AIR AND GROUND SIMULATION OF TERMINAL-AREA FMS ARRIVALS WITH AIRBORNE SPACING AND MERGING

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Abstract

A combined air and ground simulation of terminal-area arrival operations was conducted at NASA Ames Research Center to evaluate Distributed Air Ground Traffic Management (DAG-TM) project Concept Element 11 (CE 11): Terminal Arrival: Self-Spacing for Merging and In-trail Separation. The simulation was the final DAG-TM study conducted at NASA Ames with funding from the NASA Airspace Systems Program Advanced Air Transportation Technologies (AATT) project.

The study evaluated the feasibility and potential benefits of using pilot and controller decision support tools (DSTs) to support time-based airborne spacing and merging in terminal radar approach control (TRACON) airspace. Sixteen simulation trials were conducted in each treatment combination of a 2x2 repeated measures design. In trials 'with ground tools,' air traffic controller participants managed traffic using sequencing and spacing DSTs. In trials 'with air tools' seventy-five percent of aircraft assigned to the primary landing runway were equipped for airborne spacing and merging, including flight simulators equipped with an enhanced cockpit display of traffic information (CDTI) flown by commercial pilots. In all trials controllers were responsible for separation and issued clearances by voice. All aircraft were equipped with Flight Management Systems (FMSs) and ADS-B and entered TRACON airspace on charted FMS routes. Routes to the primary landing runway merged. Each scenario began with a traffic flow that was well coordinated for merging and spacing and ended with an uncoordinated flow.

This paper presents the simulation and results of from an air traffic management (ATM) perspective. The results indicate that airborne spacing improves spacing accuracy and is feasible for FMS operations and mixed spacing equipage. Airborne spacing capabilities and the degree of flow coordination affect clearance selection. Controllers and pilots can manage spacing clearances that contain two callsigns without difficulty. For best effect, both DSTs and spacing guidance should exhibit consistently predictable performance.

Introduction

DAG-TM research conducted at NASA Langley, Glenn, and Ames Research Centers investigates ATM concepts beyond the year 2015 with the aim of increasing flexibility, efficiency, and capacity while maintaining safety. DAG-TM concepts redistribute decision-making responsibilities among flight crews, dispatchers, and air traffic service providers through the use of new DSTs and procedures. DAG-TM research has progressively refined DSTs, procedures, and the simulation infrastructure over the course of several simulations. This paper describes the final DAG-TM simulation conducted in the Airspace Operations Laboratory (AOL) and the Flight Deck Display Research Laboratory (FDDRL) at NASA Ames Research Center: the NASA Ames CE 11 simulation to evaluate the feasibility and benefits of time-based airborne spacing and merging in TRACON airspace.

Previous DAG-TM simulations in the AOL [1-3] have evaluated concepts for en route trajectory negotiation using advanced data link functionality and controller DSTs and delegation of en route separation responsibility to flight crews of suitably equipped aircraft. The results of these studies suggest that trajectory-based arrival metering with well-integrated controller DSTs could improve meter fix arrival accuracy and produce more efficient, predictable, and evenly spaced flows into the TRACON.

The NASA Ames CE 11 simulation used the same simulation infrastructure [4] as the previous studies. TRACON FMS routes linked to the en route

FMS arrivals. Traffic scenarios specifically included coordinated flows of aircraft arriving into the TRACON as if they had been metered using DAG-TM en route concepts. TRACON controllers were envisioned to use DSTs to adjust traffic flows so that aircraft are 'close' to their scheduled time-of-arrival (STA) at their assigned runway, then issue spacing or merging clearances to 'lock in' the sequence and required temporal spacing. TRACON controllers maintained responsibility for safe separation, and issued all clearances by voice.

The NASA Ames CE 11 simulation relates to other research on airborne spacing, as well as TRACON FMS operations. This paper begins by providing background on related research. It then describes the Ames CE 11 simulation study and discusses the results. The paper concludes with recommendations for implementing TRACON airborne spacing operations and DSTs. The paper takes an ATM-centric perspective throughout; while it necessarily mentions some pilot-related issues, CDTI-based spacing DSTs and pilot tasks are outside its scope.

Background

Airborne spacing (ASAS 2) [5] capabilities have interested researchers for more than two decades. Capacity limitations and the advent of enabling technologies such as ADS-B have reinvigorated airborne spacing research [6]. Both European and U.S. researchers have conducted studies on the design of spacing guidance laws and the integration of spacing information on CDTIs for commercial jet aircraft.

Research on one spacing algorithm developed for integration in a flight deck tool is reported in [7]. The algorithm has been analyzed [8] and flight-tested [9]. With the addition of ADS-B information about arrival routes, final approach speed, and wake vortex class, the algorithm is extensible to merge situations. ADS-B enhancements to the algorithm are under investigation at NASA Langley Research Center [7].

EUROCONTROL spacing research has also analyzed the performance of spacing guidance laws [10]. Simulation studies have demonstrated the effectiveness of airborne spacing operations from both flight deck and controller perspectives. Delegating spacing tasks to the flight deck can improve spacing accuracy [11] and increase controller availability by enabling them to set up traffic flows earlier [12, 13]. The research in [13] is particularly relevant for its controller-centric view of spacing operations. It differs, however, in several key respects. Terminal-area routes were carefully designed to support spacing operations. In the spacing condition all aircraft entered the terminal-area under airborne spacing, while in the non-spacing condition aircraft were sequenced 8 nm in trail. Teams of two controllers (planning and executive) controlled each of two experimental sectors using current methods (i.e., paper progress strips, no sequencing DSTs).

Other areas of related research concern low-noise 'continuous descent approaches' and 'tailored arrivals.' Airborne spacing and controller DSTs hold promise as a means for controlling aircraft flying precise FMS trajectories in TRACON airspace [14].

DAG-TM CE 11 Simulation

The goal of the August 2004 NASA Ames DAG-TM CE 11 simulation was to evaluate the operational viability and potential benefits of time-based airborne spacing and merging in the TRACON. It sought to demonstrate that airborne spacing is compatible with voice clearances, FMS operations, and mixed spacing equipage. It also sought to assess the impact of en route flow conditioning and evaluate the acceptability of ground-based DSTs to support airborne spacing operations, with controllers maintaining responsibility for separation. In addition to workload reduction, potential benefits include increased throughput, decreased excess separation, and reduced losses of wake vortex separation. The simulation was a large-scale, distributed air and ground simulation that provided a rich operational environment. A 2x2 repeated-measures design yielded four experimental conditions:

- 'Air Tools'—seventy-five percent of aircraft assigned to the primary landing runway were equipped for airborne spacing (both CDTI-equipped piloted simulators and pseudo-aircraft) and controllers could issue spacing commands
- 'Air and Ground Tools'—controllers also had DSTs available to aid in issuing airborne spacing clearances and monitoring conformance
- 'Ground Tools'—controllers had DSTs available, but no aircraft were equipped for airborne spacing
- 'No Tools'—basic FMS TRACON operations;

This section presents the details of the Ames CE 11 study.

Airspace

Figure 1 depicts the simulation airspace, comprised of the western portion of Dallas-Fort Worth (DFW) TRACON configured for south-flow operations to runways 18R (the primary landing runway) and 13R. One controller staffed the 'Feeder West' position, receiving traffic arriving on FMS arrivals across the northwest (BAMBE) and southwest (FEVER) meter fixes from an en route confederate controller ('Center Ghost'). A second controller staffed the 'Final West' position and was responsible for aircraft on approach to both 18R and 13R. The Final West controller handed aircraft off to a confederate tower controller ('Tower Ghost').

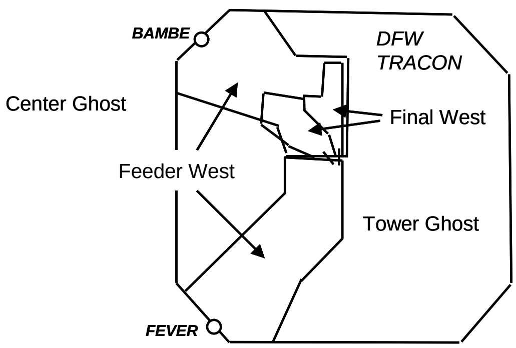

Figure 1. Simulation airspace.

FMS Procedures

All aircraft arrived in the DFW TRACON on FMS arrivals. Feeder West cleared aircraft to continue their descent on an FMS approach transition. Aircraft arriving across BAMBE flew either the HIKAY FMS transition to 18R or the HIKAY FMS transition to 13R depending on their assigned runway. FEVER aircraft flew the DELMO FMS transition to 18R. The routes conform to current-day traffic flow patterns and merge at the initial base-leg waypoint GIBBI. Altitude restrictions ensure separation from departures; different altitude restrictions also ensure northwest and southwest arrivals are altitude-separated at GIBBI. Otherwise the routes have no special provisions to support merging and spacing (cf. [12]). Figure 2 shows the chart for the two FMS transitions to runway 18R.

Participants

Four professional TRACON controllers with between 15 and 20 years experience participated in the study. Two were very familiar with DAG-TM concepts and simulations conducted in the NASA Ames Airspace Operations Laboratory (AOL); the other two were novices. Pilot participants were nine commercial pilots, all of whom had previously experienced DAG-TM simulations. Two retired controllers staffed the Ghost controller positions, and six general aviation pilots served as pseudo-aircraft pilots.

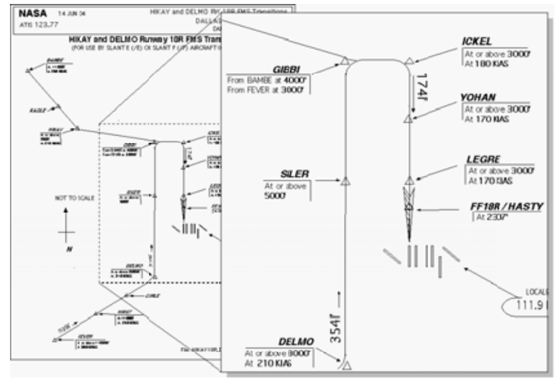

Figure 2. Charted FMS routes to runway 18R.

Controller DSTs

Controllers used the Multi Aircraft Control System (MACS) [4] STARS display emulation hosted on realistic 2048x2048 large-format displays in the AOL. Controllers configured the basic STARS display according to their individual preferences (e.g. brightness, map range, range ring center, etc.). In all simulation trials, the STARS emulation (Figure 3) enabled controllers to display aircraft FMS routes. Indicated airspeed was also displayed just beneath the aircraft target symbol. These enhancements were a consequence of having fully FMS- and ADS-B-equipped traffic.

In trials 'with ground tools,' controllers had other DSTs available to support spacing operations. A reference point at the runway threshold and a matrix of temporal spacing intervals is first specified using the MACS spacing setup panel. A runway scheduler uses this information to compute estimated times-of-arrival (ETAs) for all aircraft at the runway threshold based on flying the charted routes through the forecast wind field. The scheduler also computes a landing sequence and STAs at the runway. The schedule is first-come-first-served based on the ETAs, with the additional provision that an aircraft cannot be scheduled to arrive before its ETA. The schedule does not include any 'extra' spacing buffers, regardless of whether aircraft are equipped for spacing. Controllers view the schedule on a timeline display (Figure 3) with ETAs on the left side and STAs on the right. The timeline tool also enables controllers to perform slot reassignments and swaps.

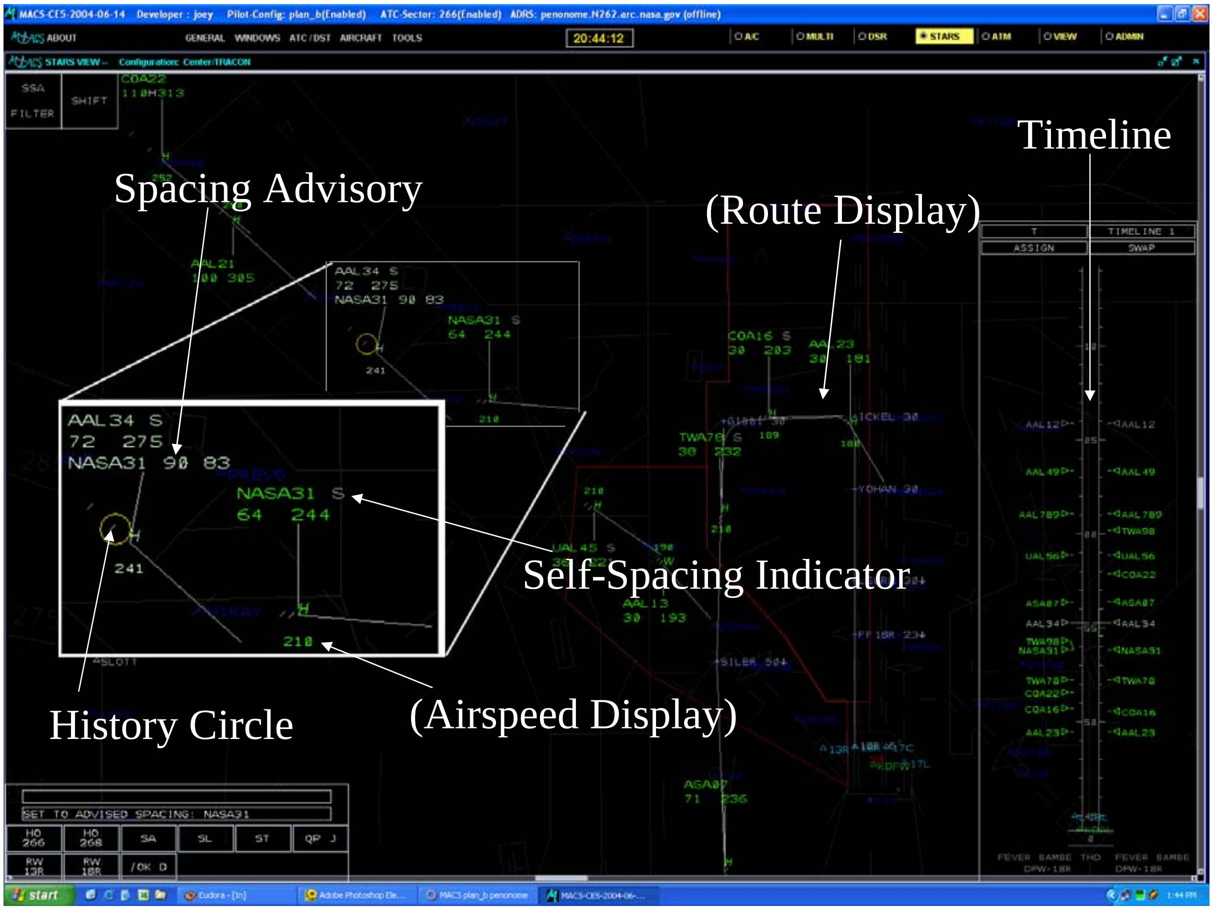

Figure 3. Enhanced MACS STARS display.

Spacing advisory DSTs use the schedule to advise a lead aircraft and spacing interval. The advised spacing interval is based on that specified for the lead aircraft's weight class. When an aircraft is within 30 seconds of the advised spacing interval, its datablock automatically expands to display a spacing advisory in the third line. For AAL34 in Figure 3, the advised lead aircraft is NASA31, the advised spacing interval is 90 seconds, and the actual current spacing is 83 seconds. A controller may change the advised lead aircraft and the advised spacing interval using the shortcut panel visible in the lower right corner of the display in Figure 3. The shortcut panel also enables controllers to perform other tasks, such as handoffs and determining the distance between aircraft.

A spacing indicator is included next to an aircraft's callsign. A green 'S' tells the controller that an aircraft is equipped for airborne spacing. If the controller issues a spacing clearance to an aircraft, she can make an entry using the shortcut panel that changes the color of the 'S' to white as a reminder that the aircraft should now be spacing (Figure 3). Dwelling on a spacing aircraft displays a 'history circle.' The circle indicates where the lead aircraft was *X* seconds ago, where *X* is the advised spacing interval. An aircraft following its lead in-trail at the correct spacing interval appears inside the history circle. The radius of the history circle indicates the distance the lead aircraft would travel in 10 seconds. In Figure 3, AAL34 appears ahead of the circle that shows where NASA31 was 90 seconds ago.

Traffic Scenarios

The Ames CE 11 traffic scenarios represent traffic consistent with DFW traffic mixes, with mostly 'large' and some 'B757'-class aircraft. The spacing matrix was configured such that aircraft should be spaced 80 seconds behind large aircraft and 100 seconds behind B757s. These values ensure 3 and 4 nm at the final approach fix, respectively, even if aircraft are spaced slightly closer (i.e. five seconds or less) than the assigned temporal interval. Twenty-one aircraft split between two flows across the BAMBE and FEVER meter fixes were assigned to runway 18R. Additional BAMBE arrivals assigned to runway 13R arrived in slots that became available to FEVER 18R aircraft when the 13R aircraft diverged from the primary BAMBE 18R flow (around waypoint HIKAY).

The traffic scenarios were partitioned into ‘coordinated’ and ‘uncoordinated’ flows. The first twelve aircraft arrived at the meter fixes within fifteen seconds of their meter fix STAs, as if they had been delivered using en route DAG-TM concepts. The meter fix STAs for these aircraft reflected the runway 18R arrival sequence. The next nine aircraft represented the uncoordinated flow intended to test the CE 11 concept in a situation where the merging traffic sequences were not well synchronized and instead arrived as if a miles-in-trail criterion was applied. In conditions ‘with air tools,’ seventy-five percent of all piloted simulators and pseudo-aircraft assigned to runway 18R were equipped for airborne spacing.

Controller Strategy

One strategy that emerged as attractive during CE 11 simulation development is described as follows. Controllers would first use the timeline to assess how closely aircraft would meet their assigned STA at the runway. Speed clearances could be used in conjunction with the charted FMS routes to adjust aircraft toward their assigned STAs. For example, controllers could issue a slower speed—or a speed prior to the nominal FMS slowdown region—to aircraft that need to absorb delay. Aircraft behind schedule could be held fast or sent direct to a downpath waypoint (in some situations, given FMS functionality and route geometry, this would also effectively cancel a deceleration). Merging badly coordinated flows might require heading vectors, but in general, aircraft could remain on the lateral FMS routes. Once aircraft were reasonably close to (perhaps within ten seconds of) their STA, controllers could use spacing clearances to effect a merge (“American 123, merge behind and follow United 345 80 seconds in trail”), or ‘lock in’ the required temporal spacing behind a lead aircraft (“United 123, follow American 345 80 seconds in trail”).

In a typical scenario Feeder West would issue the descent transition clearance (“American 123, continue your descent on the HIKAY 18R FMS transition”) upon accepting aircraft from Center Ghost. Feeder West would then issue an ‘adjustment’ clearance. For aircraft already well spaced in-trail behind their eventual leads, Feeder West would simply issue the ‘follow’ spacing clearance. Aircraft requiring significant adjustment might be handed to Final West, who would then issue the merging or spacing clearance and clear the aircraft for the approach. Final West would monitor and ensure proper spacing for the handoff to Tower Ghost. If a spacing clearance was not working out as planned, controllers would cancel it by issuing a speed clearance. Controller DSTs would support the process throughout by facilitating spacing assessment, helping select adjustment clearances, and aiding in conformance monitoring of spacing aircraft. Unequipped aircraft in the flow would be handled primarily through the use of speed clearances—first to establish spacing, then to match lead aircraft speeds.

Data Collection

The study was conducted during a two-week period that included two travel days for participants. It began with two days of training that covered the DSTs and possible strategies. During data collection, however, the only firm rule constraining controller behavior was that the first aircraft in the flow could not be ‘short cut’—an attractive control option given the FMS route geometry, but one that would alter the character of the traffic scenarios.

To obtain data for sixteen trials in each treatment combination, two parallel simulations were conducted simultaneously under the same conditions. The four controllers rotated in forming two-person teams. A given team stayed together during the course of a day. Pairs of trials in the four conditions were conducted in randomized order each day, with each team member serving as Feeder West and Final West in the test condition before moving to the next condition. Individual trials lasted thirty-five minutes with a short break between trials and a longer break between conditions. A trial ended after thirty-five minutes regardless of whether all the aircraft had been handed off to Ghost Tower.

System performance data were collected from each controller, pilot, and pseudo-pilot MACS station, as well as from dedicated data collection stations and networking hubs. Task data, such as pilot and controller interface actions, were also collected via MACS. Voice communications were recorded and participant interfaces were captured as movies. Workload Assessment Keypads (WAKs) probed controller workload at five-minute intervals during simulation trials. Workload questionnaires followed each trial, and participants completed usability/acceptability questionnaires and debrief sessions at the conclusion of the study.

Results and Discussion

This section presents the results of the Ames CE 11 study from an ATM perspective. The results address spacing accuracy, efficiency, and clearances, as well subjective controller workload, safety, and acceptability measures. Results concerning the effect of flow coordination are also presented.

Spacing Accuracy

Figure 4 depicts a histogram of time spacing errors measured at the final approach fix for runway 18R (denoted FF18R). The results show that accuracy improves when aircraft are capable of airborne spacing in conditions 'with air tools.' The addition of controller DSTs in the Air and Ground Tools condition does not improve spacing accuracy beyond that obtained in the Air Tools condition. Ground Tools did, however, help controllers err on the conservative side relative to No Tools, suggesting an improved awareness of the required spacing that may help minimize go-arounds.

The confederate Tower Ghost controller was not actively engaged in achieving accurate approach spacing. Because aircraft were actually already under control of Tower Ghost at the FF18R, spacing accuracy metrics were also computed at the point when Final West transferred communications to Tower Ghost. The 'transfer to tower' reference point provides a measure of how well the aircraft were spaced when Final West deemed them suitably spaced for the handoff. These results (Figure 5) indicate that Ground Tools yield a slight improvement in spacing accuracy at the handoff. A comparison with Figure 4 also suggests that airborne spacing helped aircraft maintain the required spacing, whereas no additional control by Tower Ghost allowed spacing accuracy to degrade in the Ground Tools and No Tools conditions. Figure 5 also shows Ground Tools produce more conservative spacing.

Efficiency

Throughput measured at FF18R is not significantly different across conditions ($p = .10$). However, the throughput measurements do not consider go-arounds that the tower controller might have assigned to aircraft that were too close. Also, temporal spacing criteria corresponded conservatively to current day wake vortex spacing requirements. The study did not test throughput increases that may be possible with airborne spacing using reduced or dynamic spacing matrices.

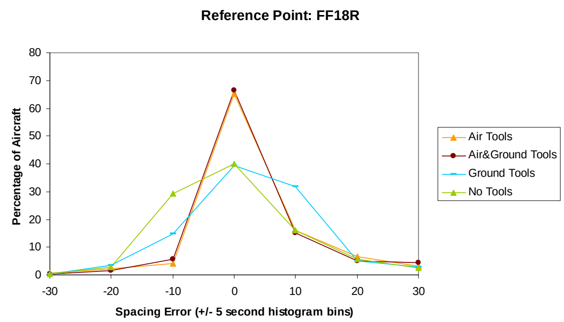

Figure 4. Spacing accuracy histogram measured at the Final Approach Fix for runway 18R.

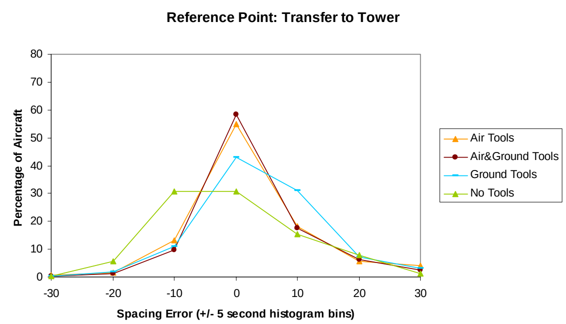

Figure 5. Spacing accuracy histogram measured upon transfer of communication to Ghost Tower.

As in previous DAG-TM simulations (e.g. [1]), flight time and distance are used as surrogate metrics for fuel efficiency. Average flight time and flight distance were measured from each metering fix to both FF18R and to the 'transfer to tower' reference point. For FF18R, no significant differences in either flight time or flight distance between conditions were found for aircraft arriving from a given metering fix. This consistency is likely due in large part to the use of the same FMS procedures in all conditions. A follow-up analysis showed that, in all conditions, on average aircraft flew coupled to the FMS approximately 90 percent of the time.

Flight distance from BAMBE was significantly longer ($p < .05$) in the Ground Tools condition when measured at the 'transfer to tower' reference point. Flight time from both BAMBE and FEVER was also significantly longer in the Ground Tools condition ($p < .05$). These results may indicate that with DSTs available and no aircraft equipped for airborne spacing, Final West maintained control of aircraft longer in order to monitor and ensure proper spacing before transferring control to Tower Ghost.

Clearances

Airborne spacing and merging clearances issued by voice used the voice callsign of the target and the voice callsign of the lead aircraft (e.g. “United 123, merge behind and follow American 345 80 seconds in trail,” or “American 123, follow United 345 80 seconds in trail”). An important result of this study was that, out of 323 airborne spacing or merging clearances, neither controllers nor pilots misidentified a target or lead aircraft.

Clearance data also provide insights about the impact of spacing clearances. The data presented here are preliminary in that they are inferred from MACS pilot logs, not directly transcribed from communication recordings. The clearance data pertain only to maneuvers (i.e., not FMS transition, approach, or handoff-related clearances); the proportion of clearances of each type is the raw count of that clearance type divided by the number of aircraft in the condition with good clearance data. Figure 6 shows that airborne spacing results in fewer clearances, particularly for Final West. When available, spacing clearances tend to supplant speed clearances and associated ‘resume charted speeds’ clearances.

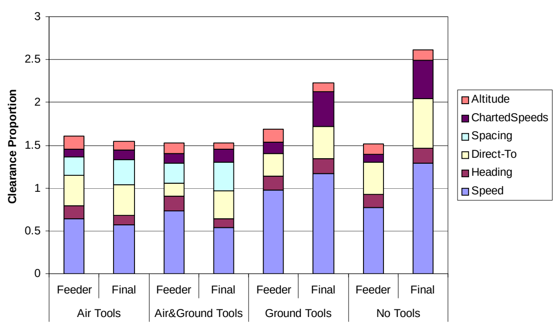

Figure 6. Relative proportions of maneuver clearances by controller, condition, and type.

Coordinated versus Uncoordinated Flows

Spacing accuracy and clearances are both affected by how well the merging flows to 18R are initially coordinated. Accuracy measures for the coordinated flows measured at FF18R strongly resemble the overall measures shown in Figure 4; uncoordinated-flow aircraft are under-represented in Figure 4 because all trials stopped after thirty-five minutes when many of the had not yet reached FF18R. Figure 7 depicts spacing accuracy histograms for the coordinated flows in each condition measured at ‘transfer to tower.’ The coordinated flows exhibit greatest accuracy for the Air and Ground Tools conditions, followed by Air Tools, then Ground Tools. Figure 8 shows accuracy measures for aircraft in uncoordinated flows. These results suggest that with airborne spacing, controllers can achieve better spacing accuracy even when merging flows are not well coordinated. Ground tools produced more conservative spacing, while No Tools showed broad variation in spacing accuracy.

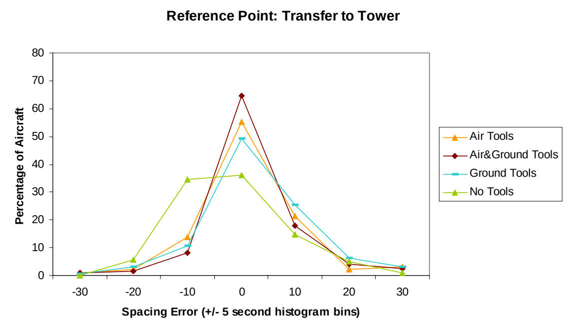

Figure 7. Spacing accuracy for aircraft in coordinated flows.

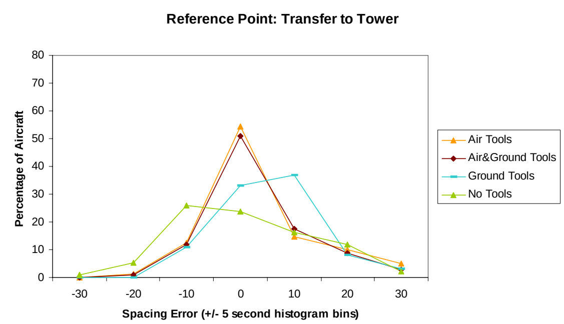

Figure 8. Spacing accuracy for aircraft in uncoordinated flows.

Flow coordination also affected the clearances controllers issued. Figures 9 and 10 separate the clearances issued to aircraft in coordinated and uncoordinated flows, respectively. The results are again expressed as proportions. The data show that both Feeder West and Final West issued a greater proportion of clearances to aircraft in the uncoordinated flow. For the coordinated flows, spacing clearances comprised a greater proportion of the clearances issued, and both controllers used smaller proportions of heading vectors and temporary altitudes, which translates into fewer disruptions to FMS operations. The relative proportions of clearances issued by Feeder West and Final West in the Ground Tools and No Tools conditions are much closer for the uncoordinated flows.

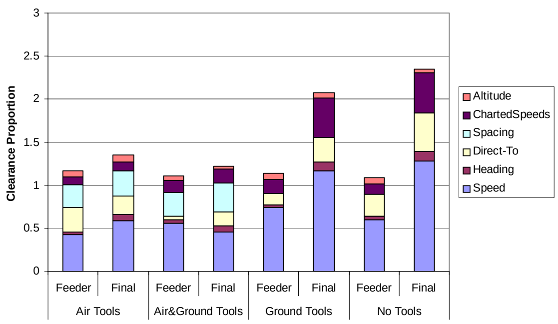

Figure 9. Maneuver clearance proportions for aircraft in coordinated flows.

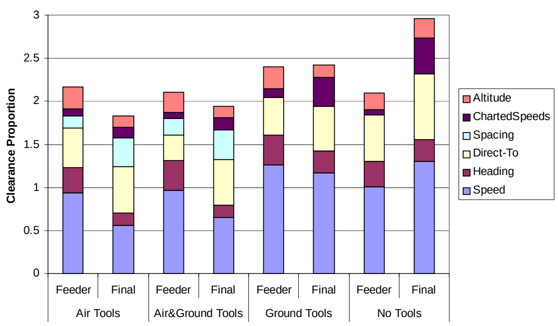

Figure 10. Maneuver clearance proportions for aircraft in uncoordinated flows.

Workload

Workload measures were assessed via Workload Assessment Keypads (WAKs) at five minute intervals during each trial. The average WAK scores for Feeder West show the lowest workload in No Tools conditions, with slightly higher workload in Air Tools conditions. Ground Tools conditions registered the most workload at the beginning of trials, while Air&Ground Tools conditions registered the most workload at the end (Figure 11). Final West average WAK scores were mostly lowest in Air Tools conditions, and mostly highest in Ground Tools conditions. Final West average WAK scores for Air&Ground Tools conditions exceeded scores for No Tools conditions toward the end of trials (Figure 12). On average, workload remained in an acceptable range for all conditions indicating that airborne spacing operations with DSTs are feasible and do not

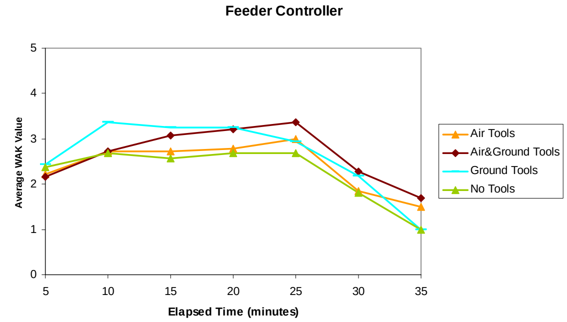

Figure 11. Average Feeder West WAK scores.

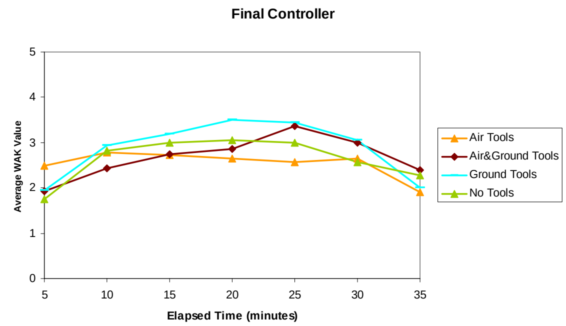

Figure 12. Average Final West WAK scores.

result in any unreasonable workload increases for the traffic loads in this simulation.

Subjective workload rankings of the conditions were also included as part of the post-simulation questionnaire (Figure 13). Interestingly, the subjective workload rankings rate Ground Tools as the lowest workload condition and Air&Ground Tools as the second lowest. Controllers ranked the Air Tools condition as the highest workload. These rankings are essentially reversed from the average WAK scores. These results may reflect a desire on

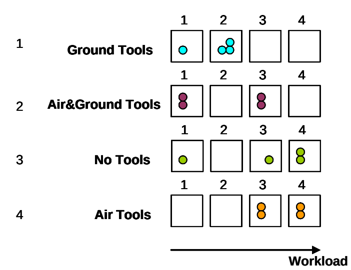

Figure 13. Post-simulation questionnaire condition workload rankings and individual controller rank assignments.

the part of controllers to have as much information as possible, as well as a perceived workload increase from maintaining responsibility for aircraft separation even after delegating spacing tasks to aircraft.

Safety

Controllers found the operations safe for all conditions. However, when asked to rank the conditions by safety, controllers ranked safety highest for Ground Tools condition, followed by No Tools, Air&Ground Tools, and Air Tools (Figure 14—note: one controller described all conditions as equally safe). These results are similar to the subjective workload rankings. Any behavior on the part of airborne spacing guidance or DSTs that controllers found unpredictable could have contributed to these rankings.

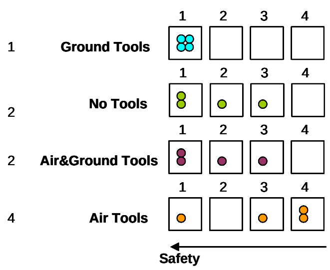

Figure 14. Post-simulation questionnaire condition safety rankings and individual controller rank assignments.

Controller Preference

Figure 15 depicts how controllers ranked the conditions in the post-simulation questionnaire according to their preference for use. A majority of controllers preferred the Air&Ground Tools condition. The Air Tools condition was least preferable. Controller comments generally mirrored these preference rankings. The DSTs and spacing guidance implemented for this study were not as mature as would be required for real-world operations, nor could the controllers be considered experts in their use. However, these results suggest that controllers would likely accept a mature implementation of airborne spacing operations with appropriate DSTs.

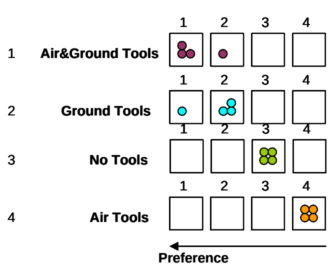

Figure 15. Post-simulation questionnaire condition preference rankings and individual controller rank assignments.

Conclusion

The Ames DAG-TM CE 11 simulation study investigated TRACON merging and spacing operations in a rich operational environment with FMS operations with mixed spacing equipage. This paper has presented results that suggest the concept is feasible and improves spacing accuracy. While workload always remained within an acceptable range, clearance data indicate that airborne spacing in the TRACON works best when linked to en route concepts capable of delivering aircraft in coordinated flows.

The results in this paper present a conservative view of what could be achieved in a fielded version of the concept with mature spacing guidance and DSTs, and experienced flight crews and controllers. Further analysis is needed to isolate and study particular situations and characterize effects unequipped aircraft may have had. Analyses should also address when particular clearance types are used (cf. [11]). Additional studies are needed to investigate how such concepts might produce benefits in heavier traffic conditions, or with reduced or dynamic separation minimums. Future studies should also include en route and tower controller participants, as well as more realistic feeder controller positions, to investigate how these controllers function together.

Acknowledgements

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