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Air and Ground Simulation of Terminal-Area Traffic Management with Airborne Spacing

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ABSTRACT

Controller and pilot decision support tools for operations with airborne spacing in the terminal area were evaluated in a simulation conducted at NASA Ames Research Center as part of the NASA Advanced Air Transportation Technologies project Distributed Air Ground Traffic Management element. The results indicate that airborne spacing improves spacing accuracy and may help reduce go-arounds. Controller workload is acceptable and spacing clearances containing lead aircraft callsigns are clear. Expected operational benefits depend on traffic flow coordination and predictable spacing guidance and support tool behavior.

INTRODUCTION

This paper describes a simulation conducted in the Airspace Operations Laboratory (AOL) and Flight Deck Display Research Laboratory (FDDRL) at NASA Ames Research Center to evaluate the feasibility and benefits of time-based airborne spacing operations in terminal radar approach control (TRACON) airspace. The simulation was conducted with funding from the NASA Airspace Systems Program Advanced Air Transportation Technologies (AATT) project Distributed Air Ground Traffic Management (DAG-TM) element. DAG-TM research has been conducted at NASA Langley, Glenn, and Ames Research Centers to investigate ATM concepts for increasing flexibility, efficiency, and capacity in the year 2015 and beyond by redistributing responsibilities among flight crews, dispatchers, and air traffic service providers.

This simulation investigated DAG-TM Concept Element 11 (CE11): Terminal Arrival: Self-Spacing for Merging and In-trail Separation. It was the final DAG-TM study conducted at NASA Ames Research Center, complementing previous simulations of en route DAG-TM concepts. Previous DAG-TM simulations in the AOL [11, 13, 15] evaluated concepts for en route trajectory negotiation using advanced data link functionality and controller decision support tools (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.

In the CE11 study, professional air traffic controllers managed traffic that included flight simulators flown by commercial pilots. A rich future operational environment was simulated, with Flight Management System (FMS) and ADS-B-equipped aircraft flying charted FMS routes to final approach. Traffic scenarios included a representative mix of ‘large’ and ‘B757’ aircraft, and traffic that initially arrived in the TRACON well coordinated for merging—as if the initial portions of the flows were conditioned using DAG-TM en route concepts—but ended with uncoordinated flows.

A 2x2 repeated-measures design evaluated controller and pilot DSTs for spacing and merging operations. In conditions in which air-side DSTs were available, piloted simulators had cockpit display of traffic information (CDTI)-based DSTs, and seventy-five percent of piloted and pseudo-aircraft were equipped for airborne spacing. In conditions with ground-side DSTs, controllers used STARS displays enhanced with a runway scheduler and timeline display, spacing advisories, and spacing ‘history circles.’ In all conditions, controllers maintained responsibility for separation.

The remainder of this paper describes the NASA Ames DAG-TM CE11 simulation from an Air Traffic Management (ATM) perspective (a flight deck perspective is provided in [3]). The paper first provides background on related research on airborne spacing and terminal-area FMS operations. It then describes the simulation environment, controller DSTs, and experimental design in detail. Finally, the paper presents the results of the simulation, which suggest that a more mature, fielded version of the concept could provide benefits including greater spacing accuracy and improved control of aircraft flying FMS routes in the TRACON.

BACKGROUND

Airborne Separation Assurance Systems (ASAS) [5] applications have interested researchers for more than two decades. They promise benefits ranging from improving all-weather situation awareness by making traffic information formerly available only to air traffic controllers available to the flight crew, to decreasing reliance on air traffic controllers to maintain safety through the use of on-board guidance. Transferring spacing and separation responsibilities to the flight crew may also reduce controller workload and required air-ground communications.

Airborne spacing ASAS applications enable air traffic controllers to designate a reference aircraft and spacing interval for a particular flight crew to achieve and maintain using on-board guidance. In airborne spacing applications, air traffic controllers retain responsibility for separation. Other categories of ASAS applications aim only to increase flight crew awareness of surrounding traffic, or go beyond airborne spacing by delegating to flight crews responsibility for separation from an assigned aircraft, or from all other traffic.

Enabling technologies such as ADS-B have spurred recent airborne spacing research [2]. Efforts have focused on the design of spacing guidance laws and the integration of spacing information on CDTIs for commercial jet aircraft [1, 9]. For example, the spacing algorithm reported in [1] has been analyzed [16] and flight-tested [12]. 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 [1].

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 [8] and increase controller availability by enabling them to set up traffic flows earlier [6, 7]. Like the research reported here, the research in [7] examines airborne spacing operations from a predominantly ground-side perspective. In that work, however, terminal-area routes were carefully designed to support spacing operations. In spacing conditions, all aircraft entered the terminal-area with airborne spacing active, 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 address low-noise continuous descent approaches (CDAs) and 'tailored arrivals' in which controllers use ground-based automation to compute trajectories that yield appropriate spacing. Clearance uplinks consist of either adjusted speeds for aircraft to fly on their assigned FMS trajectory, or new FMS trajectories altogether. Both CDAs and tailored arrivals are intended to leverage FMS capabilities for precision navigation and extend FMS operations into TRACON airspace. Without suitable tools, controllers have difficulties predicting the trajectories of aircraft on decelerating approach trajectories, and therefore either add excess spacing buffers which reduce throughput (e.g., [4]) or resort to tactical control. The central challenge is to afford controllers a means of controlling aircraft on FMS trajectories without over-burdening flight crews. Airborne spacing and controller DSTs hold promise as a means for controlling aircraft flying FMS trajectories in TRACON airspace [10], which could help realize the envisioned benefits of CDAs and tailored arrivals.

DAG-TM CE11 SIMULATION

The goal of the August 2004 simulation in the NASA Ames AOL was to evaluate the operational viability and potential benefits of time-based airborne spacing and merging in the TRACON. The simulation sought to demonstrate that airborne spacing is compatible with voice clearances, FMS operations, and mixed spacing equipage, and 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. It utilized the same simulation infrastructure as previous DAG-TM simulations in the AOL [14]. This section describes the elements of the simulation in detail.

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

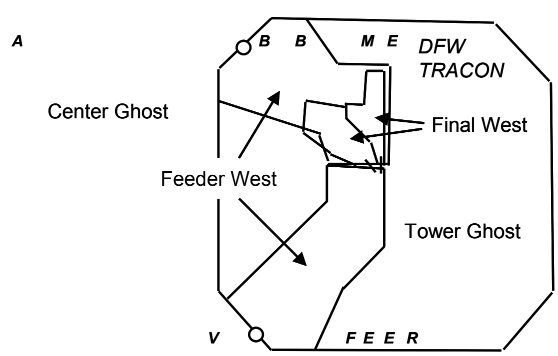


Figure 1. Simulation airspace.

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’).

PARTICIPANTS

Four professional TRACON controllers with between 15 and 20 years experience participated in the study. Two controllers were very familiar with DAG-TM concepts and simulations conducted in the NASA Ames AOL. The other two controllers were novices. Nine commercial pilots participated in the study. All Pilot participants had previously taken part in DAG-TM simulation research. Two retired controllers staffed the Ghost controller positions, and six general aviation pilots served as pseudo-aircraft pilots.

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

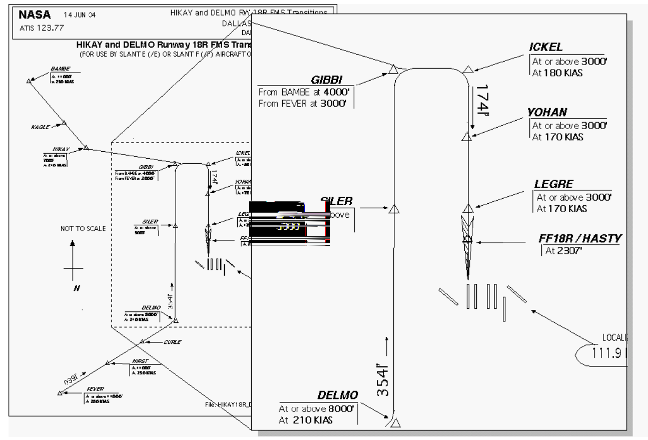


Figure 2. Charted FMS routes to runway 18R.

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. [6]). Figure 2 shows the chart for the two FMS transitions to runway 18R.

CONTROLLER DECISION SUPPORT TOOLS

Controllers used the Multi Aircraft Control System (MACS) STARS display emulation (Figure 3). The

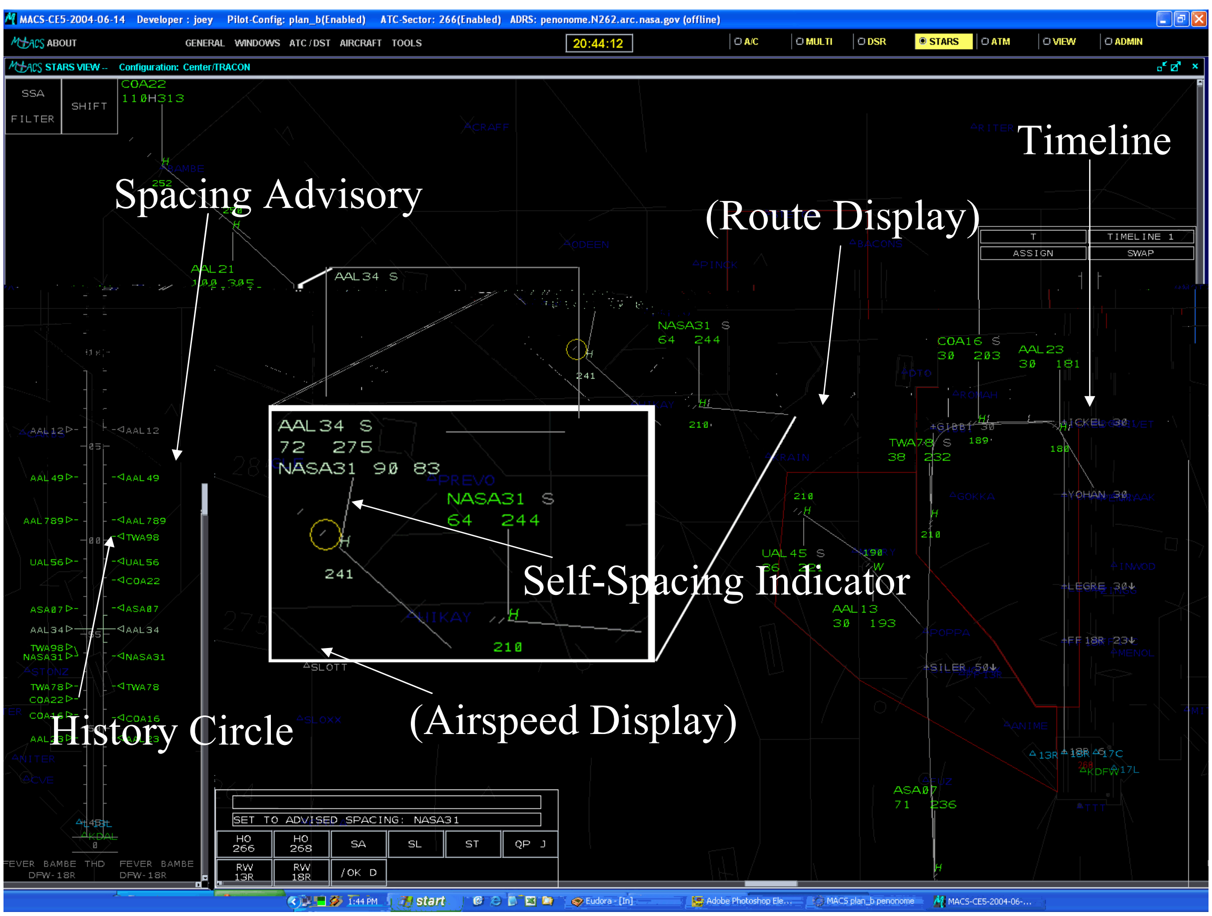


Figure 3. Enhanced MACS STARS display.

STARS display was hosted on realistic 2048x2048 large-format displays in the AOL [14]. Controllers could configure the basic STARS display according to their individual preferences (e.g. brightness, map range, range ring center, etc.). The STARS emulation enabled controllers to display aircraft FMS routes in all simulation trials. Indicated airspeed was also displayed just beneath the aircraft target symbol. These enhancements are a consequence of having fully FMS- and ADS-B-equipped traffic.

Controller DSTs to support spacing operations operate as follows. 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.

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.

CDTI-based spacing DSTs available to flight crews are beyond the scope of this paper; they are described in detail—together with the results of this study from an air-side perspective—in [3].

TRAFFIC SCENARIOS

The Ames CE 11 traffic scenarios represent traffic consistent with DFW traffic mixes. Arriving traffic flows were comprised of mostly 'large' and some 'B757'-class aircraft. In the study, the spacing matrix was configured such that aircraft should be spaced 80 seconds behind large aircraft and 100 seconds behind B757s. These values were selected to 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). Thus, an open slot in a flow from one direction would typically be filled by an aircraft coming from the other direction.

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 when air-side DSTs were available, seventy-five percent of all piloted simulators and pseudo-aircraft assigned to runway 18R were equipped for airborne spacing.

CONTROLLER STRATEGY

One DST-enabled strategy that emerged as attractive during the CE 11 simulation development process involved first using the timeline display 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—either a speed or a shortcut to a downpath waypoint. 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.

EXPERIMENTAL DESIGN AND DATA COLLECTION

Table 1 summarizes each of the four conditions of the 2x2 repeated-measures experimental design. 75% spacing equipage was selected to afford controllers ample opportunities to issue spacing clearances and use DSTs when they were available. On the other hand, it ensured that enough aircraft were unequipped for spacing that controllers needed to check that aircraft were equipped, and devise ways to manage unequipped aircraft. In all conditions, controllers were free to issue any FMS trajectory modifications or tactical clearances they deemed necessary via voice communication.

The study was conducted during a two-week period that consisted of two travel days and two training days, followed by six days of data collection. The two days of training covered the DST functionalities, exploration of controller strategies, and general familiarization of the airspace and traffic scenarios. 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 option given the FMS route geometry, but one that would invalidate some of the performance metrics across conditions.

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 overall traffic patterns were captured as movies. Workload

Table 1. 2x2 repeated measures experimental design.

Controller DSTs	Flight Deck DSTs: No	Flight Deck DSTs: Yes
No	“No Tools” ▪ No aircraft were equipped for airborne spacing ▪ Controllers could issue FMS trajectory modifications or tactical clearances	“Air Tools” ▪ 75% of aircraft assigned to primary landing runway equipped for airborne spacing (both CDTI-equipped piloted simulators and pseudo-aircraft) ▪ Controllers could issue spacing commands, FMS trajectory modifications, or tactical clearances
Yes	“Ground Tools” ▪ No aircraft were equipped for airborne spacing ▪ Controllers had DSTs available ▪ Controllers could issue FMS trajectory modifications or tactical clearances	“Air & Ground Tools” ▪ 75% of aircraft assigned to primary landing runway equipped for airborne spacing (both CDTI-equipped piloted simulators and pseudo-aircraft) ▪ Controllers had DSTs available ▪ Controllers could issue spacing commands, FMS trajectory modifications, or tactical clearances

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 when flight deck DSTs are available. The addition of controller DSTs in the Air & 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.

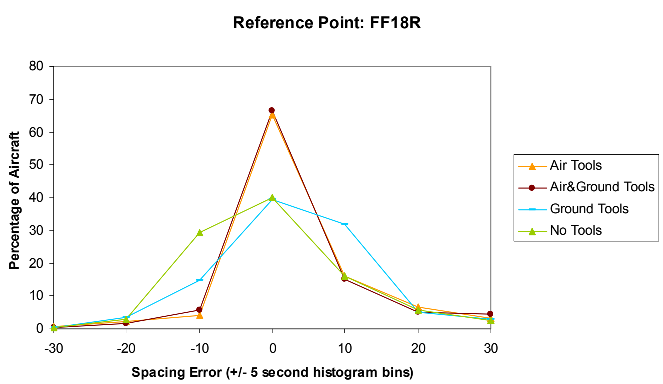


Figure 4. Spacing accuracy at the runway 18R final approach fix.

EFFICIENCY

Throughput measured at FF18R is not significantly different across conditions ($p = .10$), despite better spacing accuracy in the Air Tools condition. The main reason was due efficient delivery of aircraft in the No Tools condition, leaving little room for improvement with the addition of air and ground tools. In future studies, traffic scenarios that result in inefficient delivery of aircraft (e.g. bad weather) should be examined to maximize potential benefits of added DSTs and procedures. In addition, throughput measurements do not consider potential go-around situations. Such situations arose most often in the No Tools condition. Also, temporal spacing criteria corresponded conservatively to current day wake vortex spacing requirements. The study did not examine airborne spacing using reduced or dynamic spacing matrices.

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 FF18. 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; aircraft flew coupled to the FMS an average of approximately 90 percent of the time in all conditions.

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

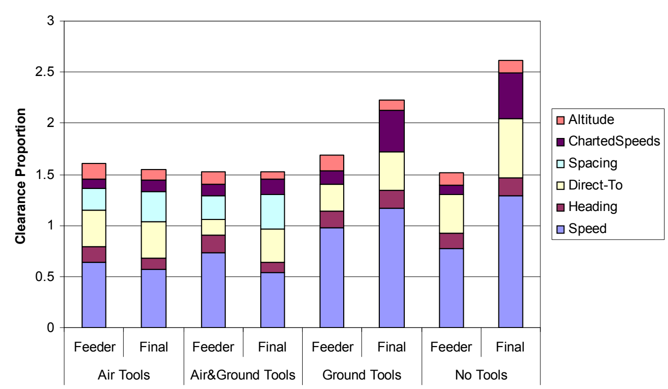


Figure 5. Relative proportions of maneuver clearances by controller, condition, and type.

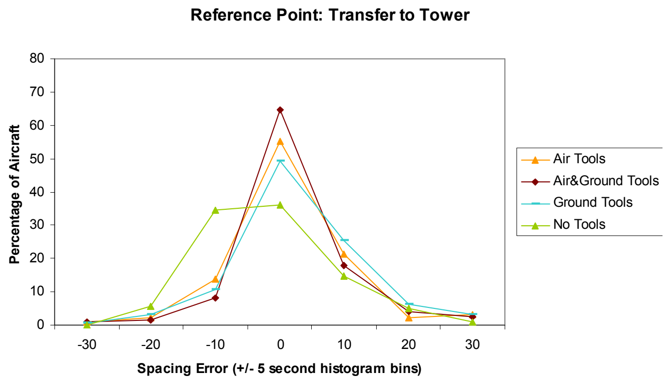


Figure 6. Spacing accuracy for aircraft in coordinated flows.

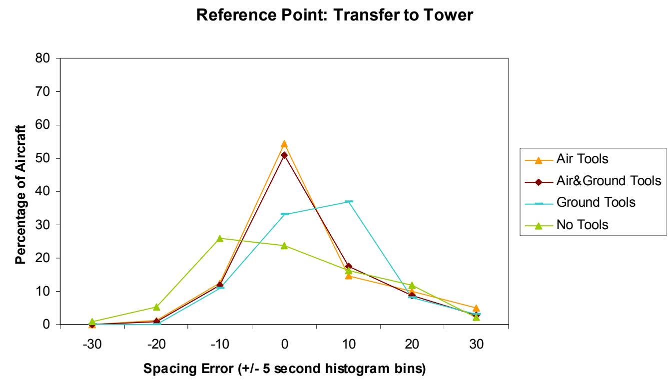


Figure 7. Spacing accuracy for aircraft in uncoordinated flows.

logs, not directly transcribed from communication recordings. However, a strong correlation exists between MACS pilot logs and voice clearances, suggesting that the logs can effectively represent the voice clearance data. 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 5 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.

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 6 depicts spacing accuracy histograms for the coordinated flows in each condition instead measured at 'transfer to tower,' when Final West transferred control of the aircraft to Tower Ghost. The coordinated flows exhibit greatest accuracy for the Air & Ground Tools conditions, followed by Air Tools, then Ground Tools. Figure 7 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.

Flow coordination also affected the clearances controllers issued. Figures 8 and 9 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.

WORKLOAD

Workload measures were assessed via Workload Assessment Keypads (WAKs) at five minute intervals

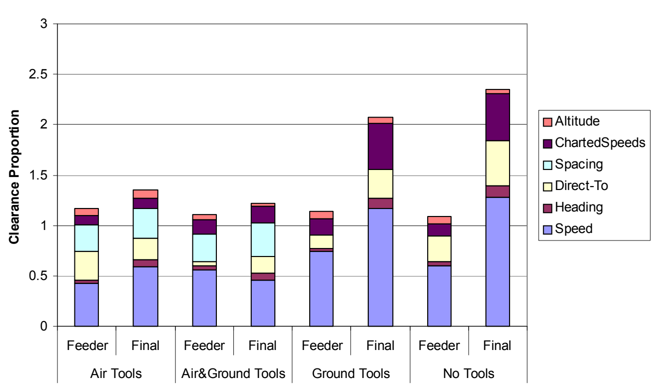


Figure 8. Maneuver clearance proportions for aircraft in coordinated flows.

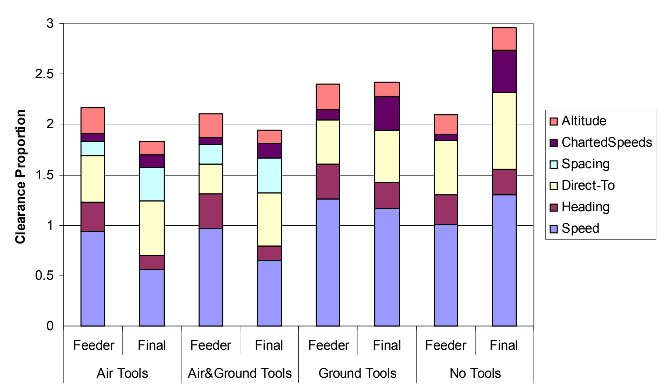


Figure 9. Maneuver clearance proportions for aircraft in uncoordinated flows.

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 10). 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 11). On average, workload remained in an acceptable range for all conditions and the differences between conditions were small, indicating that airborne spacing operations with DSTs are feasible and do not 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 12). 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 the part of controllers to have as much information as possible, as well as a perceived workload

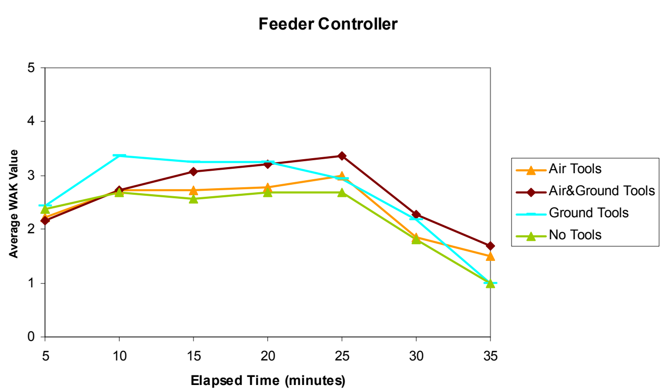


Figure 10. Average Feeder West WAK scores.

increase from maintaining responsibility for aircraft

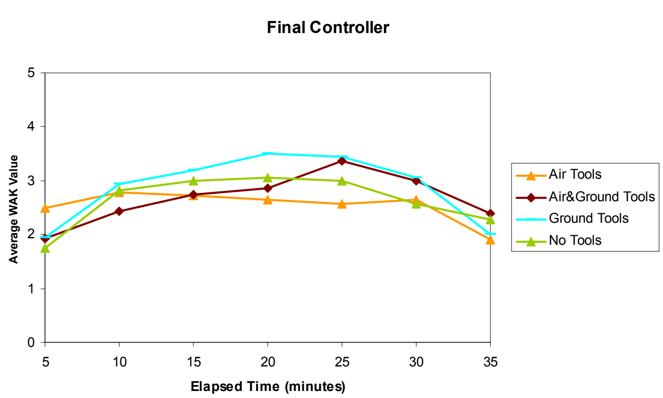


Figure 11. Average Final West WAK scores.

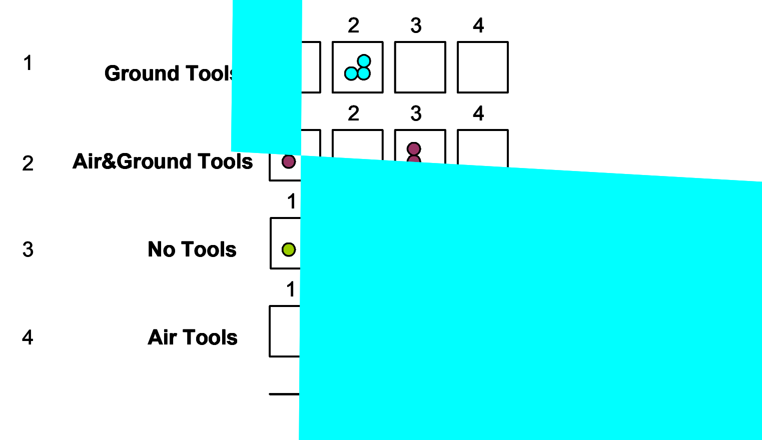
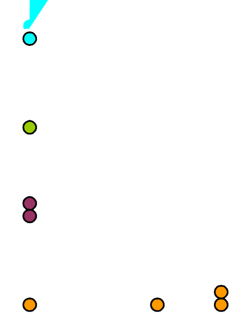


Figure 12. Post-simula
workload rankings an
assignments.

separation even after [...] to
aircraft.

SAFETY

Controllers found the op [...] conditions.
However, when asked t[...]s by safety,
controllers ranked safe[...]Ground Tools
condition, followed by No[...]und Tools, and
Air Tools (Figure 13—no[...]ller described all
conditions as equally saf[...]sults are similar to
the subjective workload [...] Any behavior on the
part of airborne spac[...]ance or DSTs that
controllers found unpredi[...]ould have contributed to
these rankings.



CONTROLLER PREFERENCE

Figure 14 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.

During the debrief discussions, controllers commented on their concerns with the self spacing aircraft. In a mixed equipage situation in which controllers had to manage an unequipped aircraft behind a self spacing aircraft, they had problems issuing speeds to maintain proper separation because the lead aircraft was flying variable speeds to maintain a targeted spacing. They felt in general that the concept would work better if they were relieved of the distance-based separation requirements (e.g. 3 nm) to self spacing aircraft.

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. [6]). 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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