AN EVALUATION OF AIRBORNE SPACING IN THE TERMINAL AREA

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Abstract

This paper describes a simulation conducted at NASA Ames Research Center to evaluate the feasibility and benefits of time-based airborne spacing and merging operations in Terminal Radar Approach Control (TRACON) airspace. Certified professional air traffic controllers managed simulated traffic in a rich future operational environment with Flight Management System (FMS) and Automatic Dependent Surveillance-Broadcast (ADS-B) equipped aircraft flying charted FMS routes to final approach.

A 2x2 repeated-measures design evaluated controller and pilot decision support tools (DSTs) for spacing and merging operations. In conditions with airborne spacing tools, 75 percent of the aircraft were equipped for airborne spacing, including single-piloted simulators flown by commercial pilots using Cockpit Display of Traffic Information (CDTI)-based DSTs. In conditions with ground-side spacing tools, controllers used Standard Terminal Automation Replacement System (STARS) displays augmented by a runway scheduler and timeline display, spacing advisories, and spacing feedback information. In all conditions, controllers maintained responsibility for separation.

This research was conducted as part of the Advanced Air Transportation Technologies (AATT) project's Distributed Air Ground Traffic Management (DAG-TM) element, with funding from the NASA Airspace Systems Program. DAG-TM research has been conducted at NASA Langley, Glenn, and Ames Research Centers.

Introduction

In December of 2004, the Joint Planning and Development Office (JPDO) produced the "Integrated National Plan for the Next Generation Air Transportation System." The plan emphasizes the need for a technology-enabled approach to future air transportation in the U.S. One of the strategies of the JPDO is to "Establish an Agile Air Traffic System", addressing critical system attributes such as performance, human factors, capacity, safety, etc [1]. A possible approach to meeting some of these goals is airborne spacing, specifically, the Airborne Separation Assistance System (ASAS) category 2 application of Enhanced Sequencing and Merging (ASPA-S&M) [2].

Airborne spacing capabilities have interested researchers for several years. Capacity limitations, combined with the arrival of enabling technologies such as ADS-B have produced insightful airborne spacing research. 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.

ADS-B enabled spacing algorithms have been developed and flight tested for integration in a flight deck tool [3, 4]. Enhanced algorithms for merging and spacing requiring additional information such as arrival routes, final approach speed, and wake vortex class are under investigation at NASA Langley Research Center [5]. Spacing research in Europe has demonstrated the effectiveness of airborne spacing operations from both flight deck and controller perspectives [6]. Delegating spacing tasks to the flight deck can improve spacing accuracy and increase controller availability by enabling them to set up traffic flows earlier [7].

Leveraging the lessons learned from prior research, a human-in-the-loop simulation at NASA Ames investigated the DAG-TM concept referred to as Terminal Arrival: Self-Spacing for Merging and In-Trail Separation, or Concept Element 11 (CE-11) [8]. The concept focuses on ASAS sequencing and merging applications.

The first objective of the simulation was to study the effect of mixed equipage on sequencing and merging operations. The second objective was to examine how controllers and pilots adapted and used the available tools to handle some off-nominal events, such as aircraft vectored far off their routes, or aircraft needing substantial delay maneuvers.

The CE-11 simulation, conducted in the Airspace Operations Laboratory (AOL) and the Flight Deck Display Research Laboratory (FDDRL), used the same simulation infrastructure as previous DAG-TM studies [9-14]. Although it was not fully utilized in this study, the simulation infrastructure allowed TRACON FMS routes to be a continuation of en route FMS arrivals, as part of a more integrated Air Traffic Management (ATM) system. Traffic scenarios included coordinated and uncoordinated flows of aircraft arriving into the TRACON. The coordinated flows were presented to the controllers as if they had been metered using other DAG-TM en route concepts.

Method

The goal of this simulation was to evaluate the operational acceptability and potential benefits of time-based airborne merging and spacing in the TRACON. 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. The simulation was a large-scale, distributed air and ground simulation that provided a rich operational environment.

Participants

Four certified professional TRACON controllers with between 15 and 20 years experience participated in the study. Two were very familiar with DAG-TM concepts and related simulations conducted in the AOL; the other two controllers had no previous exposure to the research. Pilot participants were nine commercial pilots, all of whom had previously experienced DAG-TM simulations. Two retired controllers staffed the peripheral "Ghost" controller positions, and six general aviation pilots served as pseudo-aircraft pilots.

Airspace

Figure 1 depicts the simulation airspace, encompassing the western portion of Dallas-Fort Worth (DFW) TRACON. The traffic scenarios were designed for south-flow operations to runways 18R (i.e., the primary landing runway) and 13R. One controller staffed the "Feeder" position, a combination of the "NW Feeder" and "SW Feeder" sectors. The Feeder controller received traffic arriving on FMS arrivals across the northwest (i.e., BAMBE) and southwest (i.e., FEVER) meter fixes delivered from an en route confederate controller ("Center Ghost"). A second controller staffed the "Final" position, a combination of the "13R Final" and "18R Final" sectors. The Final controller was responsible for aircraft on approach to both 18R and 13R, and also handed aircraft off to a confederate tower controller ("TRACON Ghost").

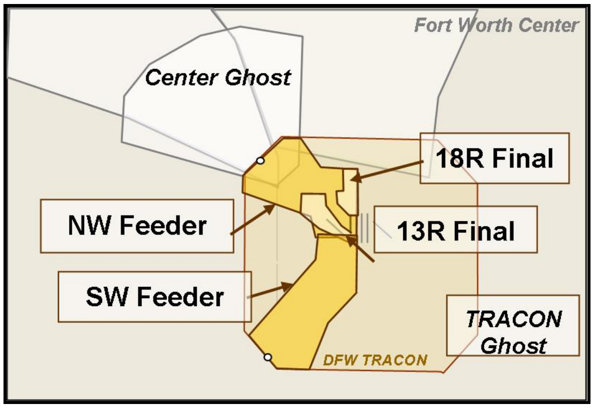

Figure 1. The airspace used in the simulation

FMS Procedures

All aircraft arrived at the DFW TRACON on FMS arrivals. The Feeder controller cleared aircraft to continue their descent on an FMS approach transition (Figure 2). Aircraft arriving across BAMBE flew either the HIKAY runway 18R FMS transition or the HIKAY runway 13R FMS transition, depending on their assigned runway. Aircraft coming over FEVER were assigned the DELMO runway 18R FMS transition. The routes conformed to current-day traffic flow patterns and merged at the initial base-leg waypoint GIBBI. Different altitude restrictions ensured that northwest and southwest arrivals were vertically separated at

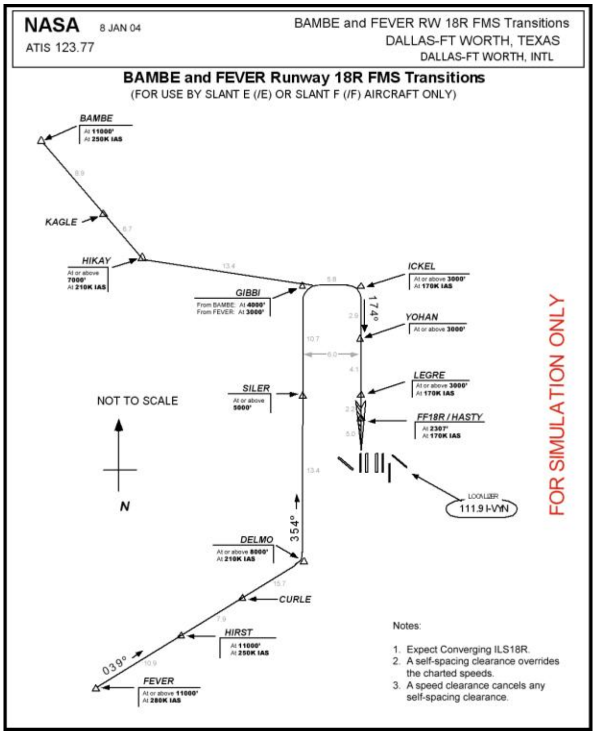

Figure 2. Chart for FMS transitions to 18R

GIBBI. Figure 2 shows the chart for the two FMS transitions to runway 18R.

Traffic Scenarios

The traffic scenarios represented traffic consistent with DFW traffic mixes, with mostly large and some B757 class aircraft. The spacing matrix was configured such that large aircraft should be spaced 80 seconds behind other large aircraft and 100 seconds behind B757 aircraft. These values ensured 3 and 4 nm at the final approach fix, respectively, even if aircraft were spaced slightly closer (i.e., five seconds or less) than the assigned temporal interval. In addition to the mixture of aircraft types, a mixture of spacing equipage was included as well (see experimental design section).

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 (i.e., around waypoint HIKAY).

The traffic scenarios were divided into coordinated and uncoordinated flows. The first twelve aircraft arrived at the meter fixes within fifteen seconds of their meter fix scheduled times of arrival (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 arrived as an uncoordinated traffic flow, intended to test the CE-11 concept in a situation where the merging traffic sequences were not well synchronized, delivered as if miles-in-trail flow restrictions were applied.

Experimental Design

Test conditions varied the availability of ground-side spacing tools, and the proportion (i.e., 0 or 75%) of aircraft equipped for airborne spacing. This 2x2 repeated-measures design yielded four experimental conditions:

1 <u>Air Tools</u> - seventy-five percent of the aircraft assigned to the primary landing runway (i.e., 18R) were equipped for airborne spacing, with controllers able to issue spacing commands

2 <u>Air and Ground Tools</u> – in addition to features of the “Air Tools” condition, controllers had DSTs available to aid in issuing airborne spacing clearances and monitoring spacing conformance

3 <u>Ground Tools</u> - controllers had additional DSTs available, but none of the aircraft were equipped for airborne spacing

4 <u>No Tools</u> – controllers had no additional DSTs available, and none of the aircraft were equipped for airborne spacing

Controller DSTs

Controllers used the Multi Aircraft Control System (MACS) [14] STARS display emulation (Figure 3) hosted on large-format monitors similar to those used in some current Air Traffic Control (ATC) facilities. In all simulation trials, the STARS emulation enabled controllers to display aircraft FMS routes. Indicated airspeed was also displayed just beneath the aircraft target symbol. These enhancements were an assumed part of the simulated future environment, namely having all aircraft fully FMS- and ADS-B-equipped.

In trials with ground-side tools available, controllers had additional DSTs to support spacing operations. An arrival scheduler was simulated in MACS. It used a reference point at the runway threshold and a matrix of temporal spacing intervals (i.e., based on weight class) to compute estimated times of arrival (ETAs) for all aircraft at the runway threshold based on flying the charted routes through the forecast three-dimensional (3D) wind field. The scheduler also computed a landing sequence and STAs at the runway. The schedule did not include any "extra" spacing buffers, regardless of whether aircraft were equipped for spacing. Controllers viewed this schedule on a timeline display (Figure 3) with ETAs on the left side and STAs on the right. Discrepancies between ETAs and STAs gave the controllers an idea of the predicted spacing between aircraft at the runway threshold. The timeline tool also enabled controllers to perform slot reassignments and swaps.

Spacing advisory DSTs used the schedule and aircrafts' routing to advise a lead aircraft and spacing interval. The advised spacing interval was based on the interval that was specified for the lead aircraft's weight class. When an aircraft was within 30 seconds of the advised spacing interval, its datablock was automatically expanded, displaying a spacing advisory in the third line. For DAL614 in Figure 3, the advised lead aircraft is NWA882, the advised spacing interval is 80 seconds, and the estimated current spacing is 102 seconds. The controller had the option to change the advised lead aircraft and/or the advised spacing interval using the shortcut panel shown in Figure 3. The shortcut panel also enables controllers to perform other tasks, such as handoffs and determining the distance between aircraft.

A spacing equipage indicator was included next to an aircraft's callsign. A green "/S" told the controller that an aircraft was equipped for airborne spacing. If the controller issued a spacing clearance to an aircraft, they could make an entry using the shortcut panel that highlighted the spacing equipage indicator in white as a reminder that the aircraft should then be spacing (Figure 3).

Dwelling on an aircraft displayed a "history circle." The center of the circle indicated where the lead aircraft was *X* seconds ago, where *X* was the advised and/or assigned spacing interval. The history circles had a radius of 10 seconds. An aircraft directly following its lead at the correct spacing interval would appear in the center of the history circle. In Figure 3, COA538 appears slightly behind the circle that shows where UAL629 was 100 seconds ago. This graphical information also complements the information displayed in the spacing advisory line of the data tag.

Controller Roles, Responsibilities, and Strategies

In order to ensure scenario repeatability and achieve the desired arrival schedule, the controllers were not allowed to change the speed, altitude profile, or routing of the first aircraft in each run. Controllers issued all clearances via voice and maintained responsibility for separation at all times.

One of the tasks of the feeder controller was to issue the descent clearance for the FMS transitions (e.g., "NASA31, continue your descent on the HIKAY 18R FMS transition") upon accepting aircraft from the center ghost controller. The feeder controller would then issue instructions and clearances to separate the aircraft and provide a good flow to the final controller. In addition to standard radar vectors the feeder controller could issue "follow" or "remain behind" spacing clearances to equipped aircraft. He or she was not allowed to issue merge clearances to aircraft arriving from different feeder sectors and merging inside the final controller's airspace. This restriction only applied to the two conditions with airborne spacing tools.

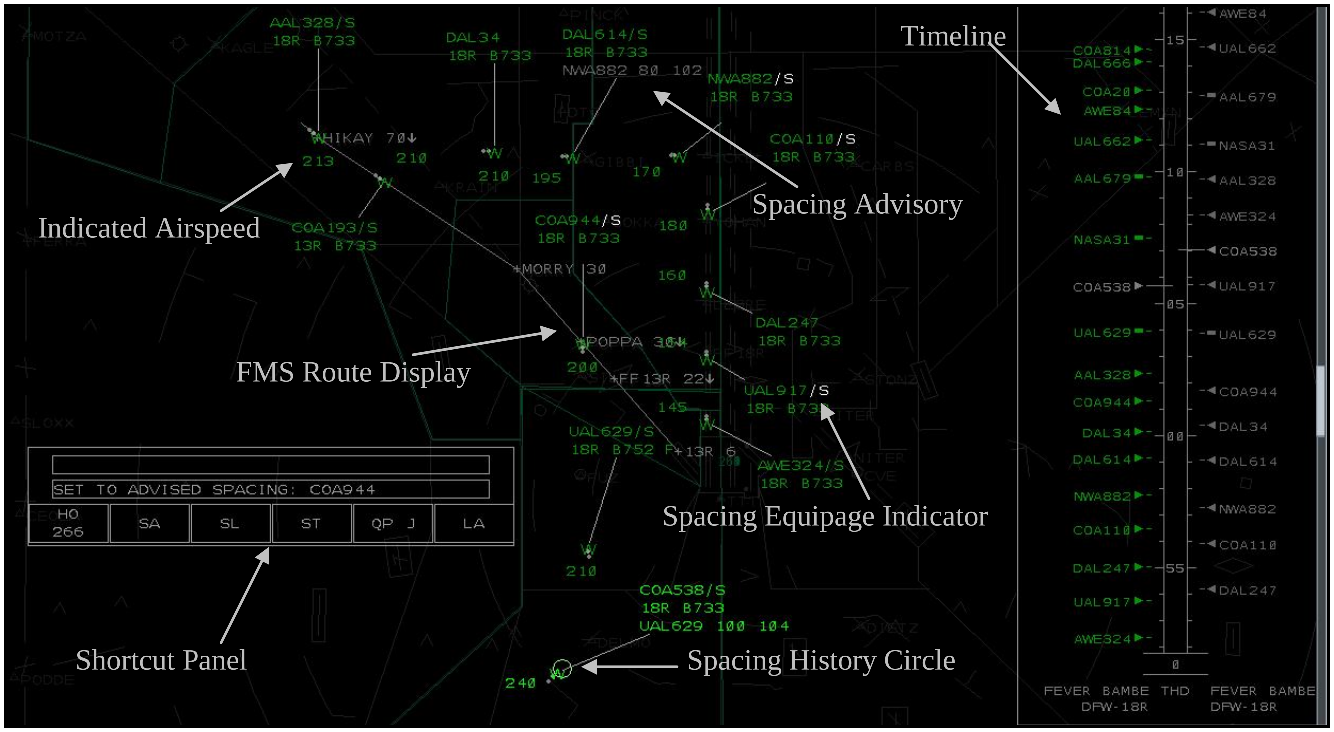

Figure 3. MACS's STARS display, showing various ground-side DSTs

When handing aircraft to the final controller, the feeder controller was encouraged to, when possible, deliver the aircraft on their trajectory. This helped give the final controller a more predictable flow. The typical "delivery points" were GIBBI, for the BAMBE flow aircraft, and SILER, for the FEVER flow aircraft.

The final controller's responsibilities included merging and spacing the two traffic flows by issuing any radar vectors or spacing clearances necessary. At any time, the controllers could cancel a spacing clearance. If a spacing clearance was not working out as planned, controllers could cancel it explicitly (e.g., "NASA31, cancel self-spacing") or cancel it by issuing a radar vector (e.g., "NASA31, maintain 190 knots"). Ground-side DSTs such as spacing advisories and conformance monitoring aids could be used at the controller's discretion. The final controller also issued the approach clearance (e.g., "NASA31, cleared ILS runway 18R") and was responsible for handing off properly spaced aircraft to the tower's TRACON ghost controller.

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.

To obtain data for sixteen trials in each treatment combination, two parallel simulations were conducted simultaneously under the same conditions. The four controllers rotated among the positions within the resultant two-person teams. A given team stayed together during the course of a day. Each day, the four conditions were tested in random order, with two trials per condition. This "trial pair" was run back to back, allowing both members of the controller team to work in both the feeder and final positions for every condition.

Individual trials lasted thirty-five minutes with a short break between trial pairs and a longer break between conditions. A trial ended after thirty-five minutes regardless of whether all the aircraft had been handed off to the tower's TRACON Ghost controller.

System data was collected via MACS from each controller stations, 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 and the CDTI. Movie captures were made from a "system overview" station, and voice communications were recorded as well. Workload Assessment Keypads (WAKs) probed controller workload at five-minute intervals during simulation trials using Air Traffic Workload Input Technique (ATWIT) ratings [15]. Workload questionnaires followed each trial, and participants provided usability/acceptability questionnaires and debriefing sessions at the conclusion of the study.

Results and Discussion

This study examined how the pilots and controllers realistically use spacing algorithms in an operational context within a large-scale, human-in-the-loop simulation. One of the unique features of this study was that the simulation included a broad variety of operating environments, including a mixture of airborne spacing equipage within traffic scenarios that, when combined with different control styles, yielded a rigorous assessment of an airborne spacing concept.

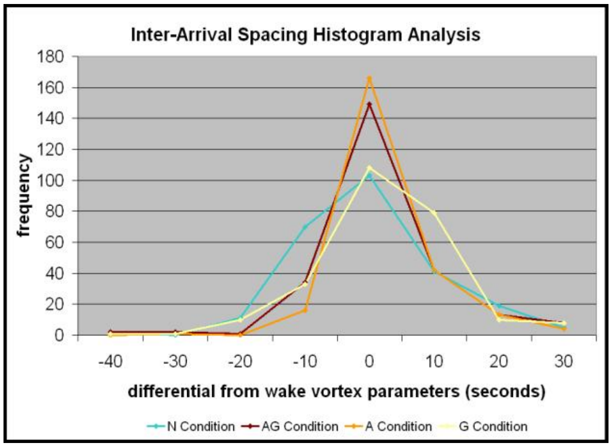

Figure 4. Inter-Arrival spacing histogram

Spacing Accuracy

Figure 4 depicts a histogram of the inter-arrival spacing between subsequent aircraft measured at the final approach fix for runway 18R (i.e., the actual spacing between consecutive aircraft compared to the required spacing between consecutive aircraft). The results indicate that inter-arrival spacing accuracy improved when aircraft were capable of airborne spacing and merging (Browne-Forsythe $t = 5.651$; $p < 0.001$). However, results for the condition with both air and ground tools revealed that the addition of controller DSTs does not seem to improve spacing accuracy beyond that obtained in the condition with air tools only. Also, the condition with only ground tools, relative to the condition with no tools, showed a qualitative difference but not much of a quantitative difference, perhaps indicating merely a shift in personal preference towards having more information on the ground, and the resulting effect on control style. The spacing accuracy data runs counter to the controller safety assessments (described below), providing an interesting contrast between objective performance and subjective safety rankings.

Controller Reactions

Workload measures were assessed via Workload Assessment Keypads (WAKs) at five minute intervals during each trial. Workload remained in an acceptable range for all conditions indicating that airborne spacing operations with DSTs are feasible and do not result in any unreasonable workload increases for the traffic loads used in this simulation.

Controllers rated the operations safe for all conditions (M = 3.36; 1 = much less safe; 5 = much safer than current day operations). However, when asked to rank the conditions by safety, controllers ranked safety highest for the condition with only ground tools, followed by the condition with no tools, the condition with both air and ground tools, and lastly the condition with only air tools (note: one controller described all conditions as equally safe). These results were consistent with the general patterns in the subjective workload ratings. Uncertainty regarding the behavior of the aircraft conducting airborne spacing under certain traffic situations seemed to have contributed to the lower safety rankings of the conditions with airborne spacing tools.

In general, controllers felt uncomfortable when, aircraft cleared to "merge behind" or "follow" a lead aircraft, made speed changes inconsistent with the controller's expectations. Predictability appears to be the key to controller acceptance. Behaviors like excessive speed fluctuations and initial speed increases followed by slow downs, may have affected the controllers' opinion of both the concept and the operation's safety. This issue was perhaps more noticeable than in other studies because of the simulation's mixed equipage environment. Controllers mentioned the increased monitoring needed when a non-equipped aircraft was following an aircraft in spacing status. They explained that these speed fluctuations made it more difficult to pick the correct speed to issue to the trailing non-equipped aircraft, when trying to match the leading "in spacing status" aircraft's speed.

Controllers also ranked the conditions according to their preference for use. A majority of controllers preferred the condition with both air and ground tools. The condition with only air tools was found to be the least preferable. Controller comments generally mirrored these preference rankings. The DSTs and behavior of the 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. Appropriate ground-side DSTs will likely increase controller acceptability particularly for mixed equipage environments.

Efficiency

Throughput measured at the final approach fix for runway 18R (FF18R) was not significantly different across conditions (p = .10). However, 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 more aggressive, reduced, or dynamic spacing matrices.

As in previous DAG-TM simulations [10-12], flight time and distance were used as surrogate metrics for fuel efficiency. Average flight time and flight distance were measured from each metering fix to FF18R. No significant differences were found in either flight time or flight distance between conditions. This consistency is likely due 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.

Clearances

Airborne spacing and merging clearances issued by voice used the spoken callsign of both the target and the lead aircraft (e.g., "United 456, merge behind then follow Delta 789, 80 seconds in trail," or "Continental 321, follow Northwest 654, 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.

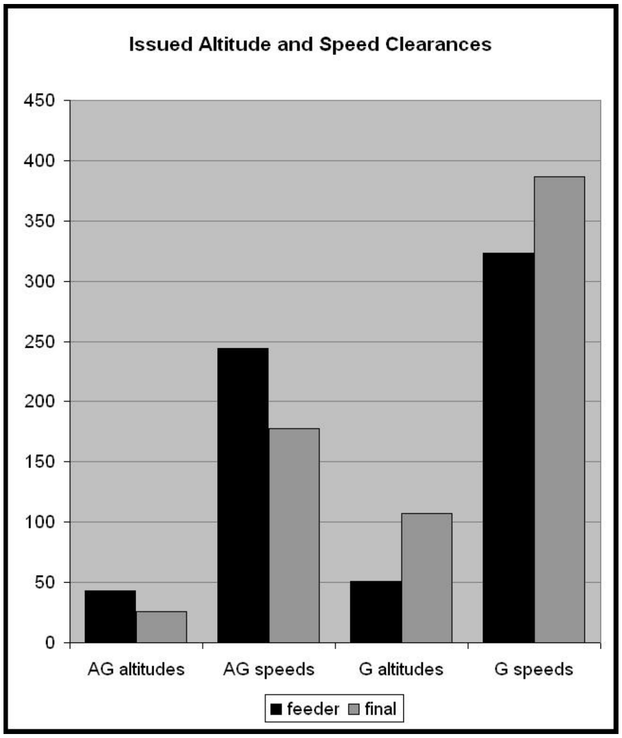

Figure 5. Altitude and speed clearance counts

Clearance data were analyzed to gain additional insights into the impact of spacing clearances on air traffic control operations. For example, Figure 5 shows a comparison between the conditions with only ground tools (G) and with both air and ground tools (AG). Altitude and speed assignments were reduced when airborne spacing and merging was available, especially for the final controller (e.g., 26 vs. 107 altitude clearances and 178 vs. 387 speed instructions). This suggests that

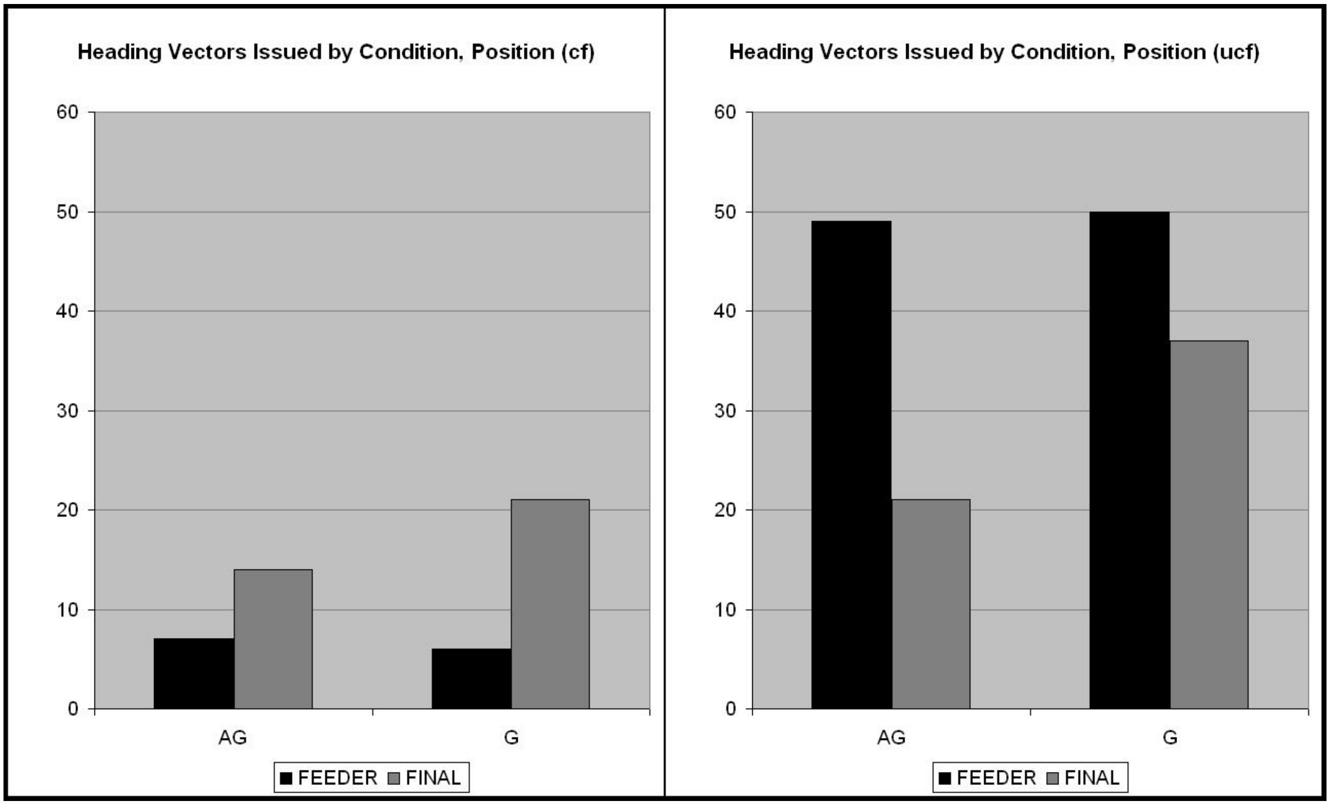

Figure 6. Heading clearance counts by position, condition, and flow type

the use of airborne spacing and merging clearances could result in fewer tactical vectors.

Looking at Figure 6, we see a similar trend. The final controller issued less heading assignments to aircraft in the condition with both air and ground tools (AG) than in the condition with only ground tools available (G). The idea of air traffic control issuing fewer "late tactical vectors" is given greater magnitude under more complex traffic environments, as indicated in the comparison of coordinated and uncoordinated flows in Figure 6.

Coordinated versus Uncoordinated Flows

In this simulation, the amount of coordination between traffic flows seemed to affect the clearances controllers issued. Figure 6 depicts the results of a preliminary analysis of heading assignments issued to aircraft in coordinated flows (cf, left) and uncoordinated flows (ucf, right). Not surprisingly, it shows that the controllers, especially the feeder controller, issued more heading assignments to aircraft in the uncoordinated flow (e.g., 50 vs. 6 when only ground tools were available).

In the coordinated flow, the controllers issued heading assignments, presumably for fine-tuning (e.g., shortcutting) the spacing of aircraft that was already relatively well-conditioned. In contrast, in the uncoordinated flow, the feeder controller presumably needed to vector the aircraft in order to deliver an acceptable feed to the final controller (e.g., delay vectors). In both cases, the controllers were able to effectively use heading assignments that took planes off of their FMS routes in conjunction with spacing clearances, demonstrating that airborne spacing operations can be used effectively, even if aircraft do not continuously remain on their FMS routes.

For the coordinated flows, spacing clearances accounted for a greater proportion of the total clearances issued, reducing the number of radar vectors such as heading assignments, speed instructions, and altitude clearances, translating into less frequent disruptions to FMS operations.

Conclusion

The Ames DAG-TM CE-11 simulation study investigated airborne spacing operations in the TRACON. The research was done in a rich operational environment with FMS operations and mixed spacing equipage. This paper presents results that suggest the concept is feasible even under mixed equipage scenarios with unconditioned traffic flows that require extensive vectoring. Furthermore, spacing accuracy improves with the use of airborne spacing tools, and ground-side spacing tools allow the controllers to provide predictable and well-conditioned traffic flows. Although the clearance data indicate that airborne spacing in the TRACON works best when aircraft are received in coordinated flows, the controllers were able to effectively use the spacing clearance even when the flow was unconditioned and needed a significant amount of work. Importantly, the controllers managed the traffic very successfully while reporting very acceptable workload ratings throughout the entire study.

The results in this paper present a conservative but promising view of what could be achieved in a fielded, more mature version of the concept with improved spacing guidance and DSTs, as well as more experienced flight crews and controllers. Based on the results from this study, further analysis is needed to isolate and study any interactions unequipped aircraft may have had on the system. In addition, better spacing algorithms are needed to increase their predictability in off-nominal situations as well as matching them more closely to controllers' expectations and strategies. Additional studies are needed to investigate how such concepts might produce benefits in heavier traffic conditions, or with reduced or dynamic separation minima. A simulation environment with more of the surrounding airspace staffed would allow for further investigation of inter-sector coordination issues.

Acknowledgements

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