Comparison of Controller and Flight Deck Algorithm Performance During Interval Management with Dynamic Arrival Trees (STARS)

Vernol Battiste*, George Lawton***, Joel Lachter*, Summer Brandt*, Robert Koteskey*, Arik-Quang Dao*, Josh Kraut*, Sarah Ligda* & Walter W. Johnson**
*San Jose State Research Foundation; **NASA Ames Research Center; ***Lawton Software

Abstract

Managing the interval between arrival aircraft is a major part of the en route and TRACON controller's job. In an effort to reduce controller workload and low altitude vectoring, algorithms have been developed to allow pilots to take responsibility for, achieve and maintain proper spacing. Additionally, algorithms have been developed to create dynamic weather-free arrival routes in the presence of convective weather. In a recent study we examined an algorithm to handle dynamic re-routing in the presence of convective weather and two distinct spacing algorithms. The spacing algorithms originated from different core algorithms; both were enhanced with trajectory intent data for the study. These two algorithms were used simultaneously in a human-in-the-loop (HITL) simulation where pilots performed weather-impacted arrival operations into Louisville International Airport while also performing interval management (IM) on some trials. The controllers retained responsibility for separation and for managing the en route airspace and some trials managing IM. The goal was a stress test of dynamic arrival algorithms with ground and airborne spacing concepts. The flight deck spacing algorithms or controller managed spacing not only had to be robust to the dynamic nature of aircraft re-routing around weather but also had to be compatible with two alternative algorithms for achieving the spacing goal. Flight deck interval management spacing in this simulation provided a clear reduction in controller workload relative to when controllers were responsible for spacing the aircraft. At the same time, spacing was much less variable with the flight deck automated spacing. Even though the approaches taken by the two spacing algorithms to achieve the interval management goals were slightly different they seem to be simpatico in achieving the interval management goal of 130 sec by the TRACON boundary.

Introduction

The Next Generation Air Transportation System (NextGen), an initiative being planned and implemented by the Joint Project Development Office (JPDO), seeks to transform the management of the National Airspace System (NAS), with one specific goal being to reduce weather related delays (JPDO, 2010). One proposal to accomplish this is to use automation to dynamically adapt the arrival and departure routing, the currently fixed STARS and SIDS, so they bypass weather systems (Krozel, Penny, Prete, & Mitchell, 2004). This could offload the problem of finding and implementing a clear path for both the pilot and controller, thus reducing the number of required communications and workload. Automation may also be able to find more efficient trajectories than the ad hoc system used by pilots and controllers today.

Today controllers manage arrival and departure traffic along Standard Instrument Departures (SIDs) and Standard Terminal Arrival Routes (STARs) that have multiple transitions or paths leading to and from an airport. Current day SIDS and STARS are invariant and are well understood by the controllers and pilots. Under nominal conditions the pilots fly and the controller manages the path, altitude and speed of aircraft to ensure that separation and spacing constraints are met. However, in the presence of weather, pilots are responsible for separation from weather, while the controller retains responsibility for traffic separation. Thus, as necessary the pilots will request deviations to avoid weather from the controller who will move aircraft off these routes to satisfy pilots' deviation requests. This added workload is further increased since such deviations can make the management of spacing and estimation of time to merge points more difficult. The challenge to the controller in weather-impacted arrival regions is not only to work with the pilots to find acceptable routes around the weather, but also to do so in a manner in which he or she is able to handle spacing/separation with speed and vector commands, all the while keeping the delivery rate as high as possible. In weather-impacted areas in the NAS it is often not possible to service all aircraft attempting to enter a weather-impacted sector. Thus, holding of aircraft in both high and low altitude sectors is the norm. Also, with prolonged weather events, ground stops or ground delay programs are implemented.

It is hypothesized that dynamic routing can help controllers and pilots handle weather-impacted arrival routing by automatically calculating and delivering weather-free routes to the flight deck prior to the aircraft leaving their en route cruise altitude. This dynamic adaptive routing will offset part of the controller's and pilot's workload because prior to top of descent, pilots will receive a tailored arrival routing that is not only weather-free but also with an optimal descent profile (OPD). However, the controller will then face the issue of managing traffic on unfamiliar and dynamically changing routes that periodically adapt to avoid convective weather systems. This unfamiliarity may potentially equal the challenge of simply managing spacing and separations with no dynamic routing tool. The primary question for this study is whether dynamic routing would be acceptable to controllers and pilots, and whether the addition of flight deck managed spacing would reduce controller workload and aid in the acceptance of the dynamic routing concept.

In-trail separation and spacing. There are at least three possible methods by which we could seek to manage in trail spacing using dynamic routing. First, we could rely on controllers who issue speed commands and path changes to ensure adequate spacing along the paths and at merge points. A second potential approach to the spacing problem is to precondition all aircraft so they enter the dynamic arrival paths at optimal times and places, see, Moertl, Beaton, Lee, Battiste & Smith, 2004. A third approach uses flight deck-based automation to aid pilots to achieve appropriate spacing relative to their leading aircraft. Work on this capability, called Interval Management, (also known as Merging and Spacing), has been ongoing for some time now (Murdoch, Barmore, Abbott, & Capron, 2009). In this simulation we will be looking at all three of these methods. Across scenarios we vary whether the controllers are responsible for spacing (similar to the first case), or pilots (similar to the third case). We also vary the degree to which aircraft are initially preconditioned to enter the arrival stream appropriately spaced.

Dynamic tree structure and airspace. In this HITL study we employ a simple tree planner with a simple binary tree structure. For a complete discussion of dynamic adaptive arrival routing and the results of the METRON's fast-time study see Krozel, Penny, Prete, & Mitchell, 2007; Prete, Krozel, Mitchell, Kim, & Zou, 2008; Krozel, Andre & Smith, 2006. The routes start about 200 miles from the airport, and about 160 miles from the TRACON entry meter fix. En route top of descent for arrivals on the optimized profile descent is about 40 nm after entering the tree. In its simplest static form, it is an arrival STAR composed of four potential routes with two merge points per route (three total merge points).

Method

Participants

Twelve commercial airline pilots with glass cockpit experience and six retired controllers participated in the study. Controller participants were familiar with the modern ATC tools available in (MACS). Pilots were divided into two person crews with the more experienced pilot chosen as the captain. They remained together for the duration of the study. The remaining aircraft on each trial were flown by confederate pseudo-pilots.

Equipment

Flight Decks. Two low fidelity desktop and one mid-fidelity fixed-based flight simulator were used in the study. All simulated Boeing transport aircraft using MACS with Cockpit Situation Displays (Prevot, Smith, Palmer, Mercer, Lee, Homola, & Callantine, 2006); Granada, S. Quang Dao, A., Wong, D., Johnson, W.W., & Battiste, V., 2005). The mid-fidelity simulator included an out-the-window display of the flight environment (e.g., weather and traffic). All participant aircraft were equipped as high-end present day glass flight decks with FANS/1A and airborne weather radar.

Controller DSR stations. Controller Display System Replacement (DSR) stations included trial planners, conflict detection and resolution tools. Dynamic NextRad weather was displayed near the eastern sector boundary. Controllers were also provided with a schedule window that showed the time each plane was predicted to cross meter fix (CBSKT). FANS-1A datalink communication between flight deck and controllers was suggested as the primary communication medium with voice radios used as needed when datalink was not appropriate due to time constraints.

Collection of Real Time Workload. In addition to the equipment described above, each participant also had a separate touch-screen computer used to collect real time workload ratings.

Display of Dynamic Trees

Under current day operations controllers work the same airspace repeatedly, often for years. They spend considerable time learning the airspace for which they have control responsibility - routing, fixes, and basic strategies for handling traffic.As a result, the explicit display of SIDs and STARs was thought necessary. With the introduction of dynamic arrival routing however, we thought it was necessary to display the dynamically changing tree structure as it reacted to the changing convective weather. To allow the trees to be differentiated with a minimum of clutter, active trees were displayed using different colors and line styles to distinguish them, since as many as three trees may be displayed at one time. The trees were drawn with line segments of one, three or five nm and in three shades of magenta (shorter lines were more blue, longer lines more red). Sample trees are shown in Figure 1. Static arrival paths were presented in magenta with 5 nm line lengths.

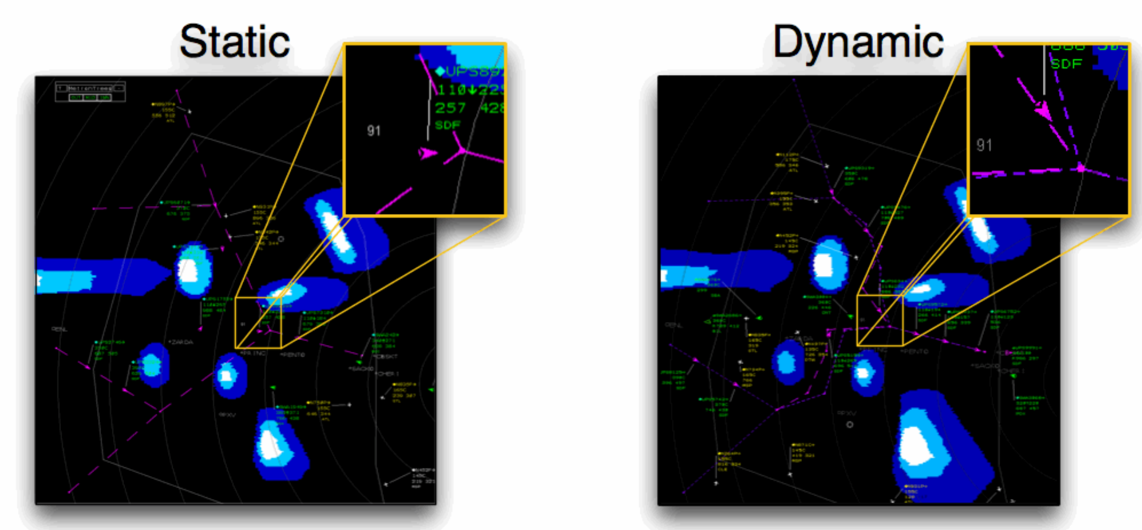

Figure 1. DSR Static and Dynamic Tree Displays

Scenarios and Procedures

All dual-pilot flight decks (those not piloted by confederates) were arrival aircraft headed for Louisville International Airport (SDF), reaching top of descent shortly after entering the sector. Flight decks flew west to east through the sector and negotiated a storm front near the center of the sector.

Departure traffic leaving SDF used FANS datacom to request deviations around weather and VFR en route traffic was created and pre-deviated to fly appropriately with respect to each weather patterns. Each arrival was assigned a time to enter the scenario 130 ± 10 seconds behind the previous aircraft (constrained so that every three planes had an average delay of 130 seconds); or and was assigned an initial flight level (FL 330, FL 350, FL 370, FL 390).

Concept of operations

In this simulation, the controller was responsible for managing aircraft in a high altitude and low altitude “super-sector” in Kansas City and Indianapolis Center’s airspace (composed of ZKC 90 and parts of the adjacent sectors, ZID 91 and ZID 17). The Kansas City Center sector is on the center’s eastern boundary adjacent to Indianapolis Center. The primary sector traffic in our simulation were the UPS arrivals into UPS’s HUB at Louisville International Airport (SDF), along with some departures from SDF and visual flight rules (VFR) over-flight traffic included to increase controller workload to a normal but manageable level. Controllers, as in today’s operation, were responsible for aircraft separation and traffic management, while pilots were responsible for weather avoidance.

Experimental Design

The study was 3X2 within subjects design with three Tree Types (Static, Dynamic and Dynamic Adjusted), by two spacing responsibility (controller or pilot) conditions. Dynamic and Dynamic Adjusted trees differed in the way the delay between successive arrival aircraft entering the tree was calculated. In the Dynamic Adjusted condition, the variance in path length is accounted for before the aircraft enter the tree. In the dynamic condition it was not.

There were two Spacing Responsibility conditions: Controllers Responsible and Pilots Responsible. In the Controllers Responsible condition, controllers managed spacing between aircraft much as they do today. Controllers could assign aircraft speeds or adjust their path length to maintain appropriate intervals. In the Pilot Responsible condition, the flight crew used an early version of a spacing algorithm developed at the NASA Langley Research Center (Oseguera-Lohr, Lohr, Abbott, & Eischeid, 2002) to which we added trajectory intent with merging capability; while for the pseudo-piloted flight decks we modified the spacing algorithm developed by Eurocontrol (Eurocontrol Experimental Centre, 2006) so that it included trajectory intent with merging capability. For both cases, the spacing logic generated speed guidance to achieve the desired spacing goal of 130 seconds at CBSKT. Unless the pilots chose to intervene, the spacing algorithm commanded speed was coupled with the autopilot and did not require manual Mode Control Panel speed inputs.

Results

Aircraft performance data for arriving aircraft on the CBSKT arrival with a 130 second target inter-aircraft arrival interval were collected and analyses based on the three tree types and controller or pilot responsibility for spacing. In addition, controller handoff acceptance time and communication frequency data were also collected and analyzed. Also, real-time subjective workload probe ratings were collected during each trial, while retrospective subjective workload and acceptability ratings were collected at the end of each trial. At the end of the simulation, study questionnaires were administered to all of the participants and additional ratings and comments gathered. For information regarding distance flown by tree conditions, pilot workload see (Johnson, et al., 2012).

Time in Trail and Separation Performance

Spacing at CBSKT. These analyses are based on the crossing times at CBSKT (final merge point). Time in trail was determined by subtracting the time a given plane crossed CBSKT from the time the previous plane crossed.

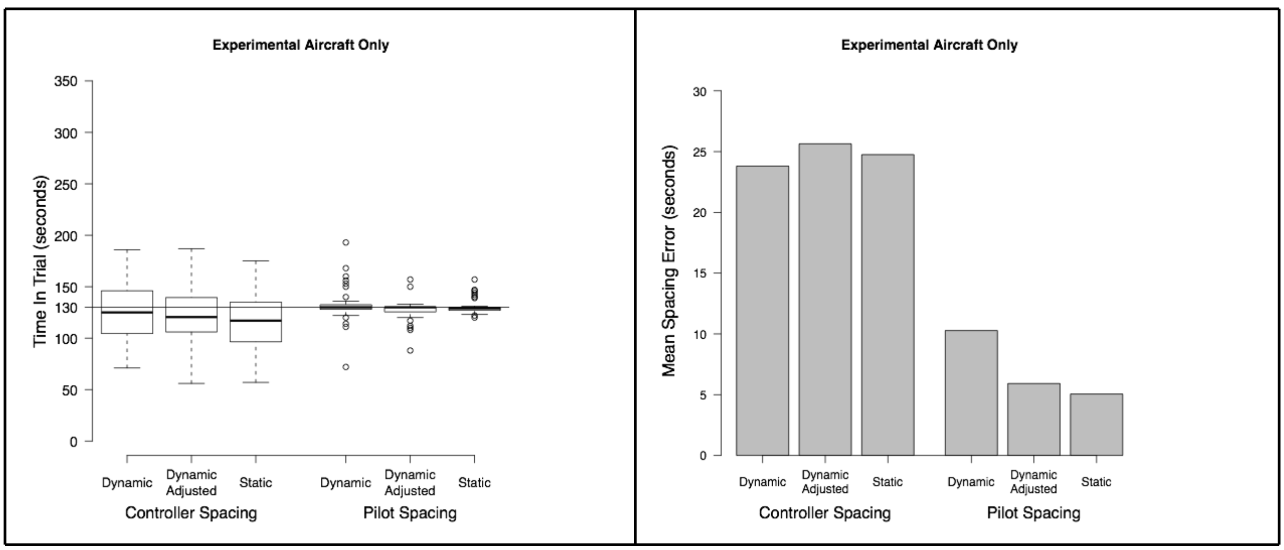

Figure 2: Time in trail and spacing errors at CBSKT, experimentals only.

An ANOVA was conducted on the spacing error at CBSKT with Tree Type and Spacing Responsibility for experimental aircraft only. The effect of Spacing Responsibility was significant, $F(1,5) = 42.84$, $p < .01$ for time in trail. As Figure 2 shows, the mean time in trail variance was smaller and the mean spacing error less for the Pilot Managed Spacing than Controller Managed Spacing trials.

Similar analyses were conducted for all aircraft including those piloted by pseudo-pilots. When all aircraft were included the effect of Spacing Responsibility was again significant ($F(1,5) = 115.16$, $p < .001$). The effect of Tree Type was also significant ($F(2,10) = 7.16$, $p < .05$). A Tree Type by Spacing Responsibility interaction was marginally significant ($F(2,10) = 3.43$, $p = .074$). As Figure 3 shows, the assistance of an on-board spacing algorithm resulted in more precise spacing times for Pilot Managed Spacing trials compared to Controller Managed Spacing trials. On average, flight crews achieved appropriate spacing regardless of tree routing: Static (M = 129.4 sec), Dynamic (M = 128.5 sec), Dynamic Adjusted (M = 128.3 sec). Controllers' spacing performance was worst when they had to manage both deviating flight and interval management in the static trials.

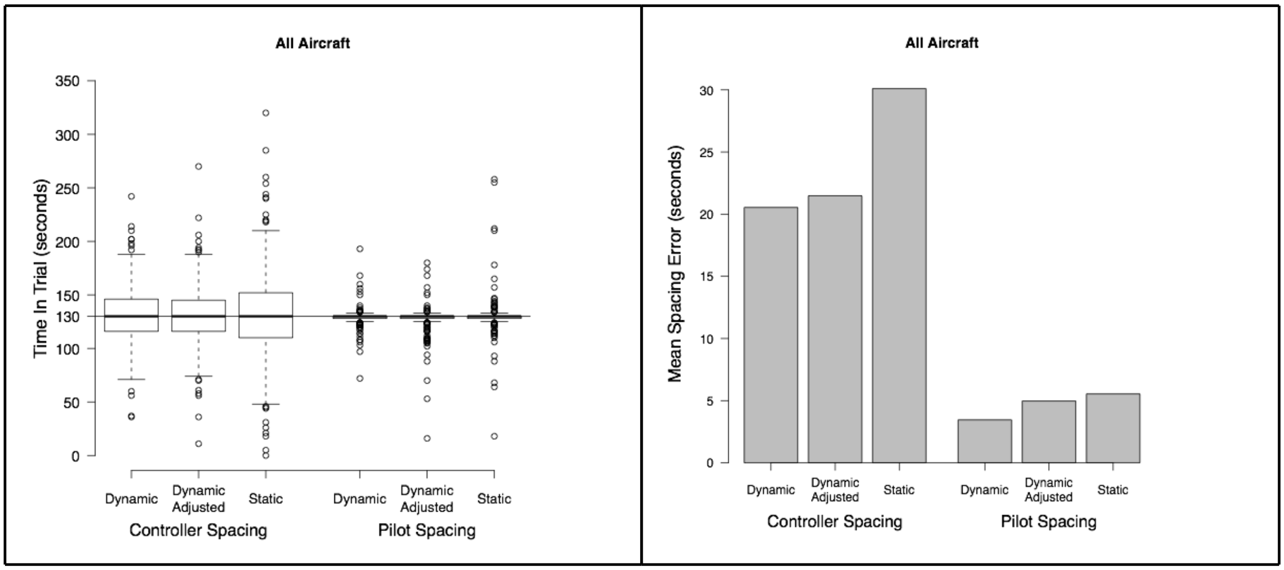

Figure 3: Time in trail and spacing errors at CBSKT, all arrivals.

Separation of Aircraft. Controller data were analyzed for any loss of separation (LOS, less than 5 nm laterally or 1000 ft vertically for IFR/IFR traffic). There was a total of 22 IFR LOSs for all controllers over the course of the study, with only 2 between IFR arrival flights. The remaining 20 LOSs were between IFR arrivals and departures. Controllers had almost twice as many LOSs when managing traffic with the dynamic adjusted routing (13) compared to the Static (6), and the least (3) LOSs in the Dynamic routing condition. However, these differences were not significant.

Hand-off accept time. Hand-off acceptance time refers to the time it took for ATC to accept the handoff of an aircraft entering the sector. When analyzing all aircraft (arrival, departure, and over-flight) in each scenario, a hand-off accept time difference was found between the Controller Managed Spacing (M = 55.5 s) and Pilot Managed Spacing (M = 37.0 s) conditions, $F(1,5) = 374.84$, $p < .001$. There were no differences between Tree Type or any significant interactions. When only analyzing arrival aircraft, a significant difference is again seen between spacing conditions, $F(1,5) = 32.61$, $p < .01$. Hand-off accept times were longer when the controllers were managing spacing (M = 31.4 s) compared to when the pilots were managing spacing (M = 24.1 s). There was also a difference in the handoff accept times between Tree Type, $F(2,10) = 5.71$, $p < .05$. Pairwise comparisons show only a marginal difference suggesting that controllers accepted hand-off faster in the Static (M = 26.0 s) versus Dynamic trees (M = 31.2 s) routing trials, but no differences in acceptance time for Dynamic Adjusted (M = 26.1 s).

Communication

Communication between the flight deck and air traffic control was also analyzed. A total of 216 aircraft were flown by participant flight crews. Each aircraft received a data link message to monitor a new frequency as it entered and exited the active sector. These aircraft also received a data link arrival message; during Pilot Monitored Spacing, this message contained pertinent spacing information.

Of the 216 flights, 48 (22.2%) flew their route without any additional communication with ATC. Three times as many of the Pilot Managed Spacing (36) flights required no additional communication compared to Controller Managed Spacing (12) flights; twice as many flights on the the Dynamic (18) and Dynamic Adjusted (21) routing required no additional communication compared to Static (9) routing.

Overall, more aircraft received a vector while on Static (11) routing compared to Dynamic (2) or Dynamic Adjusted (5) routing. Additionally, twice as many aircraft were vectored during Controller Managed Spacing (12) trials compared to Pilot Managed Spacing (6).

Controllers issued speed clearances to 72 (33.3%) flight decks during Controller Managed Spacing trials. During Pilot Managed Spacing trials, speed clearances were issued to or requested by 9 (4.2%) flight decks. Five of the speed clearances were given either when a flight deck terminated spacing or asked to re-engage spacing. Controllers intervened on 3 occasions and issued new speeds while flight decks were managing spacing and on 1 occasion called out traffic which resulted in the flight deck requesting a new speed.

Workload Ratings

Controllers rated their workload on a 1 Low - 5 Typical - 9 High scale at three-minute intervals throughout each trial. In the controller ratings there was no main effect of Tree Type on controller workload ratings ($p = .26$). There was, however, a main effect of Spacing Responsibility on controller workload ratings, $F(1,5) = 11.66$, $p < .05$. Controllers reported higher workload throughout the trial during Controller Managed Spacing ($M = 5.20$) compared to Pilot Managed Spacing ($M = 4.73$) trials. No interaction was found ($p = .93$).

Display of Tree and Tree Routing

Controller post trial tree ratings. At the end of each trial, controllers were asked to rate items pertaining to the display of the tree and tree routing on a 1 - 9 scale anchored Negatively - Excellent or Low - High depending on the question. In terms of situation awareness and support for managing arrival operations, the controllers reported that overall aid provided by the display of the tree was good ($M = 6.80$/$M = 6.79$) on both measures. When asked, compared to normal traffic flow, controllers rated the aid provided by displaying the tree as slightly lower, but also good ($M = 6.46$). Again, compared to normal sector traffic, controllers rated how many aircraft they could manage with tree routing and reported that they were able to manage more than typical sector traffic ($M = 6.32$). When asked to rate tree complexity the tree type made no difference; Static ($M = 5.44$), Dynamic ($M = 5.50$) and Dynamic Adjusted ($M = 5.50$) routing.

There was, however, a main effect of Spacing Responsibility on rated complexity, $F(1,5) = 30.00$, $p < .01$. Controllers found tree routing to be more complex when they were managing spacing ($M = 5.70$) compared to when pilots managed spacing ($M = 5.26$). Overall the controllers reported that displaying the tree aided in keeping the “Big Picture” of the arrival traffic.

Controller post simulation tree ratings. At the end of the simulation, participants were asked to rate several items pertaining to tree routing on a 5-point Likert scale ranging from 1 Strongly Disagree - 5 Strongly Agree. Controllers were also asked about their preference with managing aircraft. Overall, controllers preferred to manage aircraft using Dynamic ($M = 4.83$) routing compared to Static ($M = 2.5$) routing, $F(1,4) = 22.27$, $p < .01$. Controllers reported that they did not have any problems keeping track of which aircraft were on each of the two (or three) trees being depicted at any one time ($M = 4.33$). Lastly, controllers somewhat agreed ($M = 4.17$) that managing arrivals with Dynamic routing gave them more time and that with more practice or training, they could safely manage a higher traffic density ($M = 4.33$).

Summary and Discussion

A large simulation like this creates a very large data set with many findings. Statistically, a few differences will be found to be significant when no real difference exists and some will not be found significant even when real differences do exist. It is important, therefore, to look at which differences show up repeatedly, across a variety of measures, and which show up rarely or not at all. In doing so, a few generalizations become clear:

- Pilot spacing is rated superior to controller spacing, especially by controllers.
- In the presences of dynamic routing it was important to display the arrival tree

We will briefly discuss each of these.

Pilot vs Controller Spacing

Controllers rated their workload lower when the pilots were responsible for spacing on every measure of workload. These differences were significant for real-time workload and their post trial rating of workload associated with maintaining separation. Additionally, controllers had fewer LOSs, reduced number of communications and shorter handoff time. Overall, spacing performance at the arrival meter fix was significantly improved with pilot managed spacing. Controllers also rated the tree routing structures as being more complex when controllers managed spacing (interestingly, since objectively they were the same). The effects of Spacing Responsibility did not appear as consistently in the pilot ratings; although they did rate workload associated with avoiding weather higher when the controllers were responsible. This might be explained by the increase in controller workload slowing their response times to requests. Thus, responsibility for spacing does not appear to increase the pilots' workload. This is perhaps unsurprising since the pilots were given tools that automated their spacing task.

Display of Arrival Tree

Controllers reported that displaying the arrival tree in all three tree conditions aided in situation awareness and in traffic management. Controller reported that they could work more than typical sector traffic with the arrival tree displayed on their DSR, and that they aided in maintaining the "Big Picture."

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Acknowledgements

This study is a follow on to concept development work and fast-time explorations conducted under an Airspace Systems NRA led by Jimmy Krozel and Joe Prete of Metron Aviation, with significant help from Phil Smith of The Ohio State University.

Authors Contact Info: Vernol Battiste, NASA Ames Research Center, MS 262-2, Moffett Field, CA 94035; PH 650-604-3666; vernol.battiste@nasa.gov