to wait for the spacing algorithms to initialize. When the spacing algorithm was initialized (i.e., ready to engage spacing) the upper left corner of the CSD displayed a message indicating the spacing status. Also, the lead aircraft became highlighted in orange.

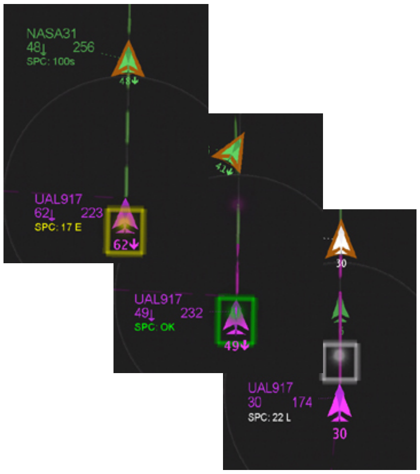

PDA: Armed
CMD: A/T [241]

5) Finally, to engage the auto throttles, pilots selected the SPC button on the MCP. This activated the algorithm to begin commanding the proper speeds (via the auto throttles) to move the aircraft towards the spacing goal.



6) When the spacing is engaged and active, feedback is provided at the upper left corner of the CDTI.


PDA: Active
CMD: A/T [192]



Visual feedback regarding Ownship spacing status was provided via a color-coded "spacing box." The color and location of the spacing box reflected Ownship position relative to the assigned temporal spacing value. That is, if Ownship was given an assigned spacing value of 100 seconds and was more than 10 seconds ahead (e.g., the aircraft is currently at 83 seconds), the spacing box was depicted as yellow and Ownship appeared slightly ahead of the box. When Ownship was less than 10 seconds ahead or less than 20 seconds behind the assigned spacing value, the spacing box was depicted as green, and Ownship appeared inside the box. Finally, if Ownship was more than 20 seconds behind the assigned spacing value, the spacing box was depicted as white and Ownship appeared behind the box.

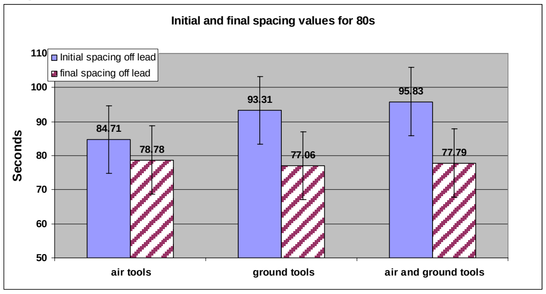
Simulation environment

The simulation study was conducted utilizing three fully integrated NASA ARC research laboratories/facilities: the Airspace Operations Laboratory (AOL), Flight Deck Display Research Laboratory (FDDRL), and Crew Vehicle Systems Research Facility (CVSRF). See DAG-TM, 2003 for a full description of each laboratory.

Results

This section presents the results of the Merging and Spacing operation at the 80 and 100 second intervals. Additionally, data on the efficiency of the merging and spacing operation, flight crew workload, safety and acceptability are described. Participating flight crews conducted 256 total approaches, 32 in each condition.

During the No Tools condition flight crews followed ATC guidance as they would today, thus no relative spacing and merging data are reported. Of the remaining 128 runs in the air tools and air and ground tools conditions controllers assigned spacing to the flight deck 116 times.



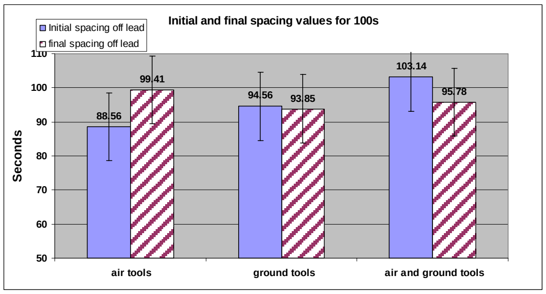


Figure 6 and 7: Initial and final spacing intervals for 80 and 100 seconds (mean and standard deviation).

Figures 6 and 7 show the spacing intervals data from the start of spacing and merging and/or spacing until spacing was discontinued at or near the final approach fix or by the controller. These graphs illustrate that, overall spacing performance was improved for All Tools condition and that performance was best in the Air Tools only condition (mean 78.8 and 99.4, respectively), followed by Air and Ground Tools (77.8 and 95.8), and finally Ground Tools (77.6 and 93.8). However, these trends were not significant (p >.05). Additionally, the expected improvement in spacing performance with air and ground tool was not found. However, controllers preferred to conduct spacing operations with only ground tools. They suggested that conducting merging and spacing operations when flight crews were managing spacing added additional variability and made it difficult to manage unequipped aircraft.

Spacing efficiency

From the flight deck perspective, a measure of efficiency was related to when aspacing and merging clearance was issued by the controller. If the clearance was issued early in the approach, the flight crews had more time to set up the systems and manage progress toward the spacing goal. If the clearance was issued late (i.e., near the base to final leg of flight), then this task may interfere with other tasks that require completion before landing. A t-test was conducted to examine this notion. The pilots' data was split into three groups; early, middle, or late approach clearances. A one-sample t-test was used to compare the three groups relative to the 80-second spacing goal. Results indicated that the early or mid approach groups did not significantly differ from the 80-second spacing goal ($p > .05$). However, when the spacing clearance was issued late, the spacing performance did significantly vary from the 80-second spacing goal, $t(22) = -3.33$, $p < .01$, indicating a decline in spacing performance (see Figure 8).

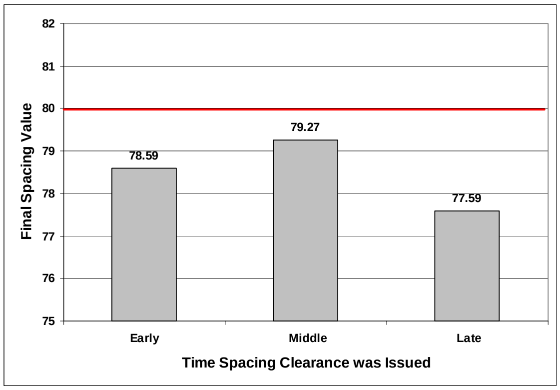


Figure 8: Spacing performance with early, mid and late spacing clearance.

	Air	**Ground**	**Air/Ground**	**None**
	M SD	*M* SD	*M* SD	*M* SD
Peak Workload	2.56 .69	2.25 .67	2.40 .72	2.23 .61
Overall Workload	2.34 .65	2.22 .67	2.28 .69	2.21 .63
ATC Communication	2.51 .75	2.52 .61	2.31 .58	2.53 .74

Table 1: Crew workload and communication by conditions.

Workload, Communication and Usability

After each approach, pilots entered a workload rating reflective of their perceived workload for the run using a modified NASA Task Load Index (TLX). There were a total of 32 trials in which the pilots provided workload data. The TLX rating scales were modified to include a peak workload assessment and an estimated communications workload relative to normal operations. Additionally, each rating was based on a Likert scale format that had "Normal Ops" as the median rating of 3 on a scale of 1 to 5, with a rating of 5 for "High" workload. This method was not used to suggest that "Normal Ops' represents a medium level of workload, but it provided a familiar baseline for the participants. For this report only the peak, overall, and ATC communication workload values are presented.

The mean Peak Workload value was 2.45, SD = .72, the mean Overall Workload was 2.25, SD = .66, while the mean ATC Communication Workload was 2.39, SD = .57. Across all conditions flight crews' ratings were relatively similar. The mean workload ratings were subsequently examined for each of the four conditions (Air tools, Ground tools, Air and Ground tools, and No Tools) separately. Table 1 includes the mean workload values for Peak Workload, Overall Workload, and ATC Communication Workload by each of the four conditions. As the table shows, flight crews rated the workload of the merging and spacing task below that of normal operations for all conditions (where normal operations was represented by a value of 3). The table also shows that crews rated communication workload lowest in the air/ground tools condition, suggesting that when both pilots and controllers have supporting tools, communication may be reduced.

ATC Clearances

An issue, which has stimulated considerable discussion over the past few years, has been the potential call sign confusion that may result in a DAG-TM environment. Specifically, the DAG-TM environment requires the use of two aircraft call signs in a single voice transmission. The concern has been that pilots may become confused by the use of two call signs and, at a minimum, may need to ask ATC to repeat the clearance. In a worst case scenario, the potential confusion could result in a pilot accepting a clearance that was meant for another aircraft. Of course, this worst-case scenario could lead to an accident or incident. An important finding in the present study was that, of 323 spacing and merging clearances, neither pilots nor controllers reported a single instance of "call sign confusion." Flight crews reported that with the inclusion of flight ID and the pulse predictor (c.f., Granada et.al., 2005) on their CDTI, they were able to identify their prospective lead aircraft and to anticipate the ATC clearance.

Acceptable		
	Merging and spacing task	4.8
	Head-down time	4.0
	Display symbols	3.4
	Symbol Color	4.3
Useful		
	Information in aircraft data tag	4.0
	Accept spacing clearance based on CDTI data only	4.8
	Accept visual approach clearance based on CDTI only data	3.7
Safety		
	CDTI improves flight safety	4.3
	Enhances safety of merging and spacing	3.8

Table 2: User Feedback on display, tools and concept (N=10; 1 = not acceptable, useful and safe, 5 = very acceptable, useful and safe scale).

As Table 2 shows, flight crews found the tools, display features and the concept acceptable, useful and safe. Also, these ratings suggest that the flight crews may be willing to take on additionally responsibility.

Discussion and conclusions

Based on flight crew and controller performance, comments and also their interactions with the tools and procedures, the concept of merging and self-spacing during arrival and approach seems feasible. Pilots consistently rated the flight deck tools favorably in terms of usability, usefulness, and rated the CSD favorably in terms of situation awareness. Generally, pilot and controller workload ratings were moderately low during spacing and merging operations. Workload differences between tools conditions were relatively small for pilots, and when spacing clearances were issued early or at the mid point of the approach, pilots had little difficulty achieving the spacing goal. In this study, pilots and controllers generally disagreed as to the best time for the spacing clearances to be issued; however, the controllers were only beginning to develop strategies for how to best utilize this new tool. Finally, this study did identify a number of issues from the flight crews' and controllers' perspectives that need to be addressed in future research.

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